Energy Clusters Offshore: A Technology Feasibility Review

Chloe Constant, Caitlyn Clark, Masha Koleva, Kaitlin Brunik, Jared Thomas, Matthew Kotarbinski, James Niffenegger, and Jochem Weber

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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List of Acronyms

CAPEX	capital expenditures
CHP	combined heat and power
DC	direct current
DOE	U.S. Department of Energy
ECO	energy cluster offshore
FCR	fixed charge rate
FOWT	floating offshore wind turbine
FP	fixed pitch
FPV	floating solar photovoltaics
FS	fixed speed
H2A	Hydrogen Analysis
H2FAST	Hydrogen Financial Analysis Scenario Tool
H2FillS	Hydrogen Filling Simulation
HAWT	horizontal-axis wind turbine
HOMER®	Hybrid Optimization of Multiple Energy Resources
HOPP	Hybrid Optimization and Performance Platform
IRENA	International Renewable Energy Agency
IRA	Inflation Reduction Act of 2022
LCOE	levelized cost of electricity
LCOH	levelized cost of hydrogen
MHK	marine hydrokinetic
MMT	million metric tons
MOF	metal organic frameworks
NG	natural gas
OPEX	operating expenditures
ORCA	Offshore Regional Cost Analyzer
OTEC	ocean thermal energy conversion
OWT	offshore wind turbine
PEC	photoelectrochemical
PV	photovoltaic
REopt®	Renewable Energy Integration and Optimization
reV	Renewable Energy Potential Model
RODeO	Revenue, Operation, and Device Optimization
SAM	System Advisor Model™
SDOM	Storage Deployment Optimization Model
TLP	tension-leg platform
TRL	technology readiness level
VAWT	vertical-axis wind turbine
VP	variable pitch
VS	variable speed

Executive Summary

The energy system of the future will need substantial amounts of renewable energy deployment to meet 100% of direct carbon-free electricity demand and to support further electrification and decarbonization of the economy. There is a growing push globally towards decarbonization, including with targets set by numerous countries including the European Union, China, and the Unites States, whose goal is to achieve net-zero carbon by 2050. In addition, businesses, cities, and other organizations are setting their own goals for decarbonizing. These efforts put significant emphasis on the need to produce renewable fuels to power sectors including transportation, buildings/heating, and other hard-to-abate industries at a large scale. One potential pathway for achieving this scale of decarbonization technologies is by deploying energy clusters offshore.

An energy cluster is an integrated and optimized system of renewable electricity generation, storage, and renewable fuel technologies that can be paired with other complementary technologies, such as carbon capture and water desalination, and direct end uses, such as production of renewable shipping fuels, industry sectors, etc. An energy cluster can be located onshore or offshore. However, locating the clustered system offshore will take advantage of the huge offshore renewable energy potential (from offshore wind, offshore solar, marine hydrokinetics, etc.) that can deliver the massive scale and flexibility necessary to transform the energy sector and link directly to critical end uses less available on land. By further optimizing the design of the integrated, fully coupled system, an energy cluster may be able to achieve transformational efficiencies to make it more cost effective, and if carefully designed, further address other key challenges facing society including greenhouse gas emissions, clean water, and food production. Figure ES-1 represents an example configuration, including potential core energy technologies of offshore energy clusters.

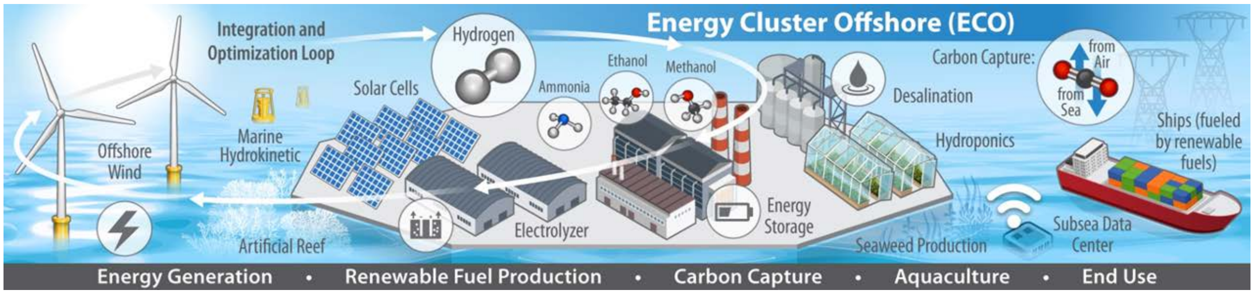

Figure ES-1. Potential core components of offshore energy clusters

In this report, we compare candidate technologies, including renewable power generation, clean fuels production, storage, and usage, to determine those with the highest potential for inclusion in an offshore energy cluster. We then make site and tool selections based on comparative analysis for future work in capability development, and system integration, modeling, and analysis.

Key Findings

Within energy generation technologies, offshore wind turbines (OWT) – floating and fixed bottom, floating solar photovoltaic (PV), tidal and wave energy, and ocean thermal energy conversion technologies have been assessed based on their levelized cost of electricity (LCOE), technology readiness level (TRL) and power generation potential in the United States. The summary of the metrics is provided in Table ES-1, from which it can be concluded that out of the studied options, fixed bottom OWTs have the highest TRL and largest energy generation potential i.e., ~13,500 TWh/year while the LCOE remains one of the lowest i.e., \$0.06 - \$0.11/kWh. Floating OWTs have the second highest potential to fixed-bottom OWTs, with a slightly higher estimated LCOE, varying between ~\$0.07/kWh and ~\$0.17/kWh. According to our findings, floating solar PV is another suitable candidate, with relatively high technical readiness, and economic and production potentials.

Table ES-1. Renewable Power Generation Technologies Comparison

Offshore Power Generation Technology	Low-end cost (\$/kWh)	High-end cost (\$/kWh)	TRL	Potential in the U.S. (TWh/year)
Fixed bottom OWT	0.06	0.11	high	13,500
Floating OWT	0.07	0.17	medium-high	13,500
Floating solar PV	0.05	0.10	medium-high*	4,600
Tidal energy	0.20	0.46	medium	220
Wave energy	0.30	0.55	medium	1,400
Ocean thermal energy conversion	0.04	0.94	low	4,100

Source: [1–3]

* TRL refers to waters with low wave categories.

A comparison of select hydrogen production technologies is shown in Table ES-2.[i]

Electrolysis is the only clean technology for producing hydrogen with a high TRL. It must be noted that costs of all the technologies, aside from electrolyzers, are reported for R&D and lab scale, meaning that they may not be cost competitive at large scale yet. Costs for renewable-based electrolysis vary between ~\$2/kg H_2 and ~\$12/kg H2, depending on the resource availability, renewable-electrolyzer configuration, interaction with the grid, and capital cost and scale of electrolyzer. According to the processes' techno-economic-environmental performance, biomass gasification could have potential as a feasible hydrogen production technology, however, it may be hard or impractical to deliver the biomass feedstock to the offshore location where hydrogen would be produced.

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[i] This report also compares hydrogen production and storage to other renewable fuel technologies, namely ammonia and methanol, but we summarize hydrogen technologies here because both ammonia and methanol are derivatives of hydrogen and no extensive techno-economic comparison has been done for using ammonia and methanol as forms of shipping hydrogen. For more information, see the main body of the report.

Table ES-2. Hydrogen Production Technologies Comparison

Technology	Low-end cost ($/kg H_2)	High-end cost ($/kg H_2)	TRL	GHG emissions (kg CO2e/kg H_2)	Efficiency (%)
Wind PEM electrolysis	2	11	high	0.6	~60%
Solar PEM electrolysis	3	12	high	2	~60%
Direct solar water splitting	2	10	low	2	~20%
Fermentation	7	8	low-medium	15	~10%
Bio-photolysis	1	18	low	N/A	~15%
Biomass gasification	1	5	medium	<4	~50%-60%

Source: [4–9]

When selecting hydrogen storage technology (see Table ES-3), besides cost and maturity, space constraints and boil off (i.e., gas escaping) are additional aspects to consider. Our storage benchmarking suggests that subsea compressed gaseous storage could be promising, but only if it is used for long-term storage, due to the challenges in charging and discharging. Although it does not have a high TRL, liquid material-based storage has promising performance and costs comparable to gaseous storage, hence, could be studied for offshore energy clusters. An alternative, depending on distance to shore, is to transport hydrogen to the shore and store it as a compressed gas in vessels or even geologic formations, if available. Due to its higher cost, boil off, and energy required for operation, liquid hydrogen storage may not be a good fit for an offshore energy cluster.

Table ES-3. Hydrogen Storage Technologies Comparison

	Low-end cost ($/kWh)	High-end cost ($/kWh)	TRL
Gaseous storage in overground pressure vessels	13	17	high
Liquid storage in overground vessels	10	30	high
Material-based storage	2	170	low-medium
Storage in salt caverns	0.5	4	medium

Source: [10–14]

End uses for hydrogen are integral to its uptake and the success of production and storage technologies. Earlier in 2022, HFTO released the National Clean Hydrogen Strategy and

Roadmap,[15] which not only outlines targets of 10 MMT, 20 MMT and 50 MMT by 2030, 2040 and 2050, respectively, but also looks at specific applications where clean hydrogen demand is projected to increase. Figure ES-2 provides a breakdown hydrogen demand by application. In applications such as ammonia and chemical refineries, the only option for decarbonization is clean hydrogen, however, hydrogen application does not require technology or process retrofitting because of the current usage of H_2 in those sectors. Thus, near-term demands are expected to be predominantly dictated by the chemical industry. An opportunity for ECO systems could be to strategically locate at sites adjacent to both potential industries that could offtake clean hydrogen in addition to serving as refueling ports for ships and export ports.

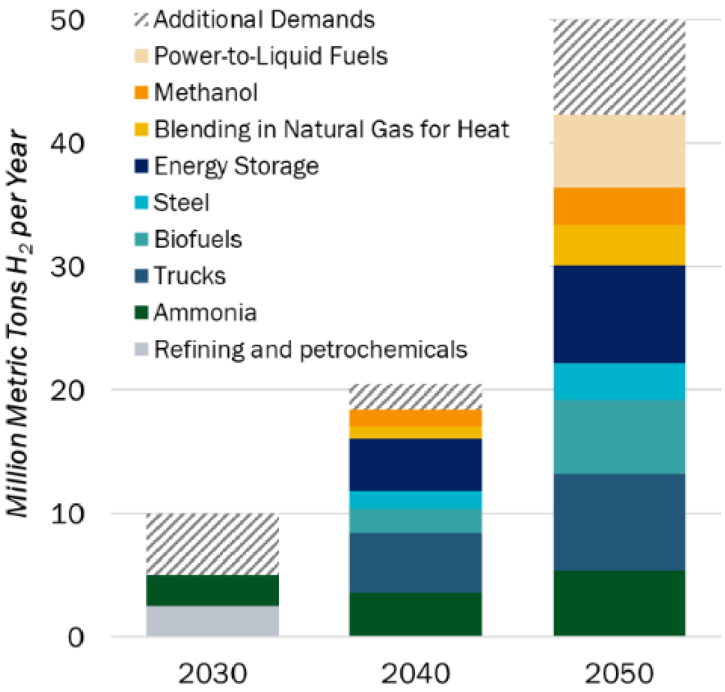

Figure ES-2. Hydrogen storage technologies comparison

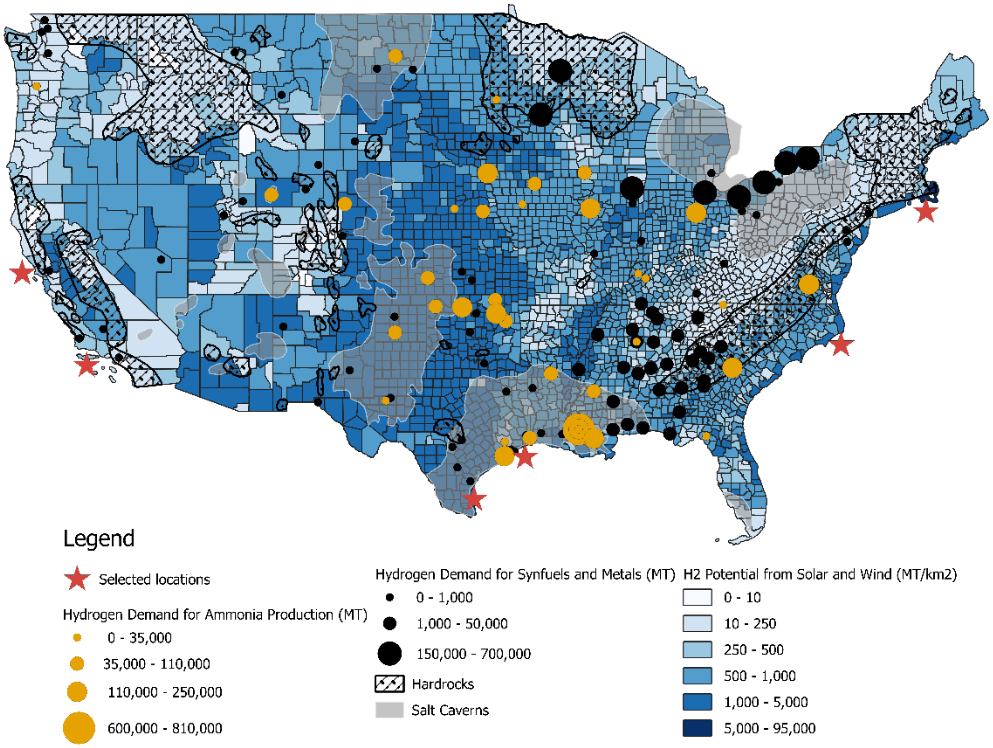

Figure ES-3. Selected locations for ECO

To explore deployment of ECOs, six indicative locations have been selected for initial analysis as shown in Figure ES-3. It must be noted that the sites are indicative and may serve as case studies rather than representation of any planned or proposed projects. Locations 1 and 2 are located off the coast of California because of the highest combined resource values in the United States. The only downside to these locations is the positive complementarity values, which indicates that the wind and solar power are being generated at the same time. The highly abundant resources likely increased the probability of wind and solar resources coinciding leading to positive complementarity. Regardless, the installation of ECOs in California would still perform well given the abundant resource. Locations 3 and 4 are located off the coast of Texas. Location 3 has the highest combined resource percentage after the California locations. The high resource abundance in combination with the low complementarity values are ideal for hybrid renewable farms. The Texas ECOs can power desalination and data centers like the California ECOs. Additionally, the Texas locations can take advantage of the existing natural gas pipeline infrastructure to transport hydrogen. A percentage of hydrogen can be pumped through the pipelines alongside the natural gas, therefore saving on construction costs. Locations 5 and 6 are situated on the east coast of the United States. Location 5 is off the coast of North Carolina. Location 6 is in New England, roughly off the coast of Rhode Island. These locations both have low complementarity values and high resource abundance.

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1 Introduction

The energy system of the future will need substantial amounts of renewable energy deployment to meet 100% of direct carbon-free electricity demand and to support further electrification and decarbonization of the economy. There is a growing push globally towards decarbonization, including with targets set by numerous countries including the European Union, China, and the Unites States, whose goal is to achieve net-zero carbon by 2050. In addition, businesses, cities, and other organizations are setting their own goals for decarbonizing. These efforts put significant emphasis on the need to produce renewable fuels to power sectors including transportation, buildings/heating, and other hard-to-abate industries at a large scale. One potential pathway for achieving this scale is deploying energy clusters offshore.

1.1 Description of the Energy Cluster Offshore (ECO) Concept

An energy cluster is an integrated and optimized system of renewable electricity generation, storage, and renewable fuel technologies that can be paired with other complementary technologies and direct end uses like carbon capture, water desalination, production of renewable shipping fuels, industry sectors, etc. An energy cluster can be located onshore or offshore, however locating the clustered system offshore will take advantage of the huge offshore renewable energy potential (offshore wind, offshore solar, marine hydrokinetics, etc.) that can deliver the massive scale and flexibility necessary to transform the energy sector and link directly to critical end uses less available on land. By further optimizing the design of the integrated system, it can achieve transformational efficiencies to make it cost effective, and if carefully designed, it can go a step further to address other key challenges facing society including carbon capture, clean water, and food production. Figure 1 represents an example configuration, including the potential energy technologies that will be integrated and optimized as part of this project, as well as other potential components and end uses that could form part of the cluster.

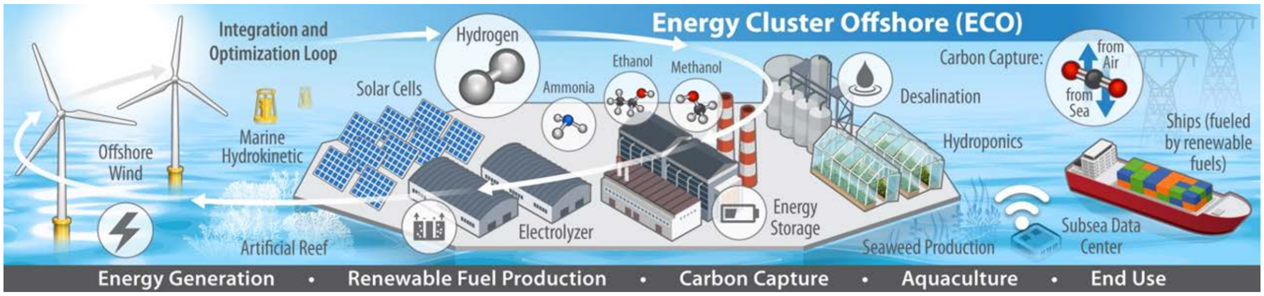


Figure 1. A nominal ECO design including potential complementary technologies

1.2 Purpose of This Report

In this report, we will identify and select the priority components to include in an energy cluster and map across their optimal conditions and key functional requirements (e.g., resource, location, size and scale, depth, etc.) to determine potential configurations. This report aims at identifying the types of components that should be included and other key technological and market considerations that need to be addressed to deploy an energy cluster. Using the results from the component map, we will perform a high-level feasibility analysis of the most promising configurations and technology combinations. The most promising potential configurations and resource/load combinations will be leveraged in system modeling, integration, and optimization, which will be documented in subsequent reports.

1.3 Research Questions To Be Answered

This work is attempting to answer the following research questions:

- What technologies are techno-economically suitable and have the Technology Readiness Level (TRL) for inclusion as components of ECO systems?
- What technologies can be combined into an ECO system?
- Where ECO clusters would be beneficial, particularly in the U.S.?
- What approaches could help determine the optimal design and operation of ECO systems?
- What are the critical techno-economic cost and performance drivers of a ECO system?
- What are the key risk and opportunity drivers in relation to robustness against failure and impact, respectively?
- How would the optimal integrated energy system vary based on differing design objectives, resource availability, physical conditions, and technologies considered?

The remainder of the report is structured as follows: Section 2 provides an overview of candidate ECO centers components i.e., renewable power generation technologies, clean fuel production technologies with a focus on hydrogen, hydrogen storage technologies and end-uses, carbon capture and storage technologies, and other potential applications. The potential of the technologies is assessed based on techno-economic published literature and maturity of the technologies. Based on the comparison, a few technologies from each sub-section are shortlisted for inclusion in the techno-economic analysis and modelling effort in Phase II of the project. Section 3 presents potential locations for ECO systems and methodology for their selection. Section 4 discusses policies and incentives ECO centers could potentially qualify for. NREL’s available modeling tools and which ones can be leveraged for future effort are discussed in Section 5. The report concludes with major takeaways and next steps.

2 ECO Systems Components

2.1 Energy Generation Technologies

In this section, major commercial and emerging renewable energy generation technologies are reviewed, along with their techno-economic parameters, and compared to one another.

2.1.1 Offshore Wind

Offshore wind power is generated by wind turbines at sea, where higher and more consistent wind speeds enable greater electricity generation per capacity installed. Different spatial and logistical constraints allow for larger turbines with higher capacity to be deployed offshore compared to onshore counterparts. These wind turbines are designed to achieve 25-year turbine operating performance reliably and efficiently. The floating wind turbine capacity is considerably altered by the stochastic nature of the sea environment with wind, waves and currents causing relative motions on the platform leading to uncertainties in energy capture and structural loads. Therefore, a floating offshore wind turbine (FOWT) requires appropriate control schemes to achieve higher energy production rates in safe conditions and to lower maintenance operation costs through health monitoring systems.[16]

Wind turbines can have vertical axis (VAWT), where the rotating axis is perpendicular to the air stream, or horizontal axis (HAWT), where the axis is parallel to the air stream. The most deployed type of turbine is the HAWT with three blades. Apart from this differentiation, turbines can be assembled with fixed-pitch (FP), or variable-pitch (VP) and they can be fixed-speed (FS) or variable-speed (VS), which allows for four different configurations. Large-scale wind turbines are manufactured with VSVP operation mode to simultaneously control the rotor speed and the blade pitch angle.[16]

Three levels of control are typically programmed for wind turbines, i.e., (1) supervisory control or high-level control is responsible to start up the wind turbine when favorable wind speed is reached and shutdown in case of high winds; (2) operational control, or intermediate level control, oversees fulfilling the control objectives during the wind turbine operation; (3) subsystem controls are in charge of the mechanism actuation such as blade pitching, nacelle yawing and generator power electronic unit.[16] The operation mode of the turbine depends on the wind speed, which is divided into 4 distinct regions: (1) zone below cut-in speed of approximately 3 m/s wind speed where the turbine would not operate; (2) Region 2 between cut-in speeds and rated power speeds (~11 m/s); (3) rated power operation in Region 3 (~11 – 25 m/s wind speeds) and (4) cut-out wind speed above 25 m/s defines Region 4, in which the turbine is not recommended for operation.[16] The Regions are depicted in Figure 2.

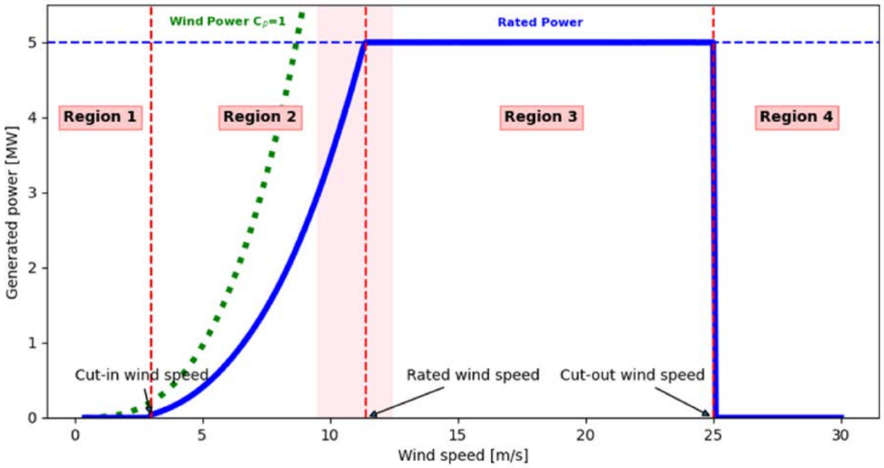


Figure 2. Regions of power generation of turbines based on the wind speed[16]

Offshore wind turbines (OWT) are designed to withstand the ocean environment, higher wind speeds and storm waves, and they are fixed to the ocean floor either by fixed-bottom foundation or anchors. Depending on the sea water depth, OWTs can be categorized into fixed OWT and floating OWT, as shown in Figure 3.[17]

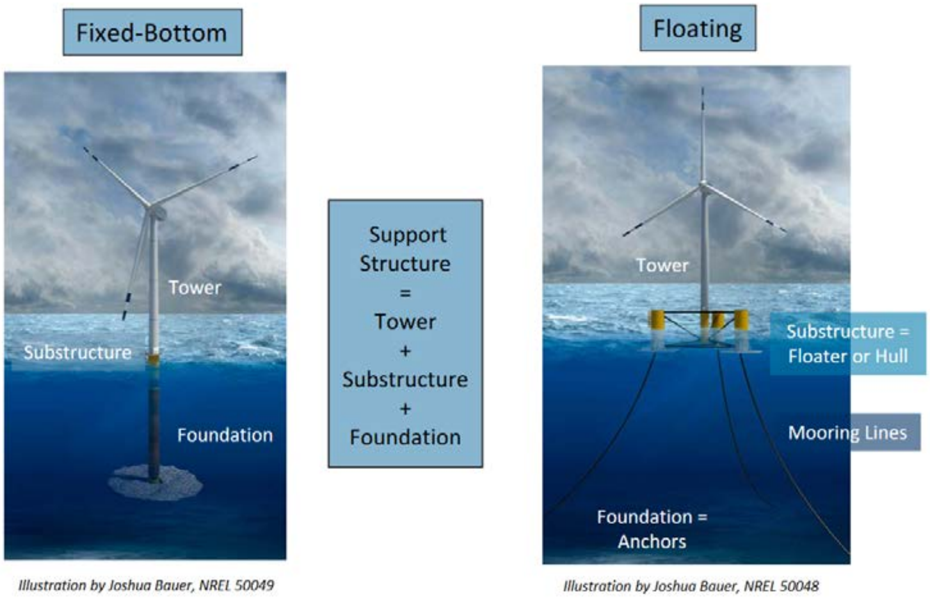


Illustration by Joshua Bauer, NREL 50049

Illustration by Joshua Bauer, NREL 50048

Figure 3. Two major types of offshore wind turbines depending on their foundation design are fixed-bottom turbines (left) and floating turbines (right)

Floating HAWTs have been tested at large scale, hence, their TRL is relatively high unlike VAWTs with floating platforms, which have not reached the same level of maturity yet. When new configurations or components are added to wind turbine systems, the TRL changes. For instance, some floating wind turbine projects currently have TRLs of up to 4-5 and TRLs are even lower for floating platforms designed for deep waters and hybrid systems.[18]

2.1.1.1 Fixed Offshore Wind Turbines

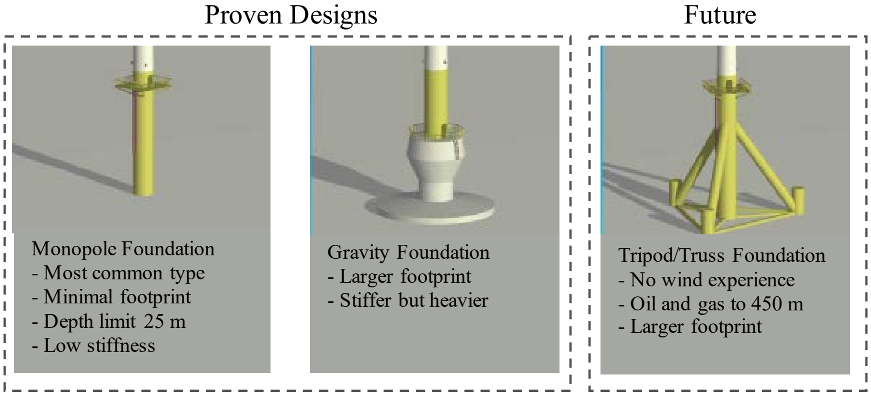


Figure 4. Offshore wind fixed bottom technology options

Fixed OWT are preferred choice for shallow waters with depths in the range 0 m - 60 m with monopile or jacket foundations.[16,19] Typical fixed bottom structure technologies are depicted in Figure 4.[20] Many OWT technologies have already reached a high technology readiness level (TRL).[21]

The total CAPEX of an 8 MW rated OWT (rotor diameter 159 m and hub height of 102 m), including turbine capital cost, balance of plant, along with other financial considerations, is approximately $3,800/kW.[22] The resulting levelized cost of electricity (LCOE) amounts at roughly $77/MWh. According to the same study, the sensitivity analysis shows that capital expenditures can span from ~$2,000/kW to ~$6,000/kW, as shown in Figure 5 below.

Figure 5. Fixed-bottom offshore wind power plant assumption and ranges for LCOEs

2.1.1.2 Floating Offshore Wind Turbines

With the increase of water depth, the costs and technical challenges of fixed foundations raise. In such cases, floating OWTs become a preferrable technology. The basic floating offshore wind turbine (FOWT) foundation concepts are listed as barge, spar, and tension leg platform (TLP)[16] and depicted in Figure 6.

Figure 6. Types of floating OWTs, from left to right: spar-buoy, tension leg and barge stabilization concepts

Each of the floating foundation types presents its own buoyancy principle, achieving some stability through it. The barge is stabilized by the large water plane area and hence by the hydrostatics. The spar foundation is restored due to a ballast allocated at the bottom of the structure generating a restoring moment due to the great distance between gravity and buoy centers. The stability of the tension-leg platform (TLP) is a consequence of the tension of the mooring lines.[16] Floating OWT technologies are no longer confined only to R&D but have transitioned to a higher TRL.[23]

NREL has conducted a number of studies to estimate the techno-economics of floating wind turbines of sizes varying from MW- to GW-scale.[22,24,25] The studies estimated LCOEs of ~$70/MWh to ~$170/MWh (see Figure 7) for turbines ranging from commercial size down to 8 MW rated power. According to NREL's 2020 study,[24] LCOE would decrease by 47% from 2019 to 2032.

Challenges associated with modeling future cost projections of commercial-scale floating OWT come down to sparse data availability only associated with lab-scale or pilot-scale. The current largest size floating array is five 6-MW turbines on floating spar platforms.[24] There are costs which are specific for floating structures such as substructure and foundation costs for dynamic array cables, installation, and maintenance. Such cost data are derived from proprietary industry data.

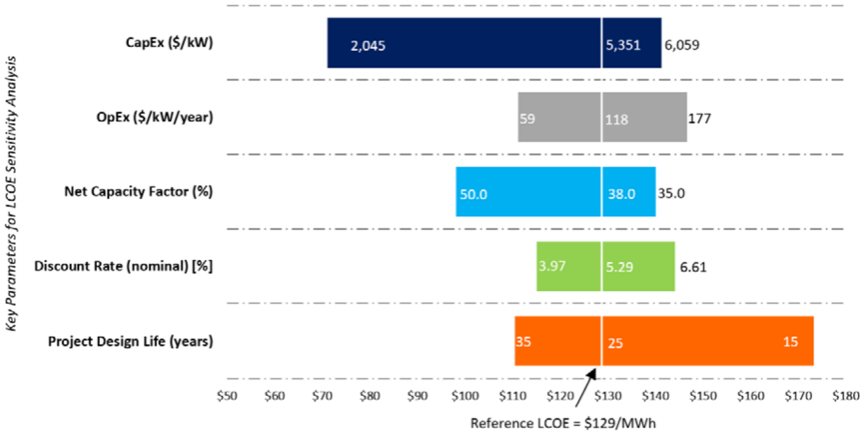


Figure 7. Floating offshore wind power plant assumption and ranges for LCOEs based on sensitivity analysis[22]

2.1.2 Floating Solar Photovoltaics (PV)

A floating solar photovoltaic (FPV) system is an emerging technology in which a solar photovoltaic (PV) installation is placed directly on top of a body of water, as opposed to on land or on building rooftops. FPV can be categorized into four groups based on the wave heights they could withstand, namely, negligible, 1 m, 2 m, and 10 m height waves.[26] A schematic of an FPV system is depicted in Figure 8.[27]

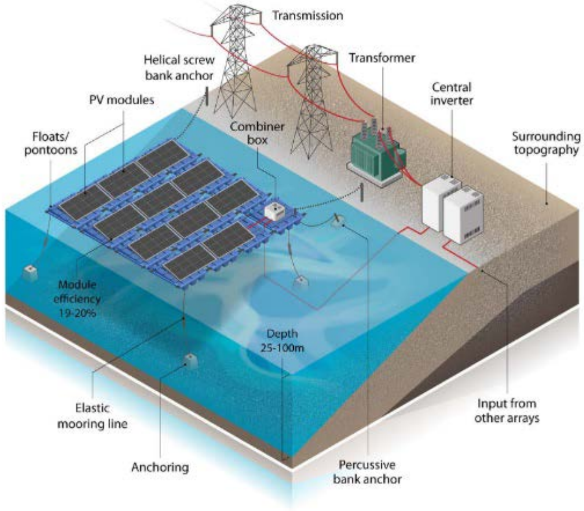


Figure 8. Schematic of a floating PV system[26]

Compared to land-based PV systems, FPV stations demonstrate unique energy and non-energy advantages, expressed as power conversion efficiency gains due to lower ambient temperatures underneath both, directly and indirectly sited-on-water panels. FPV performance research is nonetheless in its infancy.[28]

Despite existing FPVs on floating membrane platforms in coastal areas around the world, the TRL level for high wave categories remains low.[26] The FPV stations, however, are an expanding market globally with installation projections of ~1.6 GW by the end of 2022.[29] The capacity of FPV deployment in the U.S. represents ~7% of the global installations.

Techno-economic analysis performed[27] indicates that FPV's LCOE is 20% higher than ground-mounted PV systems. The analysis does not capture full proposition of FPV systems and excludes investment tax credit but provides a range of \$1.05/W$_{DC}$ - \$1.68/W$_{DC}$ based on system capacity between 2 MW - 50 MW (see Figure 9). The levelized cost of electricity would vary with location, too, where analysis and already deployed projects suggest a \$0.051/kWh - \$0.08/kWh values.[30,31]

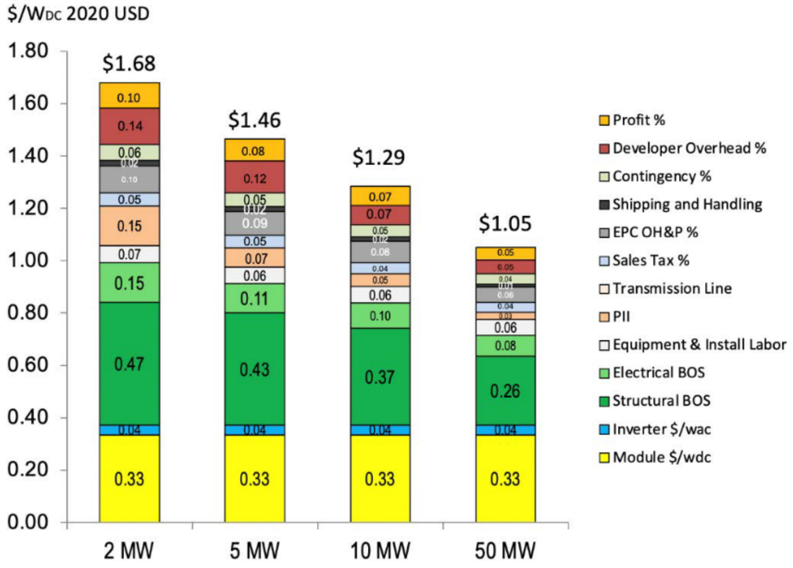
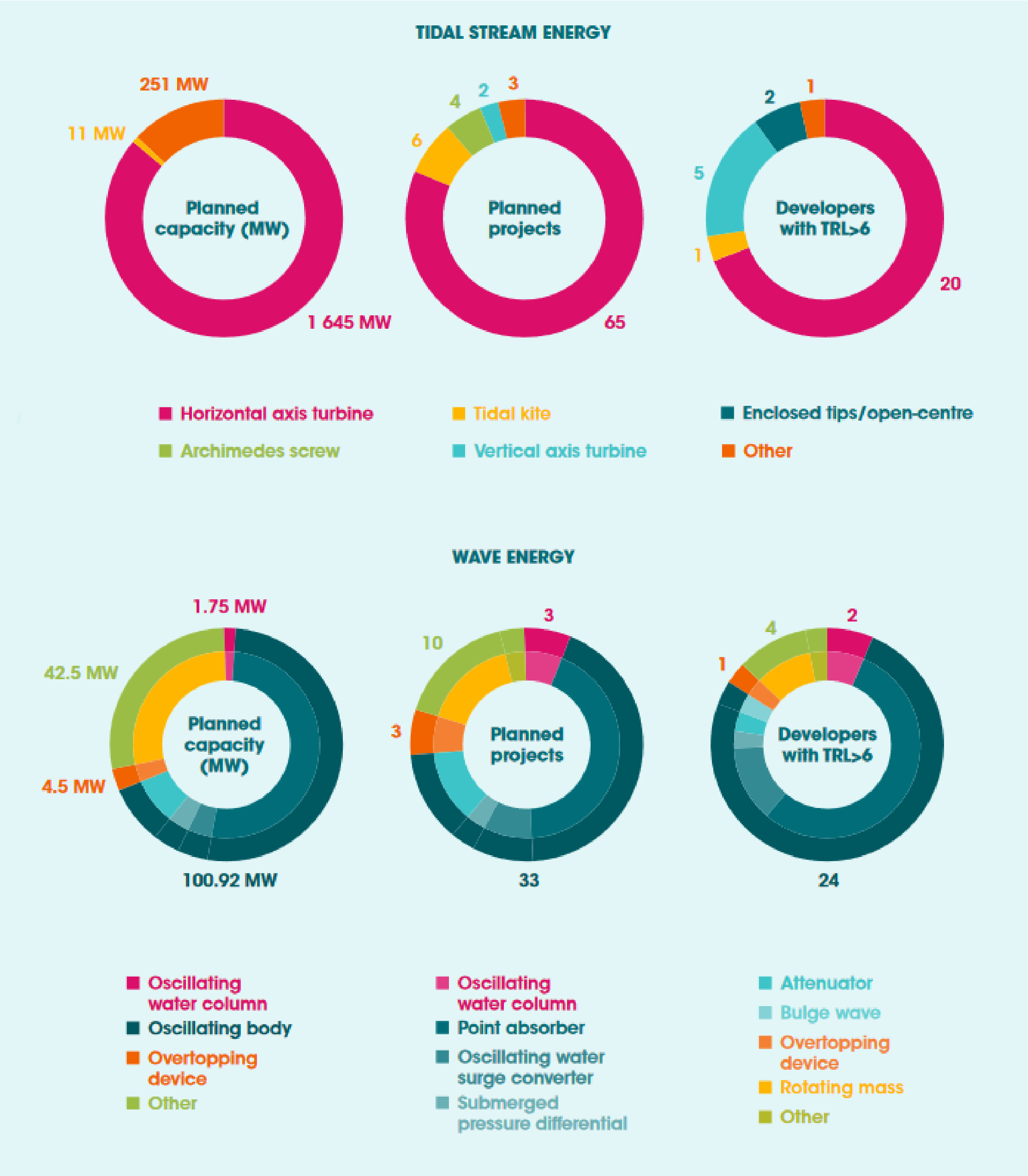


Figure 9. Benchmark cost for floating PV system with varying sizes

2.1.3 Marine and Hydrokinetic Technologies

Marine hydrokinetic (MHK) energy is an emerging but promising technology from the renewable energy portfolio that offers high predictability and supplementary energy sources for a diversified energy economy.[32] MHK technologies convert the energy of waves, tides, and river and ocean currents into electricity.[33] When determining the potential of MHK, aspects to consider include the available power density, spatial structure and temporal variability, proximity to land, population centers and connections to inland power grid. From a technical design perspective, typical considerations encompass (1) the type of prime hydrodynamic energy convert archetype and associate, mooring, anchoring and umbilical systems; (2) the total water depth and bottom type; (3) hydrodynamics variations defining operational and survival conditions; (4) and turbulence levels within the water column. The economics of MHK projects vary with the selected site, however, there is scarcity of data associated with permitting and the multitude of associated environment and social requirements such as conflicting use. General knowledge of seasonal resource variability and extreme event likelihood are available for instance though hindcast data models. It is expected that as the sector continues to grow and mature, costs will be more well-defined and will flow characteristic leaning curves for technologies of this type when under commercial production and operation in future.[32]

The International Renewable Energy Agency (IRENA) have projected the tidal and wave capacities beyond 2020 at respectively, ~1.9 GW and 150 MW globally (see Figure 10). Out of these totals, only 2% is the projected share of the United States.[34] It has been estimated that ~40% of the tidal projects and ~60% of the wave projects are above TRL 6.



Note: *The Technology Readiness Level (TRL) is a scale from 1 to 9 where 1-3 represents the research phase, 4-5 the development phase, 6 the demonstration phase and 7-9 the deployment phase (with 7 representing prototype demonstration and 9 a fully deployed, proven and operational technology).*

Source: *IRENA ocean energy database*

Figure 10. Projected capacity and number of project developers by MHK technology according to IRENA[34]

Figure 11 shows levelized cost of electricity for three current and three wave energy converters. These reference models can serve as a benchmark for future devices design. The research demonstrates costs between ~\$0.3–\$2.3/kWh, depending on the installed capacity of the system[35]. According to IRENA, the LCOE ranges for ocean energy are lower than initially estimated. They point \$0.2/kWh–\$0.46/kWh for tidal and \$0.3/kWh–\$0.55/kWh for wave energy.[34] Across all research, there exists an agreement that the MHK costs are difficult to predict and uncertain.

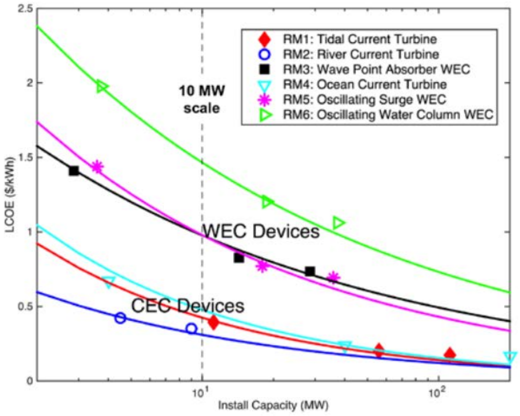


Figure 11. Levelized cost of energy for different installed capacities of marine hydrokinetic technologies; RM = reference model[35]

2.1.4 Emerging Conversion Technologies

According to IRENA, besides the tidal and wave energy technologies, potential for picking up at the end of the decade for other ocean energy systems have ocean thermal energy conversion (OTEC), salinity gradient and ocean current technologies. OTEC energy potential globally is calculated at ~44,000 TWh per year—the largest potential of all ocean energy technologies.[34,36] These technologies have been estimated to have LCOE of ~\$0.04/kWh–\$0.94/kWh, depending on the project size.[37,38] OTEC technologies remain at a low TRL level i.e., ~1–3 TRL, until technical and economic challenges are addressed by research institutions.[34]

Combining different clean offshore technologies into hybrids e.g., offshore wind—floating solar PV or wind offshore—MHK systems, etc., is another emerging potential for having complementary sources for increased power generation and lowered LCOE.

2.1.5 Comparative Analysis

In this section, the major technologies which have been discussed are compared. The systems with the lowest overall LCOEs, highest TRL and largest electricity generation potential are the OWT and FPV technologies. Although marine hydrokinetic technologies have remaining challenges to be addressed in obtaining better understanding of the marine technical resource, energy dissipation in turbine wakes, support structures of the turbines, economic viability with current conditions – array interactions, etc., they also have a substantial projected deployment and promising techno-economic performance and so will be explored further in the analysis.[3]

Table 1. Renewable Generators Comparison

Offshore Power Generation Technology	Low-end cost ($/kWh)	High-end cost ($/kWh)	TRL	Potential in the U.S. (TWh/year)
Fixed bottom OWT	0.06	0.11	~7-9 (high)	13,500
Floating OWT	0.07	0.17	~7-8 (medium-high)	13,500
Floating solar PV	0.05	0.10	~6-8 (medium-high)*	4,600
Tidal energy	0.20	0.46	~6 (medium)	220
Wave energy	0.30	0.55	~6 (medium)	1,400
Ocean thermal energy conversion	0.04	0.94	~1-3 (low)	4,100

* TRL refers to lower wave categories

2.2 Low-Carbon Fuel Production Technologies

In addition to utilizing renewable energy sources to generate electricity to meet the demand/load of energy clusters offshore, the excess electricity that is not consumed can also be used for the conversion to clean fuels such as with hydrogen and ammonia. Specifically, the existing clean fuel production technologies and processes are discussed in this section.

2.2.1 Hydrogen

Hydrogen, one of the most abundant elements in the universe, has been identified as a catalyst to helping decarbonize hard-to-abate sectors such as with long-haul transportation and heavy industry including steel and chemical production. The Biden Administration has taken recent efforts to prioritize the hydrogen economy in the United States through various bills and political frameworks designed to help reduce deployment barriers of maturing the hydrogen economy.

Together, with the Department of Energy, Commerce, and Interior, the 2035 100% renewable electricity and 2050 carbon neutral targets have been announced to support energy security and to combat the effects of climate change. Additionally, the signing of the Bipartisan Infrastructure Law followed by the recent signing of the Inflation Reduction Act, are allowing for billions of dollars of investment in hydrogen and hydrogen-related technologies, hydrogen hubs, and allocating production tax credits of up to $3/kg H_2 for low-carbon and clean energy generation facilities. Furthermore, the DOE’s Hydrogen and Fuel Cell Technologies Office released a National Clean Hydrogen Strategy and Roadmap,[15] targeting demand of clean hydrogen of 10 MMT per year in 2030 and 50 MMT per year in 2050. The demand is projected to be driven predominantly by the chemical industry, hard-to-abate sectors, storage for power generation, transportation, heat, and exports. Lastly, the Department of Energy’s Hydrogen Shot goal of reducing the cost of hydrogen to $1 per 1 kilogram of hydrogen produced in 1 decade is another initiative designed to help expedite clean hydrogen maturity and economic feasibility.[39]

The incumbent process for producing hydrogen is through steam methane reforming (SMR). Recently, proton exchange membrane (PEM) electrolysis has been gaining inertia and is already deployed at industrial scales worldwide. When paired with renewable-based electricity sources, the hydrogen produced has nearly neutral greenhouse gas emission intensity. As ECO systems require clean fuel production, SMR necessitates capture and storage for the emitted greenhouse gases, therefore this process, as well as coal gasification methods, are not considered as an option in this work.

2.2.1.1 Proton Exchange Membrane (PEM) Electrolysis

In PEM electrolysis, direct current (DC) voltage causes the separation of deionized water to protons (H^+ ions), oxygen, and electrons, where the protons are carried through the proton conductive membrane to the cathode. The electrons are transported to the cathode through the power supply circuit. The protons and electrons combine on the cathode (negative electrode) side to form hydrogen. The membrane thickness is normally less than 0.2 mm and the materials which make up the electrodes are noble metal alloys, e.g., platinum (Pt) or iridium (Ir).

PEM electrolyzers are characterized by their high efficiency, compact design, and fast response to electricity supply fluctuations. The latter makes the technology a suitable option for coupling with intermittent power sources such as wind and solar renewables. Balancing PEM-based technology plants is easier in comparison to other existing electrolysis technologies i.e., alkaline, and solid oxide electrolyzers, which translates to more desirable commercial operation. PEM's operating specifications entail current densities that go as high as approximately 10 A/cm^2. High operating pressures (~2MPa) due to mechanical strength and a wide temperature range (20 to 200ºC) result in satisfactory conversion efficiency around 60%. Hydrogen produced often exceeds 99.99% purity.

PEM electrolyzers are commercially mature with already industrial applications worldwide, meaning their TRL level is ~8-9. However, with electrodes comprised of precious metals, the per-unit cost is still high. Capital costs, including electrolyzer stack, balance of plant (BOP), hydrogen processing, power supply, installation and mark-up, for the technology fall in the range of ~$500/kW and ~$1,500/kW,[40,41] where economies of scale apply. DOE has set targets for reaching $150/kW for uninstalled PEM electrolyzer system costs, assuming large quantities of daily hydrogen production by 2035. Further, improving electrocatalysts is a way to increase the process efficiency and decrease cost.[42–44]

2.2.1.2 Emerging Hydrogen Production Technologies

The following section discusses new and emerging hydrogen production technologies.

Photoelectrochemical (PEC) electrolysis

Photoelectrochemical electrolysis, or direct water splitting, uses a photoelectrode and sunlight to produce hydrogen and oxygen from water. The technology eliminates the need for two separate technologies i.e., 1) photovoltaics to produce electricity and 2) electrolyzers to produce hydrogen from electricity. Hence, PEC electrolysis represents a more compact alternative to traditional electrolysis with PV. Currently, efforts have been focused on film-on-glass devices immersed in water and photosensitive powder catalysts suspended in water. The former method includes two-photon tandem systems and monolithic multi-junction systems, while the latter entails dual-bed redox and one-pot two-step systems. Research on PEC materials and devices has demonstrated operating efficiencies of over 16%. Semiconductor materials suffer from photo-corrosion, poor solar spectrum absorption, and the need of external bias. Accordingly, the key improvement areas associated with the technology include the development of new high efficiency and corrosion resistant photo-electrode materials. The fields for development place the technology as not yet economically competitive.

Bio-photolysis

In bio-photolysis, water is dissociated into molecular hydrogen and oxygen through microalgae or cyanobacteria excited by light energy. Bio-photolysis can be categorized into direct and indirect biophotolysis.[45] Direct bio-photolysis takes place in two reactions, i.e., 1) splitting water during photosynthesis and 2) hydrogen gas production catalyzed by hydrogenase enzyme. Within indirect bio-photolysis, algae are deprived of sulfur nutrients which causes imbalances in the photosynthesis-respiration process. This results in the net consumption of oxygen in the cells and the activation of the hydrogenase pathway to produce hydrogen. The conversion efficiency of the process can reach up to 15%[45] and preventing the inhibitory action of oxygen on hydrogenase enzymes can potentially improve the efficiencies of bio-photolysis. Further development is necessary before multi-stage reactors are put into practical applications.

High temperature decomposition

High temperature decomposition takes place at extreme temperatures, i.e., 500–3,000ºC,[46,47] where water is split at a system efficiency of approximately 10%. The water which has not been decomposed is recycled in the system. When coupled with other processes such as thermo-chemical cycles, plasma-chemical decomposition, electrolytic decomposition, efficiencies can increase to above 50%. There are two main process designs related to hydrogen separation from the gas mixture: gas quenching at high temperatures following hydrogen diffusion through a nonporous solid membrane at lower temperatures and hydrogen separation in a decomposition chamber at high temperatures.[48] The main challenges facing this process are related to corrosion and safety.[47] Hence, there are existing opportunities ahead of this technology to realize its large-scale and commercial potential.[49]

Biomass gasification

Biomass gasification resembles coal gasification in the reactions steps to produce hydrogen. The reaction temperatures often exceed 700ºC. Adsorbing columns or membranes are used for the separation of hydrogen from the gaseous stream.[50] Biomass feedstocks vary in their quality with respect to the climate, location, and crop. As a result, the procedures for producing hydrogen are variable. As a rule of thumb, low quality fuels require more extensive conversion processes. Enhancements of biomass conversion processes are needed for obtaining more consistent fuels across geographic locations. Consequently, universalization of production will drive costs down to more economically attractive values.[47] Investigations on lowering capital costs include developing new membrane technologies for enhanced hydrogen separation and combining the process into fewer operations. Although the technology is mature, proving its economic viability will determine its commercial implementation in future.[50]

Biomass pyrolysis

There are two major biomass pyrolysis techniques: slow pyrolysis and fast pyrolysis. Slow pyrolysis involves charcoal and hence, is not likely to be used within the ECO-scope. In fast pyrolysis, biomass is heated rapidly to evaporate and then, condensed to a dark brown bio-liquid. Biomass heating temperature ranges from approximately 375ºC to 525ºC at 0.1–0.5 MPa and in reduced atmosphere (absence of air), liquid oils can easily be obtained.[11] Technological and economic barriers, such as catalyst selection, scale-up, and hydrogen generation at industrial cost targets are identified as areas for improvement before the technology can become commercially viable.[51]

Fermentation

Fermentation uses organic waste, such as biomass and agricultural feedstock. Depending on whether microorganisms are under anaerobic or aerobic conditions, it can be classified into dark or photo fermentation. In photo fermentation, water is split with the assistance of nitrogenase enzymes. The process is energy intensive with low conversion and large photobioreactors required. Hydrogen generated during dark fermentation with anaerobic microorganisms and green algae uses carbon-rich substrates in the absence of light.[52] Hydrogen is produced at about 30–80ºC.[11] The hydrogen yield is maximized by manipulating the pH value between 5 and 6, the length of hydraulic retention, and gas partial pressure. Side products of the fermentation reaction are carbon dioxide and methane. Therefore, the pathway is currently not a competitive hydrogen production candidate.[11]

2.2.1.3 Comparative Analysis

Table 2 below, compares many of the existing R&D and mature technologies for hydrogen production. Despite its current high cost, the only carbon-free, modular option, which is a mature technology, is electrolysis. Therefore, PEM electrolysis will be considered further in the analysis, in combination with the renewable systems suggested in the previous section of this report.

Table 2. Hydrogen Production Processes Comparison

Process	**Electrolytic Processes**			**Direct Solar Water Splitting Processes**	**Biological Processes**	
	Alkaline electrolysis	Proton-exchange electrolysis	Solid oxide electrolysis	Photo-electrochemical	Biophotolysis	Fermentation
Resource	Wind, solar, fossil fuels	Wind, solar, fossil fuels	Wind, solar, fossil fuels, geothermal, nuclear	Solar	Solar	Solar
Reaction	$H_2O \xrightarrow{electricity} H_2 + \frac{1}{2}O_2$			$H_2O \xrightarrow{1.23V} H_2 + \frac{1}{2}O_2$	Direct biophotolysis: $H_2O \xrightarrow{solar\ energy} H_2 + \frac{1}{2}O_2$ Indirect biophotolysis: 1) $6H_2O\ + 6CO_2 \xrightarrow{light\ energy} C_6H_{12}O_6 + 6\ O_2$ 2) $6H_2O\ + C_6H_{12}O_6 \xrightarrow{light\ energy} 6H_2 + 6\ CO_2$	Photo-fermentation: $CH_3COOH + 2H_2O \xrightarrow{light\ energy} 4H_2 + 2CO_2$ Dark fermentation: $C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 4H_2 + 2CO_2$
Material	Liquid electrolyte, perovskite anodes, Ni alloy cathodes	Polymeric electrolyte, Ir- or Ti- based anodes, Pt or MoS_2 cathodes	Ceramic electrolyte, LSM-YSZ anodes, Ni-YSZ cathodes	B/TiO_2 photocatalyst; Fe_2O_3 nanoparticles	Algae, cyanobacteria; glass bioreactors	Various inoculum strains; glass beads, silicone-immobilized sludge, powdered activated carbon
Temperature	20 – 80 °C	20 – 200 °C	500 – 1000 °C	0 – 70 °C	30 – 40 °C	30 – 80 °C
Pressure		~20 bar		~ 20 bar		~ 1 bar
Hydrogen purity	99.8 –99.9%			> 98%		
Efficiency	59-70%	65-82%	< 100%	8 – 16%	0.5 – 10 %	0.1
Cost	~\$2 – \$13/kg H_2			~\$2 – \$18/kg H_2	~\$1 – \$18/kg H_2	~\$3 – \$8/kg H_2
Maturity	Mature	Mature	R&D	R&D	R&D	R&D
Advantages	low capital cost, stable	compact design, fast response, high purity; more environmentally friendly than AEL because of no alkaline fog; no usage of hazardous chemicals	enhanced kinetics, low energy demand, low capital cost; superior energy conversion efficiency	Simple process steps; wide operating temperature ranges	Reduces CO_2 in environment; non-extreme operating conditions	Dark fermentation does not require light and uses organic wastes for hydrogen production; photo-fermentation can use organic wastes was substrates from dark fermentation

Process	**Electrolytic Processes**			**Direct Solar Water Splitting Processes**	**Biological Processes**	
	Alkaline electrolysis	Proton-exchange electrolysis	Solid oxide electrolysis	Photo-electrochemical	Biophotolysis	Fermentation
Disadvantages	Corrosive electrolyte, gas permeation, slow dynamics	High-cost polymeric membrane, acidic: noble metals	mechanically unstable electrodes, improper sealing; requires hydrogen purification	Low efficiency and high capital investment, resistance losses, corrosion of materials	Low yield, limited to sunlight exposure and area; inhibition of hydrogen production by oxygen	Oxygen inhabitation on hydrogenase; gas contains CO_2 of dark fermentation; low conversion efficiency
Goals	Improve durability and oxygen evolution	Reduce noble metal utilization	Microstructural changes in the electrodes	Improve efficiency, durability, lifetime in cost by introducing protective surface coatings and reduced materials	Hybrid systems for increasing efficiency; prevent hydrogen losses by enclosing bioreactor, provision of high surface to volume ratio[39]	Improving rates and yields of hydrogen production by microbial strain enhancement, reactor design and process optimization, and identifying high-yield feedstocks, and scaling up

Process	**Thermochemical Processes**				
	Biomass gasification	Biomass pyrolysis	Steam reforming	Coal gasification	High T decomposition
Resource	Biomass	Biomass	Fossil fuels, natural gas	Coal, nuclear	Solar, nuclear
Reaction	$\mathit{biomass} + O_2 + H_2O \xrightarrow{heat} H_2 + CO + CO_2 + CH_4 + \mathit{hydrocarbons} + \mathit{char}$	$\mathit{biomass} \xrightarrow{heat} H_2 + CO + CH_4 + \mathit{hydrocarbons}$	$C_nH_m + n\,H_2O \xrightarrow{heat} n\,CO + (n + \frac{1}{2}m)\,H_2$ $CO + H_2O \rightarrow CO_2 + H_2 + Q$	$C(s) + H_2O \xrightarrow{heat} CO + H_2$	Cerium oxide cycle: Reduction reaction: $2CeO_2 \rightarrow Ce_2O_3 + \frac{1}{2}O_2$ Oxidation reaction: $Ce_2O_3 + H_2O \rightarrow 2CeO_2 + H_2$
Material	Heterogeneous catalysts such as Ni, Rh, Pt, or alkali salts	Ni, Ru, Rh, Y-type zeolite, K_2CO_3, Na_2CO_3, $CaCO_3$, Al_2O_3, SiO_2, ZrO_2, TiO_2 and Cr_2O_3 catalysts	Ni, Pt, Rh catalysts; Pb-based membrane reactors		Zi or Pd membrane depending on method
Temperature	700 – 1200 °C	377 –527 ºC	450 – 1000 ºC	700 – 1300 ºC	500 – 3000 ºC
Pressure	34 – 280 bar	1 – 5 bar	3 – 25 bar	3 – 25 bar	~ 1 bar
Hydrogen purity			90 - 99.999%		
Efficiency	35 – 50%	35 – 50 %	70 – 85 %	60 – 75 %	~10%
Cost	~\$2-4/kg H_2	~\$1 – \$5/kg H_2	~\$1 – \$2 /kg H_2	\$1 – \$2 /kg H_2	

Process	**Thermochemical Processes**				
	Biomass gasification	Biomass pyrolysis	Steam reforming	Coal gasification	High T decomposition
Maturity	R&D	R&D	Mature	Mature	R&D
Advantages	Noble but relatively low-priced metals as catalysts; abundant and cheap feedstock	Lower temperatures than biomass gasification; tar-free product; abundant and cheap feedstock	Established process, cost attractive	Established process, cost attractive	Near zero greenhouse gas emissions; can use waste heat from nuclear plants to improve safety
Disadvantages	High temperature, unstable tar content, energy intensive; feedstock quality varies	Problems with catalyst stability; feedstock quality varies	High temperature; unwanted side reactions, carbon dioxide as a byproduct; dependence on fossil fuels	Efficiency losses in fluidized bed reactors; carbon oxide as a byproduct	Safety and corrosion issues associated with high operating temperatures
Goals	Improve hydrogen selectivity and decrease reaction temperature	Optimize catalyst composition to improve its stability and regeneration, scale up	---	Minimize greenhouse gas emissions by developing carbon capture and storage technologies; new technologies for replacing the cryogenic process used for separating oxygen from air	Apply new efficient and durable materials for thermochemical cycling; efficient and robust reactor designs

2.2.2 Ammonia

The typical synthesis of ammonia (NH3) is using the Haber-Bosch (HB) process, where nitrogen and hydrogen, derived from fossil natural gas (NG) through steam methane reforming, are the reactants. Provided clean hydrogen is produced, and the air separation unit to produce nitrogen and the HB process are powered by renewably sourced electricity, the NH3 production process would be carbon-free.[54] Ammonia can be used as a fertilizer and as a medium for long-distance hydrogen shipping. The levelized cost of ammonia using different pathways has been shown in Figure 12, and can go a bit above \$1/kg of ammonia.[54]

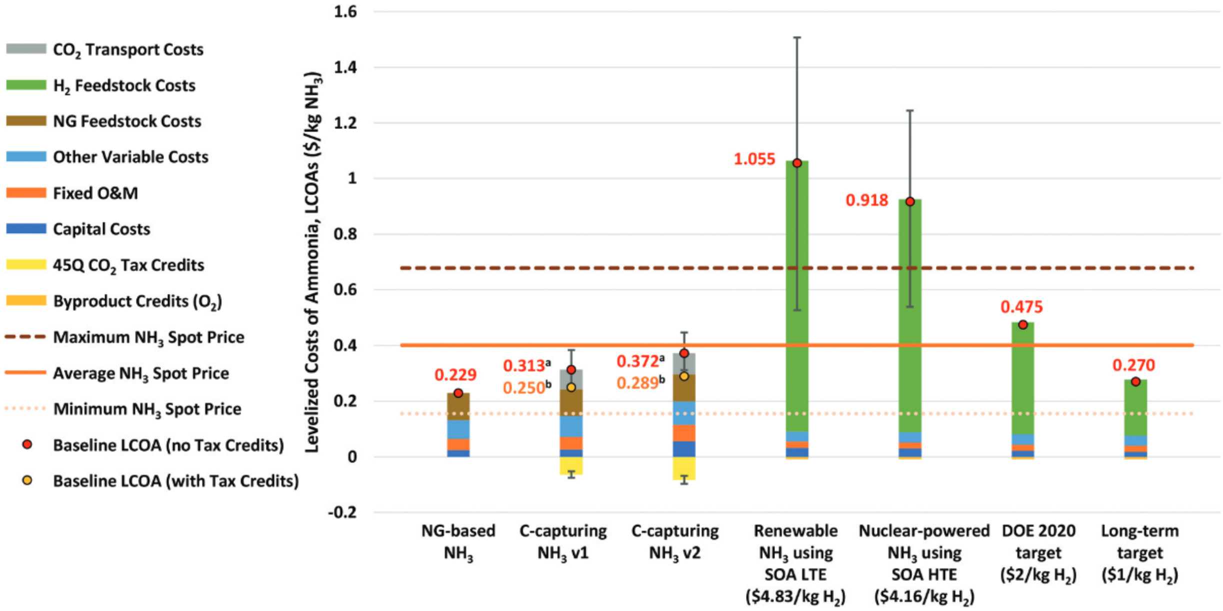


Figure 12. Levelized cost of ammonia for various production pathways[54]

2.2.3 Methanol

Methanol is another hydrogen-derived fuel source whose production process can be decarbonized. Typically, the chemical is produced from synthetic gas through the hydrogenation of CO and CO_2.[55] Methanol is widely used in the chemical industry as a solvent and reactant, and it is an ingredient to household products such as paints, varnishes, cleaning products, etc. The cost of methanol is driven by the cost of carbon dioxide and hydrogen. Currently, clean methanol production cost is estimated at \$800/t Me - \$1,600/t Me with the assumption carbon dioxide is sourced from bioenergy with carbon capture and storage. Carbon dioxide extraction from direct air capture unit will increase the costs to \$1,200/t Me - \$2,400/t Me.[56]

2.2.4 Comparative Analysis

Both ammonia and methanol are derivatives of hydrogen and besides their end-use demands, they can be seen as another means of long-distance transportation for hydrogen. To the best of the authors' knowledge, no extensive techno-economic comparison has been done for using ammonia and methanol as forms of shipping hydrogen.

2.3 Low-Carbon Fuel Storage Technologies

Technologies for hydrogen and other low-carbon fuel storage in bulk can be used in combination with hydrogen production and utilization technologies to monetize low-cost energy generation and mitigate curtailment. When looking at storage systems, gravimetric and volumetric capacities act as measures for efficiency and a basis for comparison among various technologies. The two terms are described as the amount of hydrogen stored per unit weight or volume, respectively.

2.3.1 Compressed Gas Storage Vessels

Hydrogen can be stored in pressure vessels in a compressed gas or cryogenic form. Alternative methods are in buried pipelines or geologic formations. Other storage technologies that are currently being explored include through adsorption to materials, such as with hydrides or sorbents.

Gaseous hydrogen storage in tanks or pressurized vessels makes up the largest proportion of hydrogen storage worldwide. Compressed hydrogen storage tanks are commonly classified into four types depending on the amount of overwrapping material. Types I–IV come in a cylindrical shape, but Types II–IV also commonly take a polymorph or toroid form. The major differences, including technological and economic performances, are listed in Table 3.

Table 3. Comparison Among the Four Major Hydrogen Gas Compression Vessel Types[11–13]

Metrics	Type I	Type II	Type III	Type IV
Material	Metal	Metallic vessels hoop wrapped with FRC	Metal liner fully wrapped with FRC	Polymer liner fully wrapped with FRC
Pressure	20–50MPa	≤100MPa	≤45MPa	≤100 MPa
Cost	U.S.$3.7–$5/kWh	U.S.$7–$10/kWh	U.S.$16.5–$21/kWh	U.S.$13–$17/kWh
Weight	Heavy	Moderate	Light	Light
Maturity	Very mature	Mature		
Application	Industrial/stationary	Stationary	Automotive	Automotive

The advantage of storing hydrogen in compressed tanks is that Type I–IV vessels are readily available. Drawbacks of compressed tanks are that their volumetric energy density can be prohibitively high in some applications, such as transportation. Further, overground compressed hydrogen vessels may not be an appropriate storage option when large amounts of hydrogen have to be stored for longer-duration energy storage or when space is constrained.

2.3.2 Underwater Storage Above the Seabed

An option that could be considered within the scope of this research is a vessel filled with ~60% porosity sand to keep the tank on the seabed and operating at a pressure range between 50 and 600 bar, depending on the water depth of the deployment location. Discharging of the tank allows for seawater to flow in at the bottom of the vessel while hydrogen flows out at its top. Charging the tank allows for the opposite flow dynamics. The costs associated with the deep ocean storage are in the ballpark of ~\$13-\$14/m^3 of hydrogen storage capacity, which translates to ~$5/kWh. This solution is typically suggested for long-term due to its operational impracticality.[58]

2.3.3 Liquid Storage Vessels

For hydrogen to be stored as liquid, it needs to be cooled down to -253°C from ambient conditions. This process requires a minimum theoretical energy of 3.3 kWh/kg liquid hydrogen. Previous demonstrations have shown that the actual energy needed for liquefaction is significantly higher (i.e., 10–13 kWh/kg liquid hydrogen).[59] The liquid is then stored in insulated vessels that consist of an inner pressure tank, an outer protective jacket, and a super insulation in between. Challenges with cryogenic hydrogen storage include boil-off losses that occur when hydrogen is infrequently utilized and the high cost of hydrogen liquefaction. The evaporation rate of hydrogen correlates to the tank shape, size, and thickness.

An alternative to cryogenic hydrogen storage is to store hydrogen as a super-cooled gas (i.e., cryo-compressed storage). In this method, hydrogen is stored at operating conditions of cryogenic temperatures and gaseous pressures of above 30 MPa. Cryo-compressed hydrogen storage is under research and has a low TRL.

2.3.4 Material-Based Storage

Hydrogen storage in solid and liquid materials is a promising method to store energy for stationary and mobile end-uses. Storing hydrogen in solid materials relies on physical phenomena such as adsorption and absorption (e.g., carbon materials, zeolites, metal organic frameworks, clathrate hydrates, and polymer nanocomposites), chemical phenomena where reactions take place (e.g., hydrides, amides, imides, alanates, and nitrides), and an intermediate combination between physical and chemical phenomena.

2.3.4.1 Metal Organic Frameworks

Metal organic frameworks (MOFs) are a class of crystalline materials where metal ions and organic ligands (molecules that form bonds between metals and organic components) link together in a net-like structure. MOFs have received research attention for hydrogen storage due to their advantageous properties and structure.[60] They exhibit extremely high porosity with up to 90% free volume, and their pore size can be tuned up to 9.8 nm.[61] In MOFs, hydrogen can be stored at low or ambient temperatures or in hybrid storage systems. The cost for storing hydrogen in MOF-5 at 10 MPa has been reported at $16/kWh in literature,[13] so the R&D priorities are to reduce cost to meet DOE targets.

MOFs can accommodate other hydrogen storage materials, for instance metal hydrides. The entrapped metal will be at the nanoscale. The physical properties of hydrides at the nanoscale differentiate from their bulk-scale properties. Consequently, faults such as hydrogen leaks have been observed.[62]

2.3.4.2 Carbon Nanotubes

Carbon nanotubes have received a lot of attention on account of carbon's excellent gas adsorption properties. Hydrogen adsorption in activated carbon forms highly specific areas that allow the adsorption of the gas in micropores.[63] Hydrogen uptake is proportional to the surface area and pore volume of the porous carbon with a typical adsorption capacity of 4–6 wt%. High-performance materials such as carbon nanotubes have been reported to achieve approximately 8 wt% at ambient temperatures and pressures.[64]

Nanotubes are characterized by their wall structure-that is, single-walled nanotubes and multi-walled nanotubes (MWNT). MWNTs are reported to be electrical conductors and as a result, allow for many suitable applications in various conversion technologies (e.g., solar, fuel cells, batteries, and catalyst supports). Their catalytic activity and selectivity are often superior to those of other carbon and oxide supports. Producing carbon nanotubes at a lower cost and higher quality at mass production are areas in the research pipeline to enable the technology's commercial viability.

2.3.4.3 Liquid Organic Hydrogen Carriers

Liquid organic hydrogen carriers are hydrogen-lean organic liquids that are capable of complete hydrogenation (exothermic) and dehydrogenation (endothermic) reaction cycles at elevated temperatures in the presence of a catalyst. When they bind or release hydrogen, there are no additional byproducts. Upon hydrogen release, pure gas can be obtained by condensing the liquid. Some chemical compounds exhibit a higher affinity for hydrogenation or dehydrogenation in comparison to other compounds. Operating conditions for hydrogenation in the presence of a ruthenium (Ru) or nickel (Ni) catalyst, for instance, have operating temperatures in the range of 100°– 250°C and pressures of 1–5MPa. The reverse reaction takes place at temperatures of 150°–400°C and pressures lower than 1MPa (Aakko-Saksa et al. 2018). The hydrogen storage costs of liquid organic hydrogen carriers are reported in the range of \$2–\$30/kWh.[10]

Hydrogen stored in liquid organic hydrogen carriers does not have any leaks and can be transported using standard transportation methods such as pipelines, ships, and trucks.[65] Liquid organic hydrogen carriers are seen as a key contributor to a future carbon-free economy where they can be applied for both on-grid and off-grid applications. Nevertheless, the application to hydrogen storage is in its early commercial stage and necessitates further research and testing.

2.3.5 Underground Storage

Geological underground storage represents another method of storing large quantities of hydrogen. Methods of geologic storage that have been used for natural gas include depleted gas and oil fields, aquifers, salt, and, in limited cases, rock caverns and abandoned mines.[66] Many of these options have also been considered for hydrogen storage underground. In the United States, there are currently three salt caverns that store hydrogen underground. Worldwide, there is only one lined hard-rock cavern that stores hydrogen underground in Sweden. Rock caverns are generally more expensive to build than salt caverns. Underground geologic storage could be in the scope of this work if hydrogen can be transported from the ECO cluster to storage in geologic formations inland.

2.3.6 Comparative Analysis

Table 4 compares gaseous storage in pressurized overground vessels and geological formations with focus on salt caverns, liquid storage, and material-based storage. Geological storage is the cheapest however, it is not available in proximity to any chosen ECO location. Investigating material-based storage could be another potential venue for lower cost storage while space remains constrained. Deep sea or ocean storage can be a hypothetical option for long-duration hydrogen storage.

Table 4. Comparison of Hydrogen Storage Options[10,13,14,47,58,67–73]

Storage	Gaseous storage		Liquid storage	Material-based storage	
	High pressure tanks	Geological formations		Solid-based	Liquid-based
Reaction	None	None	None	$M(s) + \frac{x}{2} H_2(g) \xrightarrow{absorption} MH_x(s) + Q$ $MH_x(s) + Q \xrightarrow{desorption} M(s) + \frac{x}{2} H_2(g)$	
Material	Steel, aluminum, polymers	Salt formation, saline water	Steel, aluminum, polymers, composite materials	Carbon, rechargeable hydrides, chemical hydrides	N-ethylcarbazole
Temperature	Ambient temperature	38°–42°C	-253°C	-200°C to ambient	100°–400°C reaction temperature; storage at ambient temperature
Pressure	200–1,000 bar	65–200 bar	1–3 bar for liquid storage 250–350 bar for cryo-compressed storage	10–60 bar	1–210 bar
Practical system gravimetric capacity	1–4.8 wt%	x	<7.5 wt%	1–9 wt%	3.2–7.3 wt%
Practical system volumetric capacity	~40 g H_2/L	x	~70 g H_2/L	~100 g H_2/L	~ 60 g H_2/L
Cost	U.S.$13–$17/kWh for composite tank Type IV	Capital costs: U.S.$5–$40/kg Levelized cost: U.S.$1.29–$1.61/kg	U.S.$9.75–$30/kWh for cryo-compressed storage	>U.S.$10/kWh for metal hydrides U.S.$18–$25/kWh for MOF-5 U.S.$51–$171/kWh for reversible aluminum hydride storage	U.S.$2–$30/kWh
Maturity	Mature; some tank construction operates in up to limited pressure windows	Mature for natural gas	Mature	R&D	Early-phase commercial market
Advantages	Type I and II tanks are low weight, inexpensive, industrially tested, and relatively safe; no need for conversion technologies or reactors	Salt caverns: hydrogen is not consumed by microorganisms because of the saline environment	High energy density; operation at lower pressures; no need for conversion technologies or reactors	Metal hydrides: volumetric and gravimetric capacity; transient performance; efficient, cost-effective regeneration of the spent storage material	High binding energy, fast hydrogen adsorption and desorption; pure hydrogen provision; no additional byproduct
Disadvantages	Large physical volume required; hydrogen compression is energy intensive	Salt caverns: not widespread	Huge energy for hydrogen liquefaction; evaporation of hydrogen; high cost	Metal hydrides: can be expensive; affected by impurities;	High pressure and reaction temperature are required for

Storage	Gaseous storage		Liquid storage	Material-based storage	
	High pressure tanks	Geological formations		Solid-based	Liquid-based
				high equilibrium pressures; complex activation procedure	both reactions; no compatibility with infrastructure
Goals	Develop more durable and cheaper materials; employ processes to recover the compression energy; reduce vessel volume	Optimize process; investigate possible chemical reactions occurring in formations; decrease equipment costs	Decrease liquefaction cost by using excessive heat from another process, thus reducing energy costs; improve safety and reduce hydrogen boil off	Improve heat management and desorption kinetics	Optimize process and catalyst

2.4 Potential Hydrogen Applications

According to DOE's National Clean Hydrogen Strategy and Roadmap,[15] future targeted hydrogen demands would be distributed across chemical, hard-to-abate sectors, storage, heating, medium- and heavy-duty transportation including trucking, aviation, and shipping, as well as additional markets, as seen in Figure 13. The latter holds a level of uncertainty, but it can be met by fueling ships and marine vessels, exports or any additional demand from the applications depicted in the figure. In order to realize DOE's H2@Scale initiative to enable decarbonization across sectors using clean hydrogen[15] for ECO centers, demands for various applications should be considered, depending on the proximity of hydrogen production.

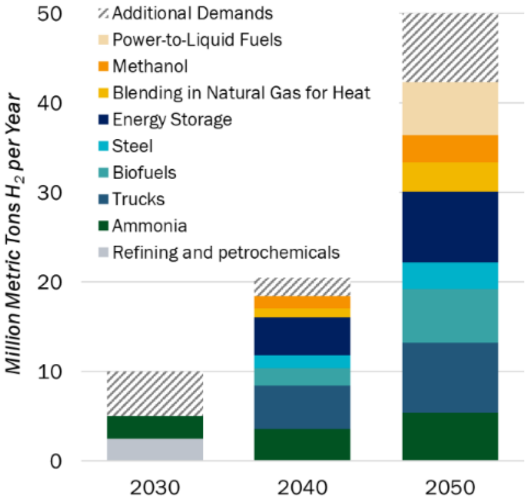


Figure 13. Clean hydrogen demand by 2030, 2040 and 2050

2.4.1 Offshore Applications

2.4.1.1 Recharging and/or Refueling Maritime Transport

Sandia National Laboratories have studied hydrogen and fuel cells in maritime vessel applications. The sample size of the study included 14 ships, varying in sizes and routes. Their findings suggest that most maritime vessels in the world's fleet would benefit from operating on zero-emission hydrogen fuel cell technologies.[74] Furthermore, ships powered by hydrogen fuel have shorter ranges than ships driven by fossil fuels, meaning it would be essential to have a network coverage of hydrogen refueling ports to ensure ships maintain their routes and corridors.[75] Therefore, one possible application for hydrogen within the ECO system is to serve as a refueling option through ECO ports.

2.4.1.2 Offshore and/or Undersea Data Centers

Another offshore application to consider is powering undersea data centers. There is already one undersea data center which has been deployed and another facility that is being developed,[76] i.e.:

- The Natick data center (Figure 14) has a deployment cycle of up to five years with an overall operating horizon of 20 years. This is the expected lifespan of the computers contained within the deep-water servers. After each 5-year period, the data center will be retrieved, and computers will be replaced.

- The Hainan data center is a project that is deploying data cabins in 20 m deep water off the coast of the Hainan Free Trade Port. Each cabin will weigh 1,300 tons and be connected to land via a "placenta" tank with a diameter of 3.6 meters, which would make it the world's largest submarine data cabin. Details are still emerging as this project develops.

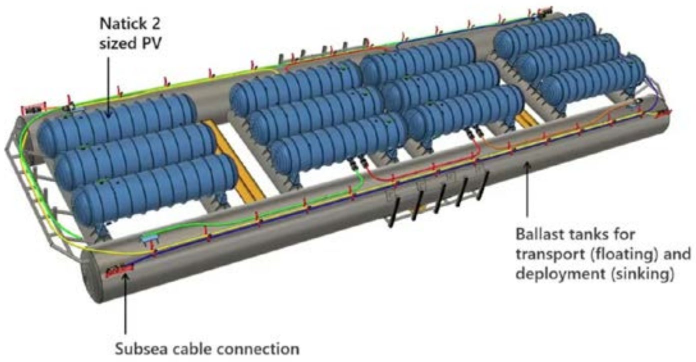


Figure 14. Natick's data center design

2.4.1.3 Habitable Shelter

When referring to habitable shelters, two types of shelters are envisioned: temporary shelters and permanent shelters. Hydrogen for heating and cooking appliances can be considered as a substitute for natural gas. Research has been ongoing about the potential in blending hydrogen for heating and the consequent implications, as well as having 100% hydrogen heating inventory.

2.4.2 Onshore applications

2.4.2.1 Hydrogen Applications

Stationary Power/Storage

Stationary hydrogen fuel cells generate electricity through a reverse electrochemical reaction to electrolysis. The only by-product is water hence, this technology can provide clean and reliable off-grid power to various demand centers such as homes, businesses, telecommunications networks, and utilities, to name a few.[77] They are 2-3 times more efficient (~ 60% efficiency) than conventional combustion (~35% efficiency) technologies.[78]

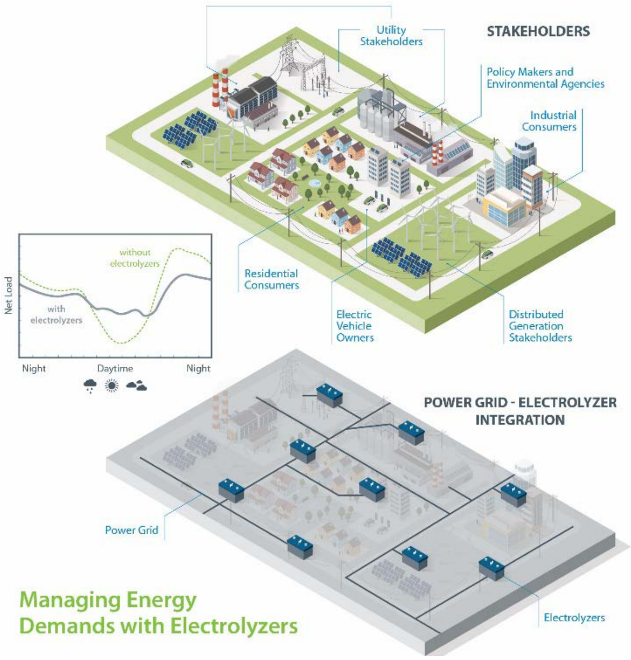


Figure 15. Example of benefits of coupling the power grid with electrolyzer/fuel cells

Primary Power

Coupling renewables with electrolyzers and fuel cells would provide resilience and reliability for the future of a grid with high renewable penetration. These hydrogen technologies can smoothen the Duck Curve (i.e., the difference in electricity demand and the amount of available renewable energy) by enabling the production of hydrogen and storage at times when there is an excess of renewably generated electricity and to generate electricity at times when there is an absence of renewable sources.[78]

Backup Power

Due to their quick response and ability to ramp up in less than a second,[79] fuel cells are an attractive option for a reliable backup power option, especially because of the historically proven vulnerability within the U.S. grid. Compared to battery generators, fuel cells can be advantageous when shorter run-times of three days or less are sufficient. Approximately 200,000 fuel cells are currently operating in Japan and major companies are emerging as leading suppliers of fuel cells for residential or backup power.[78]

Combined Heat and Power

Fuel cells are often implemented as part of a combined heat and power (CHP) system. These CHP systems use the recovered thermal energy from the fuel cell exhaust which is then used to heat or cool industrial facilities, district energy systems and commercial buildings. The CHP configuration can increase overall system efficiency and reduce carbon dioxide emissions and other pollutants by decreasing boiler operations. The thermal energy recovered from fuel cells is most often used to satisfy hot water or space heating demands, although in some cases, fuel cells have been integrated with absorption chillers to provide space cooling.[78]

2.4.2.2 Transportation

Hydrogen used as a fuel in transportation, particularly, medium- and long-haul transportation including heavy-duty trucks, buses and forklifts, for example, is positioned to play a significant role in the future by achieving the economically competitive price point at which a consumer is willing to pay for fuel, which is ~$5/kgH2. The price will unlock the potential for 5-8 MMT for hydrogen demand U.S.-wide by 2050.

Current non-significant demand for transportation is primarily located in California, where refueling stations serve more 13,000 light-duty vehicles. Additionally, more than 50,000 hydrogen fuel cell forklifts have been in operation across warehouses and manufacturing facilities in the United States. Today more than 80 buses run on hydrogen fuel.[80]

2.4.2.3 Refineries

Refineries are some of the largest consumers of the hydrogen produced in the U.S. per year, including H_2 that is produced onsite, as well as hydrogen that is consumed in hydrocracking and hydrotreating. Future hydrogen demand by refineries depends on volume and quality of crude input. It is projected that as clean fuel availability increases, so too does demand, with potential hydrogen demand for petroleum refineries to be at ~ 7.5 MMT.[81] It is an inelastic demand as there is no other alternative to clean hydrogen that could be used to decarbonize the industry.

2.4.2.4 Chemical Industry

From the chemical industry, the largest need for hydrogen is for ammonia synthesis. To produce ammonia, hydrogen and nitrogen react in a Haber-Bosch process. It is approximated that for each kg of synthesized NH_3, ~0.18 kg H_2 are required. It has been estimated that currently, 2.5 MMT H_2 are needed for NH_3. The demand is projected to grow to 3.6 MMT H_2 in 2050.[81]

Another chemical industry application where hydrogen plays an important role is for methanol production. The DOE's HFTO estimates that clean H2 demand for methanol by 2050 would reach ~5MMT.[15] For the easiest approach to decarbonizing various industries, no changes are needed to the equipment or process of using clean hydrogen within ammonia and methanol production therefore, it is expected that hydrogen would be adopted earlier in these respective sectors.

2.4.2.5 Steelmaking

In the United States ~98 MMT steel were consumed in 2021. Each ton of steel produced emits an average of ~1.85 tons of CO_2 which results in the industry being a key contributor to GHG emissions. One of the options to decarbonizing steelmaking is by using clean hydrogen as a reductant of iron ore. To fully reduce 1 metric ton of iron ore, approximately 0.08 – 0.12 metric tons of hydrogen are required.[81] It has been projected that by 2050, ~5 MMT H_2 would be in demand for steelmaking.[15]

2.5 Potential Electrochemical Energy Storage Technologies

This section briefly discusses main types of electrical energy storage with the aim of providing an overview of technologies rather than a techno-economic comparison amongst them.

2.5.1 Batteries

Battery energy storage is comprised of a pair of opposite electrodes immersed in an electrolyte, which can be made of different chemistries e.g., lead-acid, alkaline, lithium-ion, etc.[82] The oldest type of battery is the lead-acid based and considered for applications such as transportation and stationary power. Recent systems have demonstrated ~17,000 cycles ability, enabling large-scale deployments. A disadvantage of the lead-acid batteries is the toxicity associated with the lead. Nickel-based battery chemistries represent the main alkaline batteries and are applied in portable as well as stationary uses. Ther life cycles are approximately ~1,500-3,000 cycles longer than the lead-acid batteries. Areas of improvement are in their specific energy, daily self-discharge, and cost. Lithium-ion batteries take the upper hand by offering the highest specific energy and power with increased round trip efficiencies reaching almost 100%. Their life cycles are ~10,000 with a low self-discharge rate i.e., ~0.3% per day. The largest drawback of the lithium-ion batteries is their high cost. Applications where this type of chemistry are used are in portable and vehicle end-uses.[82]

2.5.2 Others

Flywheels are a type of energy storage which can offer high efficiencies (~90%), long life cycles while weather independent and free of hazardous chemical production. Because of their high self-discharge percentage i.e., ~100% daily, they are not suitable to be considered for long-duration and seasonal energy storage. Compressed air energy storage has a high TRL with two operating systems – in Germany and in the U.S. This type of storage is suitable for systems with large penetration of intermittent energy. Pumped hydro energy storage is the only proven large-scale energy storage i.e., above 100 MW.[82]

The focus of the modeling work which will be involved in the next phases of this project would be mostly on batteries, for smoothing the power availability from the renewable source to the applications under consideration.

2.6 Potential Carbon Capture Technologies

To limit warming to 1.5°C, carbon capture and storage technologies must remove 1.5 gigatons of carbon dioxide ($GtCO_2$) per year by 2040, 3 to 7 $GtCO_2$ per year by 2050, and 15 $GtCO_2$ per year by 2100, according to the Intergovernmental Panel on Climate Change.[83,84] Increasing capture up to just 1.5 $GtCO_2$ per year would involve a 35-fold increase in the current amount of carbon dioxide removal (CDR) being done by current global efforts.[83] Expanding CDR offshore on ECOs could assist in scaling capture to mitigate climate change due to the vast amount of space available in the ocean, lack of competition with space needed for other land uses, the ocean is one of the world's largest carbon sinks with a near unlimited potential for CO_2 storage, and the renewable energy that can be used to power the CDR offshore will improve the CDR efficiency by avoiding additional emissions that would be produced by fossil fuel energy sources.[85] Offshore CDR technologies include adapting land-based systems for a marine environment, such as offshore direct air capture (DAC), and using the ocean for CDR, otherwise known as marine CDR (mCDR). mCDR includes a diverse array of strategies to capture and sequester CO_2, including artificial upwelling (AU), deep ocean storage, electrochemical mCDR (eChem mCDR), offshore microalgae cultivation, and seaweed cultivation and sinking. Additionally, power is required for monitoring and verification methods used to determine if mCDR methods are appropriately capturing and sequestering CO_2 with minimal environmental risks.

Table 5: Offshore CDR CO$_2$ Capture Capabilities

CDR Method	Energy Requirement for CDR	Full Scale Capture Capability	Cost of Capture	Length of Carbon Storage
Direct Air Capture	194-3,500 kWh/tCO$_2$ [86]	3.3-11 GtCO$_2$/yr[87]	\$94-232/tCO$_2$[88]	As CO$_2$: Depends on end use (can be converted to fuel or permanently stored underground)
Artificial Upwelling	60-17,500 kWh/tCO$_2$[ii] [87,88]	0.67 GtCO$_2$/yr in ocean 2.66 GtCO$_2$/yr on land[91]	>\$100-150/tCO$_2$[92]	10-150 yrs[93]
Deep Ocean Storage	60 kWh/tCO$_2$[94]	Unlimited in theory[85]	>\$50/tCO$_2$[95]	10-1,000 yrs[93]
Electrochemical mCDR	500-4,000 kWh/tCO$_2$[86,96]	10-11 GtCO$_2$/yr in ocean[97]	\$100-2,400/tCO$_2$[97]	As CO$_2$: Depends on end use As bicarbonate: 100,000 yrs As carbonate: 100 million yrs[92]
Offshore Microalgae Cultivation	3,700-176,000 kWh/tCO$_2$[98,99]	1-5 GtCO$_2$/yr in biomass[84]	\$25->\$125/tCO$_2$[84]	Products made of microalgae: ~10 yrs[92]
Seaweed Cultivation and Sinking	Nurseries: 26.4 kWh/tCO$_2$ Biogas Production: 550 kWh/tCO$_2$ Sinking Seaweed: 10-22 kWh/tCO$_2$[100,101]	0.1-1 GtCO$_2$/yr in ocean[92]	\$71-17,000/tCO$_2$[102]	Products made of seaweed: ~10 yrs Sunk seaweed: 100-1,000 yrs[92]

[ii] Note that the low estimate is based on an anticipated but unverified capture from Aure et al. and the high estimate is based on the increase in seaweed growth due to AU as determined from field testing done by Fan et al.[89,90]

Table 6: Offshore CDR Location Requirements and Environmental Risks

CDR Method	Location Requirements	Environmental Risks
Direct Air Capture	Have low location requirements and can therefore be used in remote environments with renewable energy resources that are not cost effective to connect to the grid[87]	Limited environmental impacts due to the contained nature of these systems (they do not directly interact with the surrounding ocean); toxicity risks due to the production of the materials used in these systems but not their operation[103]
Artificial Upwelling	Can either capture or release CO_2 depending on location, season, biogeochemical factors; generally, site >3 nautical miles from coast; can limit environmental risks by siting in an enclosed bay or fjord[89,92]	Could disrupt ocean thermocline & cause more warming; ocean acidification; disturb upper & lower ocean ecosystems; hypoxia; release of greenhouse gasses; reduce precipitation[92]
Deep Ocean Storage	Sequestration times of CO_2 depends on location & depth: in the US the waters around the west coast, Alaska, & Hawaii have the longest times, reaching up to 1,000 years at 3km[93]	Formation of CO_2 lakes in the deep ocean if CO_2 is deposited close to the seafloor, killing most organisms under the lake and those that wander into it; unclear how deep sea organisms will react to overall changes in CO_2 concentrations but they are likely sensitive to these changes and could die from chronic exposure; increased acidification[104]
Electrochemical mCDR	Most cost effective when paired with existing pumping systems (ex. desalination); can be sited in semi-enclosed locations (ex. bays) or areas with strong surface currents to minimize risks[97,105,106]	Some methods generate toxic chlorine gas as a byproduct which needs to be carefully stored; methods that directly add alkalinity to the ocean need to avoid drastic pH changes; more research needed on impacts[92]
Offshore Microalgae Cultivation	Need sunlight & moderate waves, likely best to be operated in ocean bays to reduce risk of damage from storms[98]	If floating systems are destroyed, they can release algae & nutrients into the local environment & cause eutrophication[98]
Seaweed Cultivation and Sinking	Temperate waters preferred since they are more nutrient rich than tropical; strong currents support nutrient replacement & CO_2 absorption; seaweed must be sunk to >1km for sequestration[101,102]	Displacing plankton communities & reducing their CDR; impacts to benthic ecosystems unclear; hypoxia in deep sea; entangling marine life; methane release; invasive species[102]

2.6.1 *Direct Air Capture*

Direct air capture (DAC) focuses on removing the dilute concentration of CO_2 from the atmosphere rather than from concentrated flue gas emitted from fossil fuel plants, as more traditional methods of CDR do.[87] While this requires a greater amount of energy, DACs can remove CO_2 from more disperse sources that cannot simply have a CDR system attached to them such as cars and cement plants.[103] Compared to mCDR methods, DAC has been more developed and there are currently promising technologies from start-ups that they aim to scale up as quickly as possible.[86,87,103] DACs generally use a capture solution or membrane that essentially removes the CO_2 from the air and then releases the gas into a contained storage chamber. Since none of the solution or membrane material is used up or converted into a new product by interacting with the CO_2, the same materials can be used over many cycles to remove massive amounts of CO_2 from the air.[87] DACs also have low environmental risks and location requirements meaning that they can be placed in remote offshore regions that cannot cost effectively transport the power they generate to the grid.[87,103]

Overall, ECO platforms can be used to power DAC systems in a variety of locations. The captured CO_2 will either need to be stored on the energy island or sequestered using deep ocean storage.

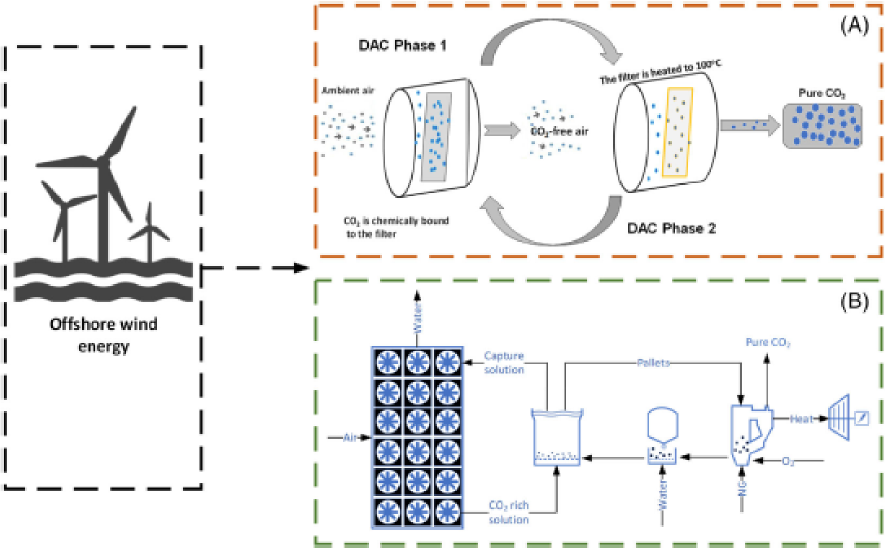


Figure 16. Conceptual schematic of using offshore wind for DAC that uses membranes (a) or a capture solution (b)[87]

2.6.2 Artificial Upwelling

Artificial upwelling (AU) involves pumping nutrient rich deep water upwards to shallow waters, providing enough growth limiting nutrients to increase the growth of phytoplankton and cause an algae bloom. The idea is that the additional carbon stored in the new biomass will eventually sink into the deep ocean for storage.[92] However, AU can also release CO_2 due to the dissolved inorganic carbon (DIC) that is also pumped to the surface from deeper waters. AU only results in overall CDR if the nutrients provided by the upwelling encourages enough phytoplankton growth to offset the CO_2 released from the DIC.[92] Therefore, AU can either overall capture or release CO_2 from the ocean depending on a variety of factors such as season, location, and local biogeochemistry.[91] At scale AU is limited to absorbing only about 0.7 $GtCO_2$/yr into the ocean while releasing about 2.7 $GtCO_2$/yr that will need to be stored to avoid release into the atmosphere, however at this level of capture AU is likely to disrupt the global ocean thermocline cycle and cause additional warming.[91,92] At smaller scales AU can still cause local and downstream ocean acidification, disrupt ecosystems throughout the water column, release other greenhouse gases, and cause hypoxia.[92] Additionally, there are no existing methods that can accurately determine the amount and longevity of carbon sequestration or long-term removal of

CO_2 from the atmosphere achieved by AU.[92] AU has been most successful in enhancing aquaculture in enclosed areas such as bays or fjords, by increasing seaweed growth or preventing the accumulation of toxic algae in mussels as found by field trials.[89,90] AU can be powered directly with electricity or use wave energy in their surrounding environment.[107]

Therefore, AU could be used for enhancing aquaculture on or near an ECO platform, using the energy island's power to pump nutrient rich deep ocean water under careful monitoring to avoid environmental damage, and enabling CDR by encouraging greater seaweed growth.

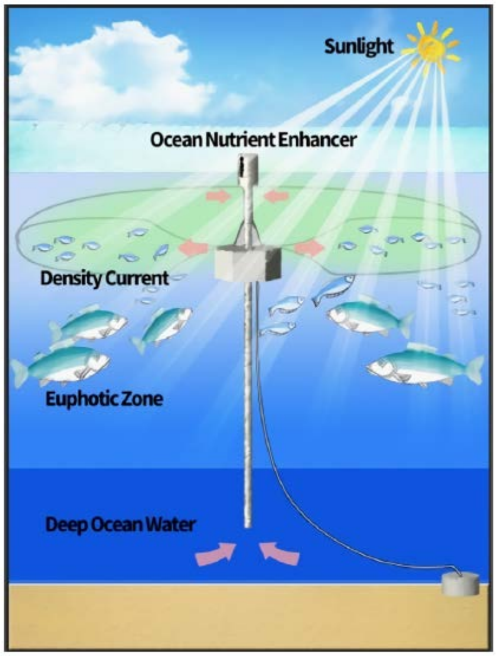


Figure 17. Simplified schematic of AU where nutrient rich deep ocean water is pumped to the upper ocean to increase growth and CO_2 uptake of phytoplankton[107]

2.6.3 Deep Ocean Storage

Deep ocean storage is a sequestration method that focuses on pumping CO_2 that has already been captured by other CDR methods and storing it in the deep ocean. The time that this carbon is stored depends on the location and depth that the CO_2 is released due to differences in overturning circulation in different oceans, for example the median carbon sequestration times are shorter in the Atlantic Ocean than in the Pacific Ocean due to the Atlantic's faster overturning circulation.[93] The longest sequestration times at 3km deep are over 1,000 years in the Pacific and about 500 years in the Atlantic.[93] While there are a variety of different methods to pump CO_2 to the deep ocean, they all have a risk of harming deep sea marine life that could face acute mortality due to chronic exposure to higher CO_2 levels or immediate mortality due to entering lakes of CO_2 that can form if CO_2 is pumped too close to the seafloor.[104]

Overall, deep ocean storage can be a useful addition to an ECO platform that is using another CDR method that separates a pure stream of CO_2 from its environment, such as DAC and certain types of eChem mCDR. However, it will be important to have access to deep waters (>1km) and conduct deep sea monitoring to minimize environmental risks.

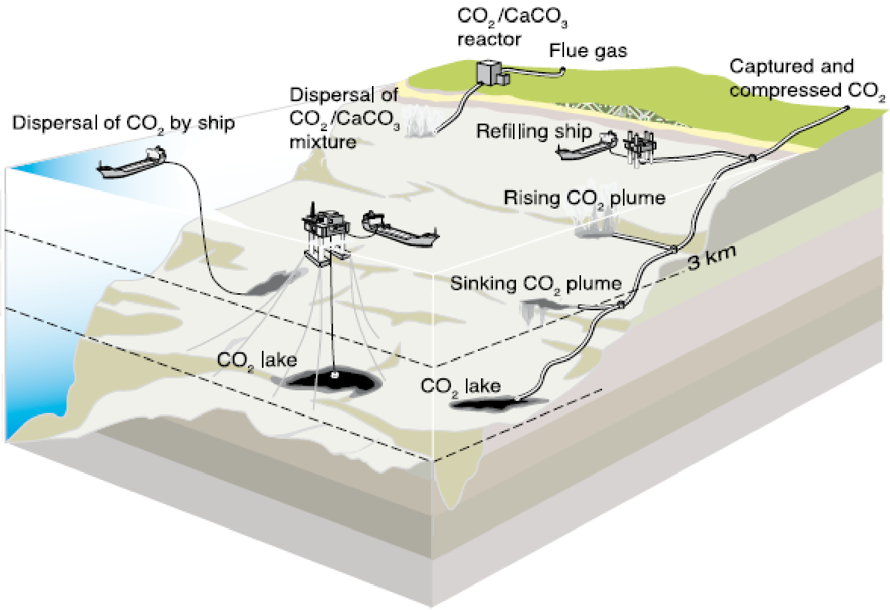


Figure 18. Illustration showing the variety of methods used for deep ocean storage[104]

2.6.4 Electrochemical mCDR

Electrochemical mCDR (eChem mCDR) covers a variety of methods that use seawater and electrochemistry either to separate and store pure CO_2 from the ocean or sequester CO_2 into the ocean by forming alkaline inorganic carbon such as bicarbonate or carbonate.[92] Generally, these strategies use electrodialysis, which makes acidic and basic solutions from seawater, or electrolysis, which also makes acidic and basic solutions but also generates valuable H_2 and toxic chlorine gas.[92] However, in electrolysis the chlorine gas can be avoided while still producing H_2 by desalinating some of the seawater entering the system.[108] Pure CO_2 can be obtained from seawater by bringing it into a chamber where it is acidified with an acidic solution, releasing the gas, which is vacuumed into a storage system, and then mixed with a basic solution to return the seawater to a neutral pH to avoid harming the local environment. Alternatively, the basic solution can be added to produce carbonates that release CO_2 and then add the acidic solution to return the seawater to neutral pH.[92] This CO_2 can then be converted into fuels and sold or sequestered using methods such as deep ocean storage.

However, even with deep ocean storage the CO_2 will eventually return to the atmosphere unless the alkalinity of the ocean is increased.[93] This can be done with eChem mCDR where the alkaline solution generated in either electrodialysis or electrolysis can be added directly to seawater, in dilute concentrations to avoid environmental impacts, to create bicarbonate ions or solid carbonate that store CO_2 from 100,000 to 100 million years.[92] However, the drawback of this method is the disposal of vast quantities of an unused acidic solution, which can be neutralized in silicate rocks, either by pumping into rock formations or by mining and transporting the minerals to the eChem mCDR system.[92] Alternatively, there is a concept that suggests pumping and gradually releasing the dilute acidic solution into the deep ocean, where carbonate deposits on the seafloor will dissolve to form bicarbonate ions and buffer the changes in pH.[105] While studies have shown that increasing alkalinity in the upper ocean can improve coral growth and recovery, the effects of adding acidity in the deep ocean require more investigation.[105,106] One benefit of all forms of eChem mCDR is that it is much easier to track and estimate CDR or sequestration since CO_2 is either stored in the system or the pH of seawater is altered which can be used more directly to determine the amount of CO_2 absorbed in the ocean than biological methods such as AU and seaweed cultivation and sinking.[92] The energy and financial costs of eChem mCDR can also be reduced by incorporating it into existing infrastructure such as desalination.[97]

Overall, eChem mCDR can benefit from being incorporated into ECO platforms due to having enough electricity for capturing and or sequestering CO_2 and can be incorporated into other uses such desalination and H_2 production.

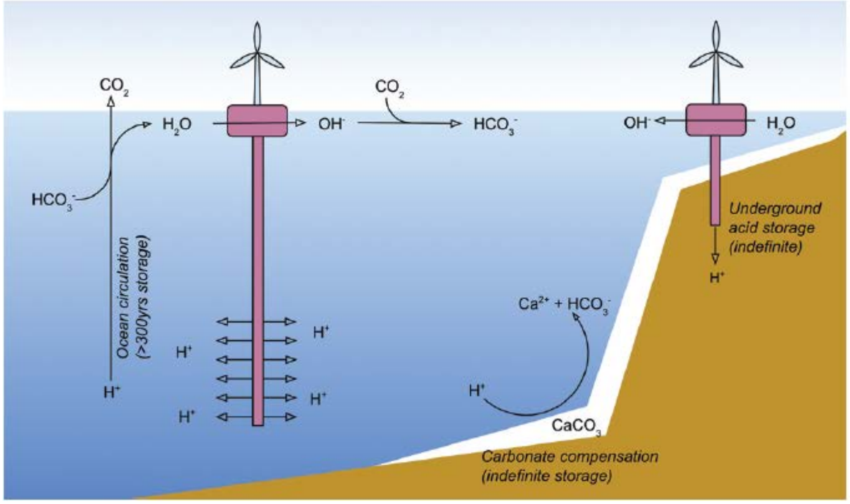


Figure 19. Schematic of using electrodialysis to create a basic solution that is released in the upper ocean and an acidic solution into the deep ocean or underground, which is neutralized by dissolving deep sea carbonate deposits, from seawater. Though more research is necessary on the environmental impacts of this strategy, this method is a promising means of in situ mCDR and sequestration that could be powered with offshore renewable energy.[105]

2.6.5 Offshore Microalgae Cultivation

Microalgae cultivation has typically been done onshore in large ponds to produce biofuels, animal feed, bioplastics, and high value chemicals such as pharmaceutical compounds. However, recently researchers have been investigating using offshore floating photobioreactors (PBRs) to reduce the financial and energy costs for growing microalgae.[109] Floating PBRs save money by using the ocean for free temperature regulation, since it has quadruple the heat capacity of air meaning that no cooling system is required, and nutrients, which can be directly absorbed from the surrounding waters via specialized membranes.[109] Additionally, these systems can use wave or current energy to simply rock themselves back and forth, mixing their internal microalgae solution, which prevents cell sedimentation and enhances the distribution of nutrients, pH, temperature, dissolved CO_2, and light, which is critical to ensuring adequate yields.[98,109] Despite being able to use energy in their ambient environment, the low amount of CDR that is achieved in floating PBRs gives them the highest energy requirement per ton of CO_2 captured of the methods examined in this section.[91] Regardless floating PBRs are still worth considering since these systems are closed and minimally interact with their marine environment, meaning that they do not disrupt ecosystems or directly harm marine life as AU, deep ocean storage, eChem mCDR, and seaweed cultivation can. However, if a PBR is broken and releases its microalgae and nutrients into its surrounding environment, then local ecosystems can be damaged from eutrophication.[91] Therefore, floating PBRs are best suited for protected bodies of water such as bays.[91] Another limiting factor of offshore microalgae cultivation as a CDR method is that CO_2 is not sequestered due to the operation of this method, carbon storage is limited to the lifetime of the product that is produced from the algae such as biofuel or bioplastic, which is typically short.[92,109]

Overall, ECO platforms could be used to protect floating PBRs from strong waves or provide power for mixing when waves or currents are too mild. The PBRs themselves can then be used to create biofuels that can be used to provide power to the energy island when needed, as a feedstock for aquaculture, or raw materials to generate high value products such as bioplastics or pharmaceuticals.

Figure 20. Example floating PBR device that uses wave energy to mix its microalgae culture solution[98]

2.6.6 Seaweed Cultivation and Sinking

Seaweed can be grown in the ocean as a method of CDR for two different purposes: to be converted into products or sunk to the deep ocean to ensure sequestration. Generally, the former is referred to as seaweed farming and the latter is called ocean afforestation.[92] Seaweed can be converted into a variety of products like those of microalgae cultivation such as biofuel, fertilizer, and food for both humans and animals.[92] Unlike microalgae cultivation, seaweed is grown in the open and can sequester CO_2 during their growth by forming and shedding recalcitrant tissue, which cannot be quickly digested by microbes meaning that more of the carbon can reach the deep ocean and be stored than that absorbed by microalgae.[92] The main hurdle for expanding seaweed production is that these organisms require adequate space, sunlight, and nutrients. While nutrients are available nearshore, there is not enough space for reaching large scale CO_2 capture. Offshore there is enough space and sunlight but not enough nutrients.[92] As a result, some groups have proposed using AU to provide enough nutrients to enhance seaweed growth offshore.[90]

Though growing seaweed can sequester some carbon through recalcitrant tissue and short-lived products, a significantly higher proportion can be stored for much longer if seaweed is quickly sunk to deep water, generally most of the carbon in the seaweed can be stored for 100 years if it is released at a 1km depth.[92] The speed of sinking is important since if it is sunk slowly, microbes will begin digesting or remineralizing the carbon into CO_2 that will be released to the atmosphere on a faster timescale.[92] However, it is unclear what the impacts of sinking large amounts of seaweed into the deep ocean will have on local ecosystems. Most likely the consumption of so much biomass will lead to hypoxia and general disruptions in local ecosystems and food chains.[102] Growing the seaweed can also harm the local environment by outcompeting with plankton communities for nutrients, entangling marine life, and introducing invasive species.[102] Sinking seaweed can also be used to potentially mitigate environmental issues such as the massive amount of methane and toxins being released by rotting seaweed that bloomed in the Caribbean, which is also significantly harming the vital tourism industry of the region.[101] The scale of damage from growing and sinking seaweed scales with the amount of seaweed grown, and the expected large scale CDR capability of seaweed is anticipated to be on the order of 0.1 to 1 $GtCO_2$ per year.[92] Energy is required for powering nurseries to grow the seaweed initially before it is placed into the ocean, converting the seaweed into biofuels, and sinking it to the deep ocean, which is generally lower per ton of CO_2 than the other CDR methods described in this section.[100,101]

Overall, ECO platforms could be used to power seaweed nurseries, biofuel conversion, and sinking if deep waters can be adequately reached. As with microalgae production, the biofuel produced could be used to provide power for the energy island when necessary. The platform could also power AU to enhance seaweed growth or use the seaweed to produce food for humans and animals or high value products like pharmaceuticals.[92]

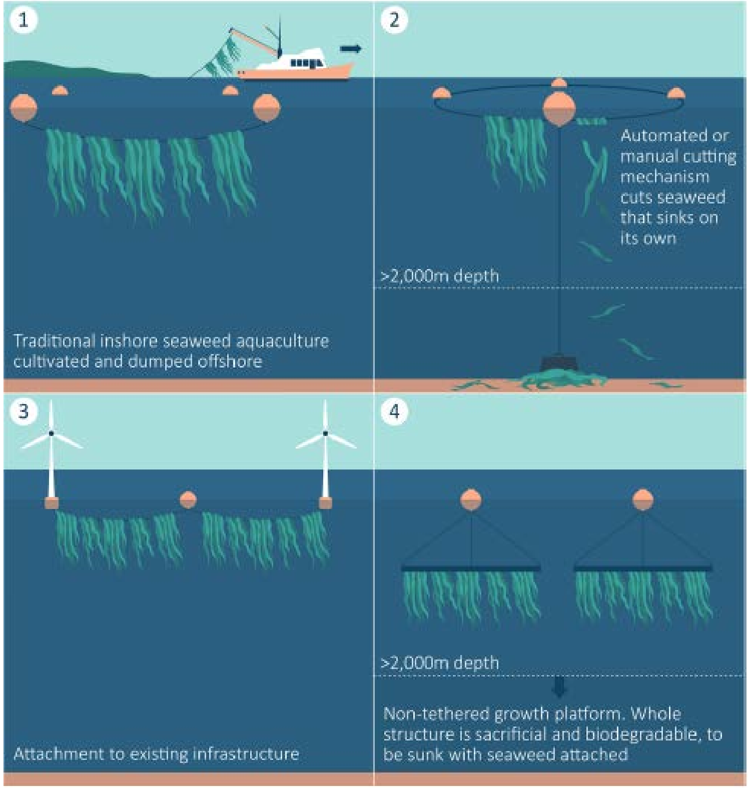


Figure 21. Example methods of growing seaweed that can be sunk to sequester the CO_2 absorbed by the biomass[102]

2.6.7 Monitoring mCDR

Generally monitoring mCDR methods will require either sensors inside of the CDR systems, such as pH or CO_2 sensors inside of an eChem mCDR device, or mobile autonomous surface or underwater vehicles equipped with sensors needed to detect environmental damages and CO_2 sequestration.[92] While there is existing equipment that can be used to monitor some aspects of CO_2 sequestration in the ocean, such as total alkalinity, pH, pCO_2, and DIC, there are no standardized and reliable ways of measuring sequestration from biological methods such as AU and seaweed cultivation and sinking, nor are there clear or consistent methods of assessing environmental damages from these methods.[92] More research is needed to ensure proper monitoring of mCDR.

Overall, ECO platforms can facilitate monitoring mCDR by serving as a charging station for autonomous vehicles that measure CO_2 capture and environmental impacts in the surrounding waters of another mCDR method being used on the energy island.

3 Offshore Reference Sites for ECO Systems Analysis

This section outlines the methodology for beneficial locations selection for ECO systems analysis, and the factors taken into consideration in it.

3.1 Site Selection Methodology

To determine advantageous positions for ECO sites, the offshore resources of the United States were assessed using reView, a data portal for NREL's Renewable Energy Potential Model (reV) that allows a user to view data as an interactive map. Using shapefiles of the United States, 2,219 coordinate points located within 110 kilometers off the coast of the contiguous US as well as the Great Lakes were recorded in a csv file using script developed in Python. To aid in this investigation, two of NREL's databases were accessed to obtain resource information: (1) WIND Toolkit: Wind Integration National Dataset Toolkit and (2) NSRDB: National Solar Radiation Database. A Python script has been developed to iterate through a list of selected coastal coordinate points and pull resource data from the NREL databases for each corresponding point. Using this data, the script calculated the yearly mean and variance of wind speed, wind power, and direct normal irradiance (DNI), the Pearson correlation coefficient, and the closest distance to shore for each coordinate point (see Figure 22).

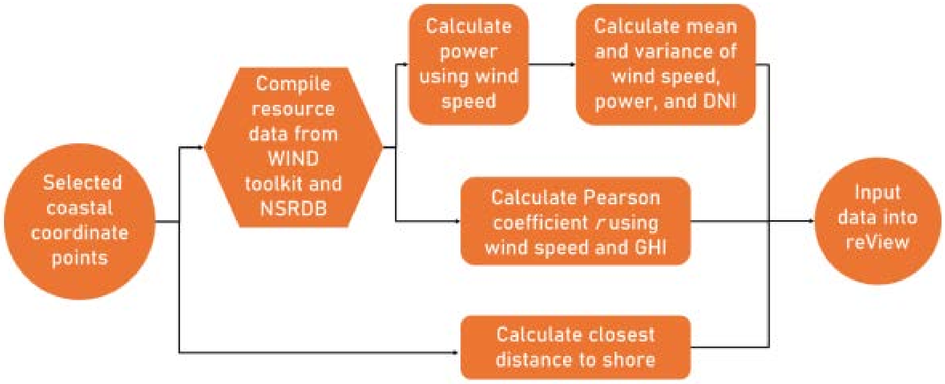


Figure 22. Methodology for ECO systems site selection

Power calculations have been based off the mean wind speed in each location and a 10 MW wind turbine with a rated wind speed of 11 m/s. If the wind speed is above the rated wind speed, then the power output is 10 MW, but if it does not meet the criteria, then the power becomes proportional to the wind speed. The Pearson correlation coefficient is used to measure complementarity and its value ranges from -1 to 1. A coefficient value of -1 represents perfect negative correlation which is when wind and solar resource occur inversely. A 1 represents perfect positive correlation which is when wind and solar resource perfectly coincide. In this context, a negative correlation value is desired to increase the resilience of the ECO. Complementarity was measured over an annual, daily averaged time scale and an annual, hourly averaged time scale. The latter takes the average over all 8,760 hours in a year. The former takes the average over all 365 days in a year.

To quantify resource abundance, the following expression uses wind speed x and DNI y and the maximum wind speed and DNI of the collected coordinate points to calculate the combined resource c: $c = 100 * [0.5 * x \; xmax + 0.5 * y \; ymax]$. The value for combined resource ranges from 0% to 100% where a higher percentage means both a stronger wind and solar resource at that location. The resulting map can be seen in Figure 23 with highest potential locations on the west coast – in Northern California.

Figure 23. Map with combined offshore wind and solar resources

3.2 Geospatial Data Collection and Processing

3.2.1 Offshore Renewable Energy Resources

Assuming a hydrogen production power requirement of 54 kWh per kg of hydrogen for water electrolysis and offshore wind potential of 13,500 TWh in the U.S., results into hydrogen production potential of ~250 MMT.

3.3 Geospatial Data Fusion and Site Selection

The combined resource map in Figure 24 was one of the primary visualizations that influenced indicative location siting. Six locations were identified based on the resource maps and complementary industries. The relevant site features for each location are compiled in Table 7.

Table 7. Site Characteristics for Potential ECO Locations

Table 1: Site characteristics for potential ECO locations

	Location 1	Location 2	Location 3
Latitude	38	33.6	26.8
Longitude	-123.8	-120	-97.2
Distance to shore (km)	69.25	88.98	21.66
Mean DNI (w/m^2)	205.57	250.71	225.03
Variance DNI (w^2/m^4)	104018	123848	97833
Mean wind speed (m/s)	9.18	8.31	8.10
Variance wind speed (m^2/s^2)	24.88	19.67	10.85
Mean power (MW)	5.48	4.84	4.70
Variance power (MW^2)	17.09	16.01	12.27
Combined resource (%)	74.73	76.75	71.70
Hourly averaged complementarity	0.043	-0.033	-0.143
Daily averaged complementarity	0.408	0.509	-0.157

	Location 4	Location 5	Location 6
Latitude	29	34.6	40.8
Longitude	-94.2	-75.6	-70.6
Distance to shore (km)	65.25	71.65	75.04
Mean DNI (w/m^2)	213.07	197.32	193.23
Variance DNI (w^2/m^4)	96015	908000	92836
Mean wind speed (m/s)	7.06	8.75	8.79
Variance wind speed (m^2/s^2)	12.29	19.97	20.66
Mean power (MW)	3.59	5.07	5.18
Variance power (MW^2)	11.76	14.96	15.17
Combined resource (%)	61.12	70.26	70.44
Hourly averaged complementarity	-0.202	-0.140	-0.163
Daily averaged complementarity	-0.454	-0.311	-0.349

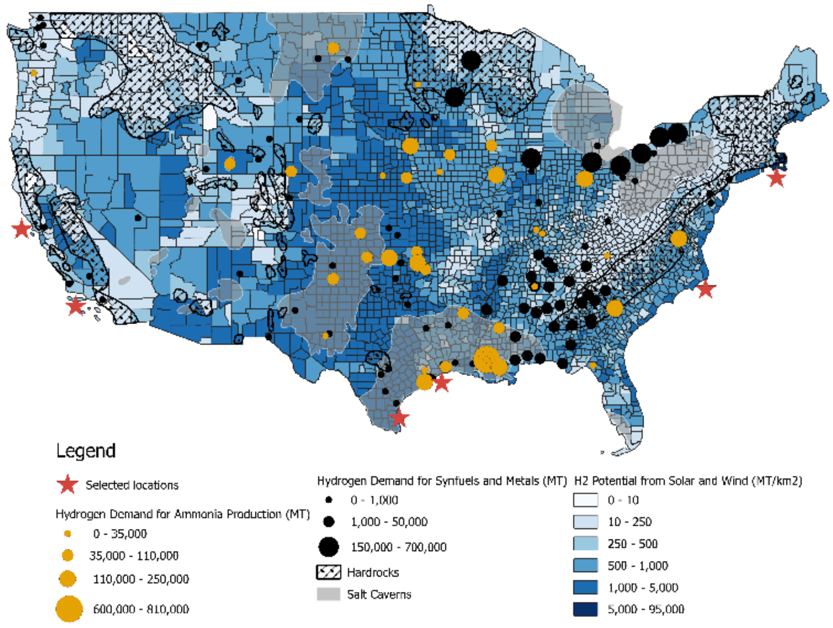


Figure 24. Map with selected locations for the ECO system

3.3.1. California

Locations 1 and 2 are located off the coast of California. Looking at the map in Figure 24, California has the highest combined resource values in the United States. As seen in Table 7, this is reflected in the California location sites since these locations also have the highest combination of solar and wind resource out of all the locations. The only downside to these locations is the positive complementarity values, which indicates that the wind and solar power are being generated at the same time. The highly abundant resources likely increased the probability of wind and solar resources coinciding leading to positive complementarity. Regardless, the installation of ECOs in California would still perform well given the abundant resource. Many areas in California have limited water resources and must import much of its water. The ECOs could power desalination plants to help meet the state's demand for freshwater. Additionally, the proximity to large urban centers would make the installation of subsea data centers at the ECO ideal.

3.3.2. Texas

Locations 3 and 4 are located off the coast of Texas. As seen in Table 7, Location 3 has the highest combined resource percentage after the California locations. Location 4 has the lowest Pearson coefficient of the six locations, and one of the lowest coefficients in the nation. The high resource abundance in combination with the low complementarity values are ideal for hybrid renewable farms. The Texas ECOs can power desalination and data centers like the California ECOs. Additionally, the Texas locations can take advantage of the existing natural gas pipeline infrastructure to transport hydrogen. A percentage of hydrogen can be pumped through the pipelines alongside the natural gas, therefore saving on construction costs. This enables the Texas locations to also have green hydrogen potential.

3.3.3. East Coast

Locations 5 and 6 are located on the east coast of the United States. Location 5 is off the coast of North Carolina. Location 6 is in New England, roughly off the coast of Rhode Island. These locations both have low complementarity values and high resource abundance (Table 7). Data centers would complement the energy production at the ECOs due to the locations' proximity to several large urban centers.

4 Policy Considerations of the Inflation Reduction Act

One of the largest and most comprehensive climate and energy bills in the United States was signed into law in August of 2022, allocating billions of dollars to invest in reducing clean energy deployment barriers. This bill, known as the Inflation Reduction Act of 2022, includes a series of policies that have been identified as relevant within this ECO scope. Although the Inflation Reduction Act is far more comprehensive in terms of what policies are included, the following identified tax policies are merely just a small glean of what is included in the bill. With the various electricity and emissions targets that have been announced by the Biden Administration, specifically the 100% clean electricity by 2035 and net-zero emissions by 2050, these identified polices have been designed to ensure low costs for both renewably generated electricity, as well as ensuring economically competitive costs for both green hydrogen and green ammonia to help achieve these targets.

These identified policies, below, act as either a tax credit to the taxpayer for when taxes are filed and submitted to the IRS, or act as a credit multiplier or bonus credit adder. If certain criteria are met to increase respective tax credit values, then the taxpayer is then eligible for values which would increase the rate of a production-based or investment-based tax credit. More details are provided in the following subsections, below.

For the scope of this research, the wind PTC (provision 45), and the investment tax credit (provision 48), are excluded. The following sections below, instead, focus on the technology-neutral PTC (45Y) and the technology-neutral ITC (48E) because these credits could be available within development timeline for an ECO center.

4.1 Technology-Neutral PTC

The technology-neutral PTC, provision 45Y, is a production-based tax credit, that once claimed, is valid for 10 years of a facilities operation. This tech-neutral PTC replaces the original wind PTC on January 1, 2025. Typically, a production-based credit has a greater value if a facility is located in an optimal resource area with a high-capacity factor or is expected to be operational more frequently, to maximize the potential cost savings that happen with production-based tax credits. This tech-neutral PTC credit is an emissions-based credit rather than a technology-based credit like its predecessor, the wind PTC, which this new credit replaces. In order to be eligible to claim this credit, the taxpayer/facility needs to have an emissions rate of zero or negative, which can be achieved utilizing carbon capture, utilization, and storage (CCUS 45Q). Lastly, this credit is only applicable to the generation components within a facility, primarily for electricity generated by sources that emit zero or negative emissions.

The tech-neutral 45Y has a base rate of $0.003 cents per kWh (in 1992 dollars) of electricity produced. This rate is then adjusted for the year which the credit is first claimed and is expected to be adjusted every year for inflation based on the inflation rate announced by the IRS. This credit is eligible for the 5X credit value multiplier that is applied if the facility/taxpayer meets Prevailing Wage and Apprenticeship requirements. If this requirement is met, then the base value of $0.003 cents per kWh is increased by five to $0.015 cents per kWh, and then this new rate is adjusted for inflation. Additionally, there are two bonus credits which could increase this respective value as well. These bonus credit adders are dependent on a few factors including whether the facility is eligible for the bonus credits, if the credits which the facility elects are also eligible for the 5X multiplier, and if the facility/taxpayer is eligible to stack bonus credits as well. A taxpayer can stack any credits during the time at which they are available prior to their respective expiration dates. The tech-neutral PTC is set to expire at the earliest being 2032, or when U.S. emissions targets are reached, which is once the power sector reaches 25% of 2022 emissions levels.

4.2 Technology-Neutral ITC

Similar to the technology-neutral PTC, provision 48E, also known as the technology-neutral ITC, is an emissions-based credit, rather than a technology-based credit, such as with its predecessor, the ITC, which this new credit replaces. Therefore, in order to be eligible to elect this credit, the facility/taxpayer must have an emissions rate of zero or negative, which can be achieved utilizing carbon capture, utilization, and storage (CCUS 45Q). The tech-neutral ITC 48E replaces provision 48 on January 1, 2025.

Provision 48E is an investment-based credit that is claimed in the first year of operation, when the taxpayer/facility submits their tax filing to the IRS. Thie tech-neutral ITC is a credit percentage of the cost to acquire and/or construct the facility which claims this credit. The credit percentage rate is dependent on a few factors including whether a facility meets the Prevailing Wage and Apprenticeship requirements for the 5X credit value multiplier, as well as if the bonus credit adders are applicable too. The base rate is 6% and if the 5x multiplier requirements are met, then the rate increases to 30%. If a facility is eligible for at least one bonus credit, in this instance, the Domestic Content credit (more info below), then the tech-neutral ITC rate can be as high as 40%.

Standalone storage with a minimum nameplate capacity of 5 kWh is now eligible to claim the tech-neutral ITC, including hydrogen storage and batteries, as long as the standalone storage facility is placed in service after December 31, 2022.

4.3 Clean Hydrogen PTC

The clean hydrogen production tax credit, provision 45V, is the first-of-its-kind production-based credit specifically designed for the production of hydrogen. This credit is intended to make clean hydrogen instantly cost-competitive with its other hydrogen-based counterparts, more specifically with grey and blue hydrogen. Once claimed, the credit is used for 10 years of a clean hydrogen production facility and is applicable for facilities that are placed in service and operational before January 1, 2033.

The clean hydrogen PTC is both a technology-based and emissions-based credit in the sense that this credit is only applicable for facilities deemed, a clean hydrogen production facility, and eligibility of the credit rate is based on the GHG lifecycle well-to-gate emissions, as determined by Argonne National Lab's GREET model. If a facility emits between 0 and .45 kg of lifecycle CO2 equivalent emissions on a per kg basis of hydrogen produced, then the facility is eligible for a credit rate of $0.60 per kg of H2 manufactured, which is the full 100% valuation of the credit. If a facility meets prevailing wage and apprenticeship requirements, then the credit rate is increased to $3 per kg of hydrogen produced. This credit is not eligible for any bonus credit adders.

Language within the Inflation Reduction Act allows for clean hydrogen facilities that are eligible for the clean hydrogen PTC to opt for the investment tax credit (provision 48E) in lieu of the clean hydrogen PTC. The following tables show credit percentage valuation based on CO2 equivalent emissions.

Table 8. 45V Credit Percentage Valuation Based on Carbon Intensity

Carbon Intensity (kg CO2e/kg H2)	Min H2 PTC ($/kg H2)	Max H2 PTC ($/kg H2) (prevailing requirements)
0-0.45	$0.60 (100%)	$3.00 (100%)
0.45-1.5	$0.20 (33.4%)	$1.00 (33.4%)
1.5-2.5	$0.15 (25%)	$0.75 (25%)
2.5-4	$0.12 (20%)	$0.60 (20%)

Table 9. 48E Credit Percentage Valuation In Lieu of 45V Based on Carbon Intensity

Carbon Intensity (kg CO2e/kg H2)	ITC % Value (% of full credit)	ITC % Value (% of full credit) (prevailing requirements)
0-0.45	6% (100%)	30% (100%)
0.45-1.5	2% (33.4%)	10% (33.4%)
1.5-2.5	1.5% (25%)	7.5% (25%)
2.5-4	1.2% (20%)	6% (20%)

4.4 Prevailing Wage and Apprenticeship Requirements

The prevailing wage and apprenticeship requirement is a 5X credit multiplier. This credit multiplier is applicable to the tech-neutral PTC, tech-neutral ITC and the clean hydrogen PTC (as relevant to this research scope), and increases respective credit values, whether on a cent per kWh or a percentage basis, by 5. In order for a taxpayer to be eligible for this credit multiplier, specific requirements need to be met for wages paid and apprentices employed, as determined by the Secretary of Labor.

This credit multiplier is applicable to facilities that are over 1MW. For production-based tax credits, the tech-neutral PTC and the clean hydrogen PTC, these requirements need to be maintained for the entire 10-year duration of the PTC-based credits, and for the tech-neutral investment-based tax credit, these requirements need to be maintained for 5 years.

4.5 Domestic Content Bonus Credit

The domestic content bonus credit is a 2% or 10% bonus adder for the tech-neutral PTC and tech-neutral ITC and is not applicable to the clean hydrogen PTC. This rate is dependent on whether the taxpayer also qualifies for the 5X prevailing wage and apprenticeship requirement which increases the 2% value up to 10%. This percentage is then added to respective tech-neutral PTC and tech-neutral ITC credit rates. This bonus percentage is added to a PTC rate by multiplying the percentage point to the PTC rate, and for the ITC rate, the bonus percentage point is merely added to the existing ITC percentage that the taxpayer is eligible for.

In order to be eligible for this bonus credit, the taxpayer must ensure that "any steel, iron, or manufactured product which is a component of such facility was produced in the U.S." Therefore, 100% of steel or iron that is a component within an ECO system must be produced in the U.S. and 40% of manufactured products intended for the components of an ECO system must be produced in the U.S. as well.

4.6 Potential Gaps or Limitations in Policy

Although the Inflation Reduction Act is a very comprehensive political framework designed to mitigate barriers for further clean energy deployment, the novelty and complexity of ECO systems that additional clarifications or even additional policies could be useful in encouraging their development. In addition, the IRA is essentially a 15-year (+/-) window on renewable energy tax credits so, depending on when ECOs were actually deployed, the policies may not be relevant.

Although ECOs differ from large-scale energy islands as they are currently being thought of, Europe is in the process of exploring different energy island options and this framework approach could be one which the U.S. can duplicated domestically. More specifically, Denmark is committed to two energy island developments, one of which is a 3MW artificial island with the potential of an increased 10MW capacity that will be located approximately 50 miles west of Jutland, Denmark, and the other located on the island of Bornholm with a rated capacity of 2GW.[iii] Belgium has also committed to the development of a 3.5MW energy island which is expected to begin construction in 2024.[iv] Germany and the Netherlands are also currently active in exploring energy island options.

Policy considerations that have helped influence these European nation energy island initiatives include the increased value/importance of becoming more energy independent by establishing greater energy security to avoid supply dependency from other nations, especially during times of war such as with the Ukrainian and Russian conflict, which has disrupted the conventional energy supply chain. Additionally, specific government agreements such as the Danish legislature agreement which has initiated the development of these two Danish energy islands could be duplicated in the United States so that there is direct government support for the development of ECOs.[v]

[iii] https://en.kefm.dk/news/news-archive/2021/feb/denmark-decides-to-construct-the-world%e2%80%99s-first-windenergy-hub-as-an-artificial-island-in-the-north-sea

[iv] https://windeurope.org/newsroom/news/energy-islands-coming-to-europes-seas/#:~:text=Belgium%20will%20start%20building%20their,can%20be%20extended%20over%20time.

[v] https://ens.dk/en/our-responsibilities/energy-islands/denmarks-energy-islands

A combination of factors can work in favor of ECO developments which highlights the importance of taking a multifaceted approach to ensuring these aggressive 2035 and 2050 targets set by the U.S. are met. In the case of Denmark's government support, the Danish Energy Agency highlights a few reasons as to why investing in this type of development is worthy, including active partnerships to optimize business opportunities; strong national and international support; and technological support to future-proof these energy islands, to name a few.[vi] These are some examples which the U.S. can reference and leverage through additional policy support that could help ensure adequate ECO center developments.

[vi] https://ens.dk/en/our-responsibilities/energy-islands/energy-island-north-sea

5 Modeling Tools Considered for ECO Systems Analysis

A key task of the ECO project was to identify existing tools capable of modeling components of a hybrid system that we could integrate and build upon. As the only national laboratory solely dedicated to energy efficiency and renewable energy, NREL has developed a repertoire of modeling tools and capabilities, discussed below.

5.1 Hydrogen Analysis Production Models (H2A)

The Hydrogen Analysis (H2A) hydrogen production models and case studies "provide transparent reporting of process design assumptions and a consistent cost analysis methodology for hydrogen production at central and distributed (forecourt/filling-station) facilities. Required input to the models includes capital and operating costs for the hydrogen production process, fuel type and use, and financial parameters such as the type of financing, plant life, and desired internal rate of return. The models include default values, developed by the H2A team, for many of the input parameters, but users may also enter their own values. The models use a standard discounted cash flow rate of return analysis methodology to determine the hydrogen selling cost for the desired internal rate of return."[111]

5.2 Hydrogen Financial Analysis Scenario Tool (H2FAST/ProFAST)

The Hydrogen Financial Analysis Scenario Tool (H2FAST) "provides a quick and convenient in-depth financial analysis for hydrogen and nonhydrogen systems and services. The model uses a generally accepted accounting principles analysis framework and provides annual projections of income statements, cash flow statements, and balance sheets. H2FAST allows users to generate a side-by-side scenario analysis, where a base system can be tested by varying key operating or financing parameters. Detailed capital structure, taxation, and incentives are included. The model has built-in risk analysis allowing impact assessment of parameters bearing user-specified uncertainty ranges. Financial articulation is presented in graphical and tabular format for the user-specified analysis period. The model is self-documented, with embedded help functions and annotation of input parameters."[112]

A Python implementation called ProFAST is available, making the tools of H2FAST simple to integrate with other available software tools.

5.3 Hydrogen Filling Simulation (H2FillS)

The Hydrogen Filling Simulation (H2FillS) software is "a thermodynamic model designed to track and report on the transient change in hydrogen temperature, pressure, and mass flow when filling a fuel cell electric vehicle (FCEV). H2FillS will automatically output fill performance data from the vehicle by tracking pressure and temperature throughout the fill. Users can input their own fill profiles into the model to run a variety of simulations."[113]

5.4 Hybrid Optimization of Multiple Energy Resources (HOMER®)

Hybrid Optimization of Multiple Energy Resources (HOMER) is "the micro-power optimization model, helps you design off-grid and grid-connected systems. HOMER finds the least cost combination of components that meet electrical and thermal loads. HOMER simulates thousands of system configurations, optimizes for lifecycle cost, and generates results of sensitivity analyses on most inputs."[114]

5.5 Hybrid Optimization and Performance Platform (HOPP)

HOPP is "a software tool that enables detailed analysis and optimization of hybrid power plants down to the component level. It has the capability to assess and optimize projects that contain combinations of wind (onshore and offshore), solar, storage, geothermal, and hydro. The HOPP platform aims to answer the crucial question 'When and where do hybrid plants make sense, and how can we design them optimally?' HOPP leverages other NREL-developed tools—ReOpt®, SAM, WISDEM®—to size, analyze, and design the hybrid power plants of the future, allowing for detailed output on a myriad of design conditions, from number and type of turbine to the overall layout and topology of assets within the system."

5.6 Renewable Energy Integration and Optimization (REopt)

The REopt techno-economic decision support platform "is used by NREL researchers to optimize energy systems for buildings, campuses, communities, microgrids, and more. REopt recommends the optimal mix of renewable energy, conventional generation, and energy storage technologies to meet cost savings, resilience, emissions reductions, and energy performance goals."[115]

5.7 System Advisor Model™ (SAM) / PySAM

SAM is a techno-economic software, which can model many types of renewable energy systems:

- Photovoltaic systems, from small residential rooftop to large utility-scale systems
- Battery storage with Lithium ion, lead acid, or flow batteries for front-of-meter or behind-the-meter applications
- Concentrating Solar Power systems for electric power generation, including parabolic trough, power tower, and linear Fresnel
- Industrial process heat from parabolic trough and linear Fresnel systems
- Wind power, from individual turbines to large wind farms
- Marine energy wave and tidal systems
- Solar water heating
- Fuel cells
- Geothermal power generation
- Biomass combustion for power generation
- High concentration photovoltaic systems.[116]

5.8 Revenue, Operation, and Device Optimization (RODeO)

The Revenue, Operation, and Device Optimization (RODeO) model "explores optimal system design and operation considering different levels of grid integration, equipment cost, operating limitations, financing, and credits and incentives. RODeO is a price-taker model formulated as a mixed-integer linear programming (MILP) model in the GAMS modeling platform. The objective is to maximizes the net revenue for a collection of equipment at a given site. The equipment includes generators (e.g., gas turbine, steam turbine, solar, wind, hydro, fuel cells, etc.), storage systems (batteries, pumped hydro, gas-fired compressed air energy storage, long-duration systems, hydrogen), and flexible loads (e.g., electric vehicles, electrolyzers, flexible building loads). The input data required by RODeO can be classified into three bins. 1). utility service data, which refers to retail utility rate information (meter cost, energy, and demand charges). 2). Electricity market data, which include energy and reserve prices. 3) other inputs, which refer to additional electrical demand, product output demand, technological assumptions, financial properties, and operational parameters."[117]

5.9 Storage Deployment Optimization Model (SDOM)

SDOM is "designed to accurately represent the operation of storage across different timescales, including long-duration and seasonal applications, and the spatiotemporal diversity and complementarity among VRE sources. SDOM uses an hourly temporal resolution, a fine spatial resolution for VRE sources, and a 1-year optimization window."[118]

5.10 Offshore Regional Cost Analyzer (ORCA)

ORCA was developed and is maintained by NREL with funding from DOE. "The tool computes the LCOE of fixed-bottom and floating wind installations at thousands of U.S. offshore sites. That analysis helps identify the most economically attractive sites and, more importantly, the key drivers of offshore LCOE across the United States."[119]

5.11 Modeling Tools Selection and Integration

When combining various modeling frameworks with different objectives, constraints, in different platforms, using different modeling approaches, first, the effort for integration and resulting tool should be assessed, and if it would be feasible and practical to tie various pieces together. Then, it could be considered implementing ideas from existing frameworks into a master model which would result in a more cohesive environment. It is out of the scope of this work to look at a methodology for modeling tools integration. Instead, we suggest which of the tools above are suitable given the components discussed in earlier sections. Then, gaps in the modeling capabilities are discussed.

SAM, REopt, HOPP or HOMER are good candidates for modeling the renewable energy generation part of the ECO clusters where ORCA could be useful for the specific LCOE related to the types of turbines selected for the study. Depending on the desired techno-economic approach to be undertaken, if optimization is desirable, RODeO and SDOM could provide insight into the optimal design and operation for the electrolytic hydrogen production, and type and capacity of storage needed. If financial frameworks are more valuable for the project, H2A and H2FAST would provide a detailed breakdown of the levelized cost of hydrogen and a thorough understanding of the underlying financials of hydrogen projects. An existing gap in NREL's modeling suite is optimizing for the hydrogen supply chains and the many demands that could be served from the point of hydrogen production. It is one potential area that could be investigated in this project.

For this project we need to model systems in an offshore environment and in a connected way that allows for optimization and overall financial assessment. HOPP contains models for many components of the systems we envision and is open-source, which will allow us to add models that are not already a part of HOPP, such as off-shore solar. In connection with HOPP we plan to use the H2FAST financial model through ProFAST, analyze wind turbine installation costs using

ORBIT, NREL's offshore renewables balance of system and installation tool, and possibly incorporate some models from PySAM through HOPP. We also plan to compare our results to ARIES data. For this reason, we will begin with an ECO containing wind, PV solar, battery energy storage, PEM electrolysis hydrogen production, and hydrogen storage.

6 Conclusions and Recommendations

By nature, an ECO concept has the potential to include a large number of technologies and applications, only a segment of which have been considered in this report, which is not exhaustive. In addition, the most appropriate technology combinations for any given ECO project will be highly dependent on specific project characteristics, location, and objectives. However, based on the assessments summarized in this report, we have prioritized technologies for further consideration and optimization for potential ECO applications.

6.1 Selection of Most Promising Technologies and Applications

In assessing the applicability of the various technologies to potential ECO concepts and further analysis and optimization, we have prioritized the technologies according to four main categories:

1. High-priority technologies that are sufficiently advanced and will be included in further optimization efforts as part of the project
2. Other higher priority technologies that will be generally considered as part of the further analysis but not included in the optimization
3. Other technologies that are potentially promising for ECO applications but will not be considered as part of the current project
4. Technologies that we currently consider less appropriate for ECO applications and won't be considered further

The prioritization and categorization are based on various factors including the technology's current TRL, economic performance, applicability to an ECO concept and/or ocean environment, complementarity to other included technologies, and NREL's current capability to model and optimize these technologies.

6.1.1 High-Priority Technologies

The technologies outlined below have been categorized as high priority potential for an ECO concept and will be included in the modeling and optimization efforts.

- Power generation technologies will include fixed and floating offshore wind, oscillating body wave energy converters, and floating solar photovoltaics
- Hydrogen and fuel technologies will include hydrogen produced using PEM electrolysis
- Storage technologies will include battery storage and compressed gas storage vessels
- End use technologies will include maritime transport applications
- Carbon capture technologies will include direct air capture

6.1.2 Other Priority Technologies

The technologies outlined below have been categorized as priorities for potential ECO concepts and will generally be considered in the analysis but will not be included in the optimization efforts.

- Fuel technologies will include ammonia and methanol production from the hydrogen produced

- Storage technologies will include underwater hydrogen storage above the seabed
- End use technologies will include desalination using seawater, offshore/undersea data centers, hydrogen for use in refineries, chemical production, steel production, and hydrogen fuel cell applications (including stationary power, storage, and backup power)
- Carbon capture technologies will include artificial upwelling, eChem m CDR, floating PBRs, and seaweed cultivation

6.1.3 Potential for Future Consideration

The technologies outlined below have been categorized as potentially interesting for consideration in an ECO concept but will not be included in the current analysis. However, there may still be value in considering these technologies further in future analyses.

- Generation technologies like ocean thermal energy conversion, bio-photolysis, and biomass gasification and slow biomass pyrolysis using collocated farmed seaweed
- Storage technologies like liquid organic hydrogen carriers
- End use technologies like habitat shelter offshore and other transportation fuels used for land-based or air transport (as opposed to maritime transport)
- Carbon capture technologies like deep ocean carbon storage and seaweed processing for biofuels

6.1.4 Low-Priority Technologies

The technologies outlined below have been categorized as less appropriate for an ECO concept and will therefore not be considered further. These technologies may still offer value in other applications but are of lower priority in an ECO concept.

- Generation technologies like fixed-bottom offshore wind (considering scales that are likely to be at water depths that can't accommodate fixed bottom technology), tidal, PEC electrolysis, high temperature decomposition, and fermentation
- Storage technologies like liquid storage vessels, MOFs, carbon nanotubes, and underground storage
- End use technologies like CHP

6.2 Next Steps

The next steps for this project would include but are not limited to:

- Modify HOPP to leverage the capabilities of other NREL existing modeling tools based on the high-priority technologies selected
- Expand the HOPP capabilities with modeling technologies that NREL does not currently have capabilities for
- In leveraging and expanding, apply optimization techniques for the computational performance improvement of HOPP
- A journal article publication with the optimal design for the technologies at the selected ECO locations
- If possible, validate mathematical framework with ARIES

References

1. Hartman, L. (2022). Top 10 Things You Didn't Know About Offshore Wind Energy. https://www.energy.gov/eere/wind/articles/top-10-things-you-didnt-know-about-offshore-wind-energy.

2. Gheorghiu, I. (2019). Floating solar PV could power 10% of nation but O&M questions remain, NREL says. https://www.utilitydive.com/news/floating-solar-pv-could-power-10-of-nation-but-om-questions-remain-nrel/545281/.

3. Kilcher, L., Fogarty, M., and Lawson, M. (2021). Marine Energy in the United States: An Overview of Opportunities (NREL).

4. Ahmed, S.F., Rafa, N., Mofijur, M., Badruddin, I.A., Inayat, A., Ali, M.S., Farrok, O., and Yunus Khan, T.M. (2021). Biohydrogen Production From Biomass Sources: Metabolic Pathways and Economic Analysis. Front. Energy Res. *9*. 10.3389/fenrg.2021.753878.

5. Hosseinzadeh, A., Zhou, J.L., Li, X., Afsari, M., and Altaee, A. (2022). Techno-economic and environmental impact assessment of hydrogen production processes using bio-waste as renewable energy resource. Renew. Sustain. Energy Rev. *156*, 111991. 10.1016/j.rser.2021.111991.

6. Frowijn, L.S.F., and van Sark, W.G.J.H.M. (2021). Analysis of photon-driven solar-to-hydrogen production methods in the Netherlands. Sustain. Energy Technol. Assess. *48*, 101631. 10.1016/j.seta.2021.101631.

7. NREL (2022). H2@Scale Program Multi-Party Cooperative Research and Development Agreement: California Hydrogen Infrastructure Research Consortium Task.

8. Binder, M., Kraussler, M., Kuba, M., and Luisser, M. (2018). Hydrogen from biomass gasification (IEA Bioenergy).

9. DOE (2022). U.S. Department of Energy Clean Hydrogen Production Standard (CHPS) Draft Guidance.

10. Azzaro-Pantel, C. ed. (2018). Hydrogen Supply Chains. Design, Deployment and Operation (Elsevier Ltd.).

11. Abdalla, A.M., Hossain, S., Nisfindy, O.B., Azad, A.T., Dawood, M., and Azad, A.K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. Energy Convers. Manag. *165*, 602–627. 10.1016/j.enconman.2018.03.088.

12. Barthelemy, H., Weber, M., and Barbier, F. (2017). Hydrogen storage: Recent improvements and industrial perspectives. Spec. Issue 6th Int. Conf. Hydrog. Saf. ICHS 2015 19-21 Oct. 2015 Yokohama Jpn. *42*, 7254–7262. 10.1016/j.ijhydene.2016.03.178.

13. Zhang, F., Zhao, P., Niu, M., and Maddy, J. (2016). The survey of key technologies in hydrogen energy storage. Int. J. Hydrog. Energy *41*, 14535–14552. 10.1016/j.ijhydene.2016.05.293.

14. Papadias, D.D., and Ahluwalia, R.K. (2021). Bulk storage of hydrogen. Int. J. Hydrog. Energy *46*, 34527–34541. 10.1016/j.ijhydene.2021.08.028.

15. DOE (2022). DOE National Clean Hydrogen Strategy and Roadmap (DOE).

16. López-Queija, J., Robles, E., Jugo, J., and Alonso-Quesada, S. (2022). Review of control technologies for floating offshore wind turbines. Renew. Sustain. Energy Rev. *167*, 112787. 10.1016/j.rser.2022.112787.

17. Kreider, M. (2022). Offshore Wind Energy: Technology Below the Water.

18. Watson, S., Moro, A., Reis, V., Baniotopoulos, C., Barth, S., Bartoli, G., Bauer, F., Boelman, E., Bosse, D., Cherubini, A., et al. (2019). Future emerging technologies in the wind power sector: A European perspective. Renew. Sustain. Energy Rev. *113*, 109270. 10.1016/j.rser.2019.109270.

19. Musial, W., Spitsen, P., Duffy, P., Beiter, P., Marquis, M., Hammond, R., and Shields, M. (2022). Offshore Wind Market Report: 2022 Edition (DOE).

20. Robinson, M. (2006). Offshore Wind Technology Overview.

21. Jiang, Z. (2021). Installation of offshore wind turbines: A technical review. Renew. Sustain. Energy Rev. *139*, 110576. 10.1016/j.rser.2020.110576.

22. Stehly, T., and Duffy, P. (2021). 2020 Cost of Wind Energy Review (National Renewable Energy Laboratory).

23. Wind Europe (2017). Floating Offshore Wind Vision Statement.

24. Musial, W., Beiter, P., and Nunemaker, J. (2020). Cost of Floating Offshore Wind Energy Using New Englands Aqua Ventus Concrete Semisubersible Technology (National Renewable Energy Laboratory).

25. Beiter, P., Musial, W., Duffy, P., Cooperman, A., Shields, M., Heimiller, D., and Optis, M. (2020). The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032 (National Renewable Energy Laboratory).

26. Ziar, H. (2021). Floating solar stations (TU Delft).

27. Ramasamy, V., and Margolis, R. Floating Photovoltaic System Cost Benchmark: Q1 2021 Installations on Artificial Water Bodies (NREL).

28. Spencer, R.S., Macknick, J., Aznar, A., Warren, A., and Reese, M.O. (2019). Floating Photovoltaic Systems: Assessing the Technical Potential of Photovoltaic Systems on Man-

Made Water Bodies in the Continental United States. Environ. Sci. Technol. *53*, 1680–1689. 10.1021/acs.est.8b04735.

29. Beshilas, L. (2019). Floating Solar Photovoltaics Could Make a Big Splash in the USA.

30. PV Magazine (2020). Floating solar plant with LCOE of $0.051/kWh comes online in Malaysia.

31. López, M., Soto, F., and Hernández, Z.A. (2022). Assessment of the potential of floating solar photovoltaic panels in bodies of water in mainland Spain. J. Clean. Prod. *340*, 130752. 10.1016/j.jclepro.2022.130752.

32. Kilcher, L., and Thresher, R. (2016). Marine Hydrokinetic Energy Site Identification and Ranking Methodology Part I: Wave Energy.

33. O'Neil, R., Staines, G., and Freeman, M. (2019). Marine Hydrokinetics Regulatory Processes Literature Review (PNNL).

34. IRENA (2020). Innovation Outlook. Ocean Energy Technologies (International Renewable Energy Agency).

35. Jenne, D.S., Yu, Y.-H., and Neary, V. (2015). Levelized Cost of Energy Analysis of Marine and Hydrokinetic Reference Models (NREL & Sandia).

36. Ocean Energy Systems (2017). An International Vision for Ocean Energy 2017.

37. IRENA (2014). Ocean Thermal Energy Conversion. Technology Brief.

38. Langer, J., Quist, J., and Blok, K. (2020). Recent progress in the economics of ocean thermal energy conversion: Critical review and research agenda. Renew. Sustain. Energy Rev. *130*, 109960. 10.1016/j.rser.2020.109960.

39. Hydrogen and Fuel Cell Technologies Office (2021). Hydrogen Shot. https://www.energy.gov/eere/fuelcells/hydrogen-shot.

40. IRENA (2020). Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^0C Climate Goal.

41. Bristowe, G., and Smallbone, A. (2021). The Key Techno-Economic and Manufacturing Drivers for Reducing the Cost of Power-to-Gas and a Hydrogen-Enabled Energy System. Hydrogen *2*, 273–300. 10.3390/hydrogen2030015.

42. Marshall, A., Børresen, B., Hagen, G., Tsypkin, M., and Tunold, R. (2007). Hydrogen production by advanced proton exchange membrane (PEM) water electrolysers—Reduced energy consumption by improved electrocatalysis. ECOS 05 18th Int. Conf. Effic. Cost Optim. Simul. Environ. Impact Energy Syst. *32*, 431–436. 10.1016/j.energy.2006.07.014.

43. Chi, J., and Yu, H. (2018). Water electrolysis based on renewable energy for hydrogen production. Chin. J. Catal. *39*, 390–394. 10.1016/S1872-2067(17)62949-8.

44. Ito, H., Miyazaki, N., Ishida, M., and Nakano, A. (2016). Cross-permeation and consumption of hydrogen during proton exchange membrane electrolysis. Int. J. Hydrog. Energy *41*, 20439–20446. 10.1016/j.ijhydene.2016.08.119.

45. Show, K.-Y., Yan, Y., Ling, M., Ye, G., Li, T., and Lee, D.-J. (2018). Hydrogen production from algal biomass – Advances, challenges and prospects. Bioresour. Technol. *257*, 290–300. 10.1016/j.biortech.2018.02.105.

46. Fuel Cell Technologies Office (2018). Thermochemical water splitting. https://www.energy.gov/eere/fuelcells/hydrogen-production-thermochemical-water-splitting.

47. Riis, T., Hagen, E.F., Vie, P.J.S., and Ulleberg, O. (2006). Hydrogen Production and Storage. R&D Priorities and Gaps (International Energy Agency (IEA)).

48. Baykara, S.Z. (2004). Hydrogen production by direct solar thermal decomposition of water, possibilities for improvement of process efficiency. Int. J. Hydrog. Energy *29*, 1451–1458. 10.1016/j.ijhydene.2004.02.014.

49. Rao, C.N.R., and Dey, S. (2017). Solar thermochemical splitting of water to generate hydrogen. Proc. Natl. Acad. Sci. *114*, 13385. 10.1073/pnas.1700104114.

50. Fuel Cell Technologies Office (2018). Hydrogen Production: Biomass Gasification. https://www.energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification.

51. Department of Energy (2017). Thermochemical Conversion R&D. Technology Area.

52. Kuppam, C., Pandit, S., Kadier, A., Dasagrandhi, C., and Velpuri, J. (2017). Biohydrogen Production: Integrated Approaches to Improve the Process Efficiency. In Microbial Applications Vol.1: Bioremediation and Bioenergy, V. C. Kalia and P. Kumar, eds. (Springer International Publishing), pp. 189–210. 10.1007/978-3-319-52666-9_9.

53. Khetkorn, W., Rastogi, R.P., Incharoensakdi, A., Lindblad, P., Madamwar, D., Pandey, A., and Larroche, C. (2017). Microalgal hydrogen production – A review. Bioresour. Technol. *243*, 1194–1206. 10.1016/j.biortech.2017.07.085.

54. Lee, K., Liu, X., Vyawahare, P., Sun, P., Elgowainy, A., and Wang, M. (2022). Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production. Green Chem. *24*, 4830–4844. 10.1039/D2GC00843B.

55. Borisut, P., and Nuchitprasittichai, A. (2019). Methanol Production via CO2 Hydrogenation: Sensitivity Analysis and Simulation—Based Optimization. Front. Energy Res. *7*. 10.3389/fenrg.2019.00081.

56. IRENA, and Methanol Institute (2021). Innovation Outlook: Renewable Methanol.

57. James, B., Huya-Kouadio, J., Houchins, C., and DeSantis (2017). Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2016 Update.

58. Hunt, J.D., Nascimento, A., Zakeri, B., and Barbosa, P.S.F. (2022). Hydrogen Deep Ocean Link: a global sustainable interconnected energy grid. Energy *249*, 123660. 10.1016/j.energy.2022.123660.

59. Gardiner, M. (2009). Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs.

60. Langmi, H.W., Ren, J., and Musyoka, N.M. (2016). 7 - Metal–organic frameworks for hydrogen storage. In Compendium of Hydrogen Energy, R. B. Gupta, A. Basile, and T. N. Veziroğlu, eds. (Woodhead Publishing), pp. 163–188. 10.1016/B978-1-78242-362-1.00007-9.

61. Jiao, L., Seow, J.Y.R., Skinner, W.S., Wang, Z.U., and Jiang, H.-L. (2018). Metal–organic frameworks: Structures and functional applications. Mater. Today. 10.1016/j.mattod.2018.10.038.

62. Wu, H. (2008). Strategies for the Improvement of the Hydrogen Storage Properties of Metal Hydride Materials. ChemPhysChem *9*, 2157–2162. 10.1002/cphc.200800498.

63. Darkrim, F.L., Malbrunot, P., and Tartaglia, G.P. (2002). Review of hydrogen storage by adsorption in carbon nanotubes. Int. J. Hydrog. Energy *27*, 193–202. 10.1016/S0360-3199(01)00103-3.

64. Rajaura, R.S., Srivastava, S., Sharma, P.K., Mathur, S., Shrivastava, R., Sharma, S.S., and Vijay, Y.K. (2018). Structural and surface modification of carbon nanotubes for enhanced hydrogen storage density. Nano-Struct. Nano-Objects *14*, 57–65. 10.1016/j.nanoso.2018.01.005.

65. Preuster, P., Papp, C., and Wasserscheid, P. (2017). Liquid Organic Hydrogen Carriers (LOHCs): Toward a Hydrogen-free Hydrogen Economy. Acc. Chem. Res. *50*, 74–85. 10.1021/acs.accounts.6b00474.

66. Kruck, O., Crotogino, F., Prelicz, R., and Rudolph, T. (2013). “Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe.”

67. James, B.D., and Houchins, C. (2018). 2018 DOE Hydrogen and Fuel Cells Program Review. Hydrogen Storage Cost Analysis.

68. Sreedhar, I., Kamani, K.M., Kamani, B.M., Reddy, B.M., and Venugopal, A. (2018). A Bird’s Eye view on process and engineering aspects of hydrogen storage. Renew. Sustain. Energy Rev. *91*, 838–860. 10.1016/j.rser.2018.04.028.

69. Ahluwalia, R.K., Hua, T.Q., Peng, J.-K., Kromer, M., Lasher, L., McKenney, K., Law, K., and Sinha, J. (2011). Technical Assessment of Organic Liquid Carrier Hydrogen Storage Systems for Automotive Applications.

70. Aakko-Saksa, P.T., Cook, C., Kiviaho, J., and Repo, T. (2018). Liquid organic hydrogen carriers for transportation and storing of renewable energy – Review and discussion. J. Power Sources *396*, 803–823. 10.1016/j.jpowsour.2018.04.011.

71. Godula-Jopek, A. ed. (2015). Hydrogen Production: Electrolysis (Wiley - VCH).

72. Jensen, C., Brayton, D., Jorgensen, S.W., and Hou, P. (2017). Development of a Practical Hydrogen Storage System Based on Liquid Organic Hydrogen Carriers and a Homogeneous Catalyst (Hawaii Hydrogen Carriers, LLC & General Motors, LLC).

73. Shashikala, K., Banerjee, S., Kumar, A., Pai, M.R., and Pillai, C.G.S. (2009). Improvement of hydrogen storage properties of TiCrV alloy by Zr substitution for Ti. 4th Dubrov. Conf. *34*, 6684–6689. 10.1016/j.ijhydene.2009.06.065.

74. Sandia National Laboratories (2022). Maritime Applications for Hydrogen Fuel Cells. https://energy.sandia.gov/programs/sustainable-transportation/hydrogen/fuel-cells/maritime-applications/.

75. International Council on Clean Hydrogen Transportation (2020). Liquid hydrogen refueling infrastructure to support a zero-emission U.S.–China container shipping corridor.

76. Judge, P. (2022). Building underwater. https://www.datacenterdynamics.com/en/analysis/building-underwater/.

77. Fuel Cell & Hydrogen Energy Association (2022). Stationary Power. https://www.fchea.org/stationary.

78. DOE (2018). Fuel Cells for Stationary Power Applications.

79. Eichman, J., Harrison, K., and Peters, M. (2014). Novel Electrolyzer Applications: Providing More Than Just Hydrogen.

80. Satyapal, S. (2022). 2022 AMR Plenary Session. https://www.hydrogen.energy.gov/pdfs/review22/plenary4_satyapal_2022_o.pdf.

81. Argonne National Laboratory (2020). Assessment of Potential Future Demands for Hydrogen in the United States.

82. Nikolaidis, P., and Poullikkas, A. (2018). Cost metrics of electrical energy storage technologies in potential power system operations. Sustain. Energy Technol. Assess. *25*, 43–59. 10.1016/j.seta.2017.12.001.

83. Friedman, J., Zapantis, A., Page, B., Consoli, C., Fan, Z., Havercrosft, I., Emeka Ochu, H., Raji, N., Rassool, D., Sheerazi, H., et al. (2020). NET-ZERO AND GEOSPHERIC RETURN: ACTIONS TODAY FOR 2030 AND BEYOND (The Center on Global Energy Policy, The School of Internationa and Public Affairs).

84. Energy Futures Initiative (2020). Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments.

85. Gagern, A., and Kapsenberg, L. (2020). Ocean - based carbon dioxide removal: A Primer for Philanthropy (Climateworks Foundation).

86. Davies, P.A., Yuan, Q., and de Richter, R. (2018). Desalination as a negative emissions technology. Environ. Sci. Water Res. Technol. *4*, 839–850. 10.1039/C7EW00502D.

87. Ishaq, H., and Crawford, C. (2022). Potential of offshore wind energy for direct air capture. Int. J. Energy Res. *46*, 18919–18927. 10.1002/er.8506.

88. Digdaya, I.A., Sullivan, I., Lin, M., Han, L., Cheng, W.-H., Atwater, H.A., and Xiang, C. (2020). A direct coupled electrochemical system for capture and conversion of CO2 from oceanwater. Nat. Commun. *11*. 10.1038/s41467-020-18232-y.

89. Aure, J., Strand, ø, Erga, S., and Strohmeier, T. (2007). Primary production enhancement by artificial upwelling in a western Norwegian fjord. Mar. Ecol. Prog. Ser. *352*, 39–52. 10.3354/meps07139.

90. Fan, W., Zhang, Z., Yao, Z., Xiao, C., Zhang, Y., Zhang, Y., Liu, J., Di, Y., Chen, Y., and Pan, Y. (2020). A sea trial of enhancing carbon removal from Chinese coastal waters by stimulating seaweed cultivation through artificial upwelling. Appl. Ocean Res. *101*, 102260. 10.1016/j.apor.2020.102260.

91. Pan, Y., You, L., Li, Y., Fan, W., Chen, C.-T., Wang, B.-J., and Chen, Y. (2018). Achieving Highly Efficient Atmospheric CO2 Uptake by Artificial Upwelling. Sustainability *10*, 664. 10.3390/su10030664.

92. Doney, S. (2021). A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration.

93. Siegel, D.A., DeVries, T., Doney, S.C., and Bell, T. (2021). Assessing the sequestration time scales of some ocean-based carbon dioxide reduction strategies. Environ. Res. Lett. *16*, 104003. 10.1088/1748-9326/ac0be0.

94. IEA Greenhouse Gas R&D Programme (2004). Gas Hydrates for Deep Ocean Storage of CO2.

95. Energy Futures Initiative (2020). Rock Solid. Harnessing Mineralization for Large-Scale Carbon Management.

96. de Lannoy, C.-F., Eisaman, M.D., Jose, A., Karnitz, S.D., DeVaul, R.W., Hannun, K., and Rivest, J.L.B. (2018). Indirect ocean capture of atmospheric CO2: Part I. Prototype of a negative emissions technology. Int. J. Greenh. Gas Control *70*, 243–253. 10.1016/j.ijggc.2017.10.007.

97. Eisaman, M.D., Rivest, J.L.B., Karnitz, S.D., de Lannoy, C.-F., Jose, A., DeVaul, R.W., and Hannun, K. (2018). Indirect ocean capture of atmospheric CO2: Part II. Understanding the cost of negative emissions. Int. J. Greenh. Gas Control *70*, 254–261. 10.1016/j.ijggc.2018.02.020.

98. Zhu, C., Zhai, X., Xi, Y., Wang, J., Kong, F., Zhao, Y., and Chi, Z. (2019). Progress on the development of floating photobioreactor for microalgae cultivation and its application potential. World J. Microbiol. Biotechnol. *35*, 190. 10.1007/s11274-019-2767-x.

99. Sayre, R. (2010). Microalgae: The Potential for Carbon Capture. BioScience *60*, 722–727. 10.1525/bio.2010.60.9.9.

100. Alvarado-Morales, M., Boldrin, A., Karakashev, D.B., Holdt, S.L., Angelidaki, I., and Astrup, T. (2013). Life cycle assessment of biofuel production from brown seaweed in Nordic conditions. Bioresour. Technol. *129*, 92–99. 10.1016/j.biortech.2012.11.029.

101. Gray, L.A., Bisonó León, A.G., Rojas, F.E., Veroneau, S.S., and Slocum, A.H. (2021). Caribbean-Wide, Negative Emissions Solution to Sargassum spp. Low-Cost Collection Device and Sustainable Disposal Method. Phycology *1*, 49–75. 10.3390/phycology1010004.

102. Ross, F., Tarbuck, P., and Macreadie, P.I. (2022). Seaweed afforestation at large-scales exclusively for carbon sequestration: Critical assessment of risks, viability and the state of knowledge. Front. Mar. Sci. *9*, 1015612. 10.3389/fmars.2022.1015612.

103. Qiu, Y., Lamers, P., Daioglou, V., McQueen, N., de Boer, H.-S., Harmsen, M., Wilcox, J., Bardow, A., and Suh, S. (2022). Environmental trade-offs of direct air capture technologies in climate change mitigation toward 2100. Nat. Commun. *13*. 10.1038/s41467-022-31146-1.

104. Intergovernmental Panel on Climate Change (2005). Carbon Dioxide Capture and Storage.

105. Tyka, M.D., Van Arsdale, C., and Platt, J.C. (2022). CO $_2$ capture by pumping surface acidity to the deep ocean. Energy Environ. Sci. *15*, 786–798. 10.1039/D1EE01532J.

106. Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J.K., Mason, B.M., Nebuchina, Y., Ninokawa, A., Pongratz, J., Ricke, K.L., et al. (2016). Reversal of ocean acidification enhances net coral reef calcification. Nature *531*, 362–365. 10.1038/nature17155.

107. Zhang, D., Fan, W., Yang, J., Pan, Y., Chen, Y., Huang, H., and Chen, J. (2016). Reviews of power supply and environmental energy conversions for artificial upwelling. Renew. Sustain. Energy Rev. *56*, 659–668. 10.1016/j.rser.2015.11.041.

108. Willauer, H.D., DiMascio, F., Hardy, D.R., and Williams, F.W. (2017). Development of an Electrolytic Cation Exchange Module for the Simultaneous Extraction of Carbon Dioxide and Hydrogen Gas from Natural Seawater. Energy Fuels *31*, 1723–1730. 10.1021/acs.energyfuels.6b02586.

109. Khor, W.H., Kang, H.-S., Lim, J.-W., Iwamoto, K., Tang, C.H.-H., Goh, P.S., Quen, L.K., Shaharuddin, N.M.R.B., and Lai, N.Y.G. (2022). Microalgae cultivation in offshore floating

photobioreactor: State-of-the-art, opportunities and challenges. Aquac. Eng. *98*, 102269. 10.1016/j.aquaeng.2022.102269.

110. Ibrahim, O.S., Singlitico, A., Proskovics, R., McDonagh, S., Desmond, C., and Murphy, J.D. (2022). Dedicated large-scale floating offshore wind to hydrogen: Assessing design variables in proposed typologies. Renew. Sustain. Energy Rev. *160*, 112310. 10.1016/j.rser.2022.112310.

111. NREL (2022). H2A: Hydrogen Analysis Production Models. https://www.nrel.gov/hydrogen/h2a-production-models.html.

112. NREL (2022). H2FAST: Hydrogen Financial Analysis Scenario Tool. https://www.nrel.gov/hydrogen/h2fast.html.

113. NREL (2021). H2FillS: Hydrogen Filling Simulation. https://www.nrel.gov/hydrogen/h2fills.html.

114. NREL (2004). HOMER.

115. NREL (2020). REopt: Renewable Energy Integration & Optimization.

116. NREL (2018). System Advisor Model (SAM). https://sam.nrel.gov/.

117. NREL (2020). RODeO. https://github.com/NREL/RODeO.

118. Guerra, O.J., Eichman, J., and Denholm, P. (2021). Optimal energy storage portfolio for high and ultrahigh carbon-free and renewable power systems. Energy Environ. Sci. *14*, 5132–5146. 10.1039/D1EE01835C.

119. NREL (2020). Offshore Wind Industry Prepares To Ride Economic High Tide. https://www.nrel.gov/news/program/2020/offshore-wind-to-ride-economic-high-tide.html.