OCS Study
BOEM 2020-017

Survey and Assessment of the Ocean Renewable Energy Resources in the US Gulf of Mexico

U.S. Department of the Interior
Bureau of Ocean Energy Management
New Orleans Office

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Abbreviations and Acronyms

Short Form	Long Form
A/C	air conditioning
API	American Petroleum Institute
BOEM	Bureau of Ocean Energy Management
BSEE	Bureau of Safety and Environmental Enforcement
DOE	Department of Energy
EEZ	Exclusive Economic Zone
EPAct	Energy Policy Act of 2005
GOM	Gulf of Mexico
GW	gigawatt
HTE	high temperature electrolyzer
H_2	hydrogen
HDPE	high density polyethylene
IEC	International Electrotechnical Commission
kWh	kilowatt-hour
LACE	levelized avoided cost of energy
LCOE	levelized cost of energy
LSU	Louisiana State University
LTE	low temperature electrolyzer
m	meter
m/s	meters per second
MHK	marine hydrokinetic
mph	miles per hour
MW	megawatt
NELA	Natural Energy Laboratory of Hawaii Authority
N/A	not applicable
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OCS	Outer Continental Shelf
OTEC	Ocean Thermal Energy Conversion
PEM	proton exchange membrane
PTO	power take-off
PV	photovoltaics
R&D	research and development
REN	renewable energy
s	second
SOEC	solid oxide electrolyzer
SMR	steam methane reformation
STC	standard test conditions
THw/yr	terawatt hours per year

Short Form	Long Form
TRL	technologies readiness levels
US	United States
USDOI	US Department of the Interior
WEC	wave energy convertor
yr	year

Summary

This study was conducted by the National Renewable Energy Laboratory (NREL) and funded by the Bureau of Ocean Energy Management (BOEM). It provides a comprehensive feasibility assessment of multiple offshore renewable energy technologies in the Gulf of Mexico (GOM) to inform BOEM's strategic plans related to possible Outer Continental Shelf (OCS) alternative energy leasing activities in the GOM. In coordination with Gulf Coast states, for future energy planning, this study also includes some information on offshore renewable energy potential in state waters.

The goal of this study is to survey potential offshore renewable energy sources in the GOM and quantify their feasibility relating to resource adequacy, technology maturity, and the potential for competitive cost. The study provides a review of available technologies and concepts for generating offshore renewable energy, including a high-level assessment of the current state of each technology and its potential for future advances. It provides a breakdown of resource capacity for each renewable energy technology as well as a recommendation that offshore wind be pursued for future study as it was found to be the most promising ocean renewable technology.

The renewable technologies that were considered include:

- Offshore wind
- Wave energy
- Tidal energy
- Ocean current energy
- Offshore solar energy
- Ocean thermal energy conversion (OTEC)
- Cold water source cooling
- Hydrogen (as a storage medium to use existing pipeline infrastructure).

The resource capacity for each of these renewable energy sources was quantified for both the gross resource capacity potential (gross resource)[1] and the technical resource capacity potential (technical resource)[2] using the methodology described in an earlier NREL report by Musial et al. (2016). Many of these sources are very immature from a commercial perspective, which makes some of the comparisons difficult. In many cases, it was necessary to develop new methods to estimate nominal power density for some technology types in order to convert the respective resource areas into deployable gross and technical resource capacity potentials. The resource for each technology type is shown in Figure S-1. The vertical scale of the chart is logarithmic to enable the chart to show resource quantities for all the technologies, which, in some cases, vary by orders of magnitudes.

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[1] Resource capacity potential (gross resource) is limited to the boundaries of the US Exclusive Economic Zone (EEZ) (up to 200 nm from shore). The calculation of gross resource does not discriminate on the basis of possible technology, use conflicts, or environmental impacts. Therefore, it intentionally includes areas that might not be economical to develop or could be unsuitable for various reasons that normal site screening might eliminate using today's base knowledge (Musial et al. 2016).

[2] The technical resource potential capture the subset of gross resource potential that may be commercially viable within a reasonable timeframe (Musial et al. 2016). It takes into account technical limits of the developing the renewable resource offshore.

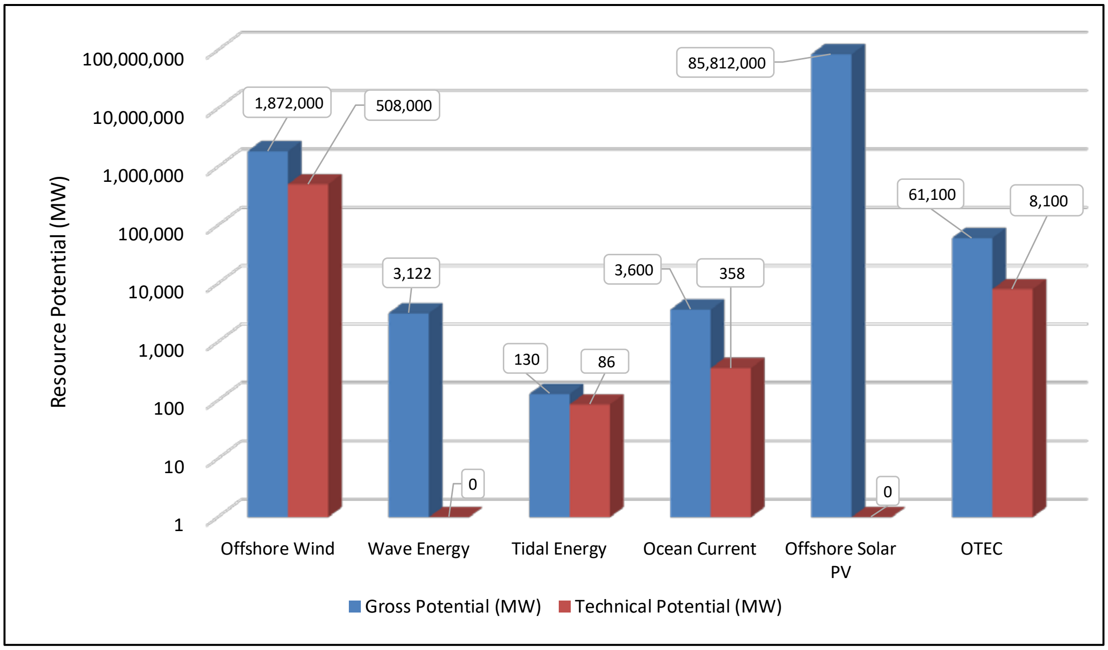

Figure S-1. Gross and technical offshore renewable energy potential for the Gulf of Mexico (GOM) by technology.

The analysis found that offshore solar photovoltaics had the greatest gross potential resource but, without a demonstrable method of surviving extreme waves on the open ocean, none of that resource was counted toward the technical resource potential. However, it was noted that there are many sheltered sites in state waters that may be suitable for offshore solar; these were not evaluated in this study. Of all the technologies, offshore wind had the largest quantity of technical resource potential with 508 gigawatt (GW) covering all GOM states, although Texas and Louisiana show the highest overall technical offshore wind resource potential.

A qualitative assessment of the commercial readiness and commercial cost projections was also conducted for each technology type. Offshore wind has the highest readiness levels. It ranges from pre-commercial demonstration to commercially-proven. Although there are more than 16 GW of offshore wind deployed around the globe, additional technology development is still needed for the GOM to develop and validate hurricane designs and to simultaneously optimize GOM rotors for the lower wind regimes found in this region.

Wave technology readiness levels are low. They span from early stage research and development to pre-commercial demonstration. Although multiple wave energy conversion devices have been deployed, there has not been sustained operation of any wave device for enough time to demonstrate commercial operation or predictable energy production profiles. The industry is still actively engaged in developing new concepts at a research and development scale without significant convergence.

Tidal energy has had some pre-commercial success globally and is approaching commercialization in some projects, partly due to the adaptation of horizontal axis wind energy technology, which has similar engineering attributes, but the tidal resource is generally small, limiting deployment and slowing industry maturation.

Ocean current technology has only been validated at the laboratory and/or prototype scale; no prototypes have yet been deployed in open ocean, despite the similarities to tidal turbines.

Ocean-based solar photovoltaics (PV) benefit from proven technology on land where PV has achieved vast commercial success. This success has been extended commercially to deployment over sheltered lakes and reservoirs. However, it has yet to be commercially deployed or tested in open-ocean conditions where the challenges are immense due to extreme waves.

Studies suggest that the scale of OTEC power plants must grow to 100 megawatt (MW) to realize cost reductions large enough for commercialization and technological success. Deployments to date have been at a scale 1/100th of that size. Therefore, the technology has not demonstrated economic or performance feasibility, and significant technical challenges are still unresolved, even at the smaller scales. The technology requires significant additional research, prototyping and demonstration before it can be deployed commercially.

Cold water source cooling has successfully been used in multiple locations around the world, but its application in the GOM will likely be limited to the Florida Keys and may require additional technology to overcome longer pipe lengths.

Hydrogen conversion using electrolysis has been technically proven and significantly larger demonstration projects continue to be deployed. Successful deployment in an offshore ocean application would be technically feasible with a significant amount of additional testing. However, hydrogen as a means of energy transport from offshore wind installations does not appear to be economically feasible under any scenario investigated.

Levelized cost of energy varied widely across the technologies examined with a wider range of uncertainty, especially for the more nascent technologies that have not yet had successful demonstration at full scale. As a result, costs and cost ranges were difficult to compare, and cost data tends to be more optimistic for nascent technologies that have not been validated or have had actual field experience. Taking that into account, offshore wind showed the most favorable cost and is closest to commercialization.

Based on the criteria established for three categories: 1) resource adequacy, 2) technology readiness, and 3) cost competitiveness–a down-select process was conducted to rank each offshore renewable technology. Each technology was ranked from 1 to 5 for each category, with a score of 5 being the best. The scores were summed, and the results indicated that offshore wind was ranked highest (13 out of 15). Consequently, offshore wind is recommended as the primary technology for future focus. The scoring results are shown in Table S-1.

Table S-1. Gulf of Mexico (GOM) Technology Scoring Assessment Results

Technology Type	Resource Adequacy	Technology Readiness	Cost Competitiveness Potential	Total Score
Offshore wind	5	4	4	13
Wave energy	1	2	2	5
Tidal energy	2	3	3	8
Ocean current	1	2	2	5
Offshore solar energy	3	3	3	9
OTEC	3	2	2	7
Cold water source cooling	1	4	N/A	-
Hydrogen conversion	N/A	3	1	-

The technical resource of offshore wind for the GOM is estimated at 508 GW, the largest of any of the technologies examined. Its deployment and ability to serve a significant percentage of the load in the GOM depends primarily on improving the economics over the next decade. Based on global trends, the economics of offshore wind are improving rapidly, making economic deployment of offshore wind turbines in the GOM likely by 2030 ([Department of Energy] DOE 2018) when costs may be approaching acceptable market levels. During this timeframe, new offshore wind technologies will be needed to optimize energy capture in the lower wind regimes of the GOM, to better understand hurricane risks, and to design wind turbines suitable for hurricane-prone areas.

Ocean-based solar has an enormous gross resource potential in the GOM but is severely constrained by extreme wave conditions on the ocean surface that would likely damage conventional photovoltaic systems and support structures. However, state waters in the GOM have sheltered bays and water bodies closer to urban load centers that could better take advantage of solar resources and may present a future opportunity, especially if new technology concepts for floating solar are developed.

Other renewable energy technologies surveyed in this study may present opportunities for energy generation on a limited basis. Tidal energy has very little resource in the GOM. However, specific sites in Florida and Texas that were identified in this study have potential for small distributed systems. Cold water source cooling is limited in the GOM because the best resource is located far from shore where it cannot be easily accessed. A few sites near Key West, Florida may be accessible for this purpose but will not make a major contribution to the GOM electricity needs. Wave energy, OTEC, and ocean current all have major challenges that may preclude their implementation in the GOM in the foreseeable future. However, longer term technological and economic improvements are possible.

The potential for developing offshore wind to serve loads in the GOM is realistic in the next 10 to 15 years and will be explored further in later tasks.

1 Overview and Project Background

A variety of renewable energy (REN) technologies are available and are maturing with expanded opportunities for offshore renewable energy generation in United States (US) federal and state waters. The Bureau of Ocean Energy Management (BOEM) needs to assess the full range of these technologies in the context of how they may be applied in the Gulf of Mexico (GOM) and to inform development activities within the Bureau's purview under the Energy Policy Act of 2005 (EPAct), which gave BOEM the authority to regulate renewable energy projects on the outer continental shelf (OCS). In 2009, the US Department of the Interior (USDOI) finalized the 30 CFR 585 regulations which provide BOEM with a framework for issuing leases, easements and rights-of-way for OCS activities that support production and transmission of renewable energy. Renewable energy resources under BOEM's jurisdiction include, but are not limited to, offshore wind, solar, ocean waves, tides, thermal gradients, and current.

This study, conducted by the National Renewable Energy Laboratory (NREL), provides a feasibility assessment for offshore renewable energy technologies and is intended to inform BOEM's strategic plans related to possible OCS alternative-leasing activities in the GOM. In coordination with Gulf Coast States, this study also includes information on offshore renewable energy potential in state waters and will provide rationale for possible near-term and long-term offshore renewable energy planning. For more than 40 years, BOEM's Environmental Studies Program has been supporting scientific research to inform policy decisions regarding the development of OCS energy and mineral resources. Since EPAct 2005 was passed, BOEM has worked with NREL on offshore renewable energy projects and studies related to energy potential assessment, stakeholder engagement, and feasibility analyses to inform offshore development opportunities across BOEM (also known as "bureau") OCS regions.

In July 2011, a bureau-funded study by researchers at Louisiana State University (LSU) was: "Assessment of Opportunities for Alternative Uses of Hydrocarbon Infrastructure in the Gulf of Mexico" (Kaiser et al. 2011). The 2011 LSU report was targeted primarily at examining the potential for offshore wind to benefit the existing oil and gas infrastructure and the feasibility of offshore wind in terms of the regulatory process. It concluded that offshore wind could provide little value to the oil and gas industries. Results from this current research do not conflict with those 2011 findings. For this study, we examine the problem more comprehensively, examining the potential for a range of ocean renewable energy sources to deliver electricity to the existing land-based grid on the utility power market. The study does not address renewable energy's value to the oil and gas industries. It should also be noted that offshore wind energy technologies have evolved significantly since 2011; assumptions about cost, technology maturity, and resource availability are more detailed and current than in previous studies.

In the US, several commercial offshore wind projects are currently in the planning phases; the first 30 MW pilot-scale project began transmitting power off Block Island in late 2016. Though the technology looks very promising for near-term development in the northeastern US, in this study we examine resource, cost, and technology maturity for the GOM. A host of other marine renewable energy technologies are in various stages of research, development, and testing, including wave, tidal, ocean currents, ocean-based solar, ocean thermal gradients, and cold water source cooling. Wave power devices extract energy directly from the motion of ocean waves, with several wave technologies proposed to convert that energy to electricity; some are undergoing demonstration testing. Tidal and ocean currents also carry an enormous amount of energy that can potentially be captured and converted to electricity with various configurations of submerged water turbines. Recent cost reductions in photovoltaic solar energy may also enable large solar power plants in some sheltered locations, and resource assessments indicate ocean thermal energy conversion (OTEC) projects could be possible in some GOM locations where high thermal gradients exist in the water column. For this study, we examine each of these technologies for the Gulf region, which includes the west coast of Florida, Alabama, Mississippi, Louisiana, and Texas.

This chapter explains the methods and results from a feasibility study on potential offshore renewable energy sources in the GOM and the down-select process to choose one technology.

1.1 Goal and Objectives

The goal of this study is to survey potential offshore renewable energy resources in the GOM and to quantify the feasibility of each technology relating to its technical and economic potential. The intent is to inform federal and GOM state strategic planning over the next decade. The objectives are:

- To review available technologies and concepts for generating offshore renewable energy, including a high-level assessment of the current state of each technology and its potential for future advances;
- To provide a breakdown of resource capacity for each renewable energy technology by state;
- To select the most promising renewable energy technology based on resource adequacy, technology maturity, and the potential for competitive cost of energy.

1.2 Technical Approach

1.2.1 Technology Types

This study examines the following ocean-based renewable technologies:

- Offshore wind
- Wave energy
- Tidal energy
- Ocean current energy
- Offshore solar energy
- Ocean thermal energy conversion (OTEC)
- Cold water source cooling
- Hydrogen (as a storage medium to use existing pipeline infrastructure).

The research team conducted a thorough literature review and performed a high-level quantitative assessment of each technology based on resource adequacy, technology readiness, and cost. To calculate resource adequacy for each renewable energy source, we first estimated the gross resource capacity potential (gross resource) for each source, measured in gigawatts (GW). From gross resource, we applied technology filters for each technology to determine the technical resource capacity potential (technical resource) using the methodology described in the NREL report by Musial et al. (2016). We did not consider energy production potential, energy production values, or capacity factors in this first level study. However, it was necessary to estimate nominal power density for each technology type to convert the resource area for each technology type into deployable gross and technical resource capacity potential.

We also conducted a qualitative assessment of the commercial readiness and commercial cost projections, for each technology type. The advantages and challenges of each technology are documented in Section 2.0. In some cases, the technologies are too immature and have not been sufficiently evaluated to make basic assessments about resource, technology readiness, and cost. In these cases, NREL engineers developed criteria to assess the technology parameters to allow cross-comparisons and conduct a down-select process to identify the most promising technology. This down-select process was conducted by a technical review team of NREL and BOEM staff and is described below. A single technology was chosen for further evaluation.

1.2.2 Definition of Study Area: State and Federal Water Distance Zones

The study area was defined as the ocean area from the shore out to the international exclusive economic zone (EEZ) as shown in Figure 1. Within the total resource area domain, data were classified into the following four distance zones:

- **0 to 3 nautical miles (nm) zone**. This zone is in state waters that are outside BOEM's jurisdiction. For Texas and the western coast of Florida, state waters extend to 9 nm (Musial and Ram 2010).
- **3 to 12 nm zone**. This zone extends to the territorial waters boundary at 12 nm. In this zone, conflicting-use impacts may be higher than in areas farther out. Some studies have found that opposition to offshore wind projects based on viewshed or aesthetics begins to decline rapidly beyond 12 nm (Lilley et al. 2010).
- **12 to 50 nm zone**. The 50 nm boundary was originally selected to focus resource evaluations on the near-shore area where access to grid and shore-based support services is more feasible (Schwartz et al. 2010). Subsequent assessments show that project feasibility is not necessarily limited to 50 nm. For this study, the 50 nm delineation was retained as a reference to help describe the differences between far-shore and near-shore impacts out to the 200 nm EEZ limit.
- **50 to 200 nm zone**. This distance from shore is included in the gross resource area to provide the possibility of development beyond 50 nm as conflicts may be lower with large areas of developable water.

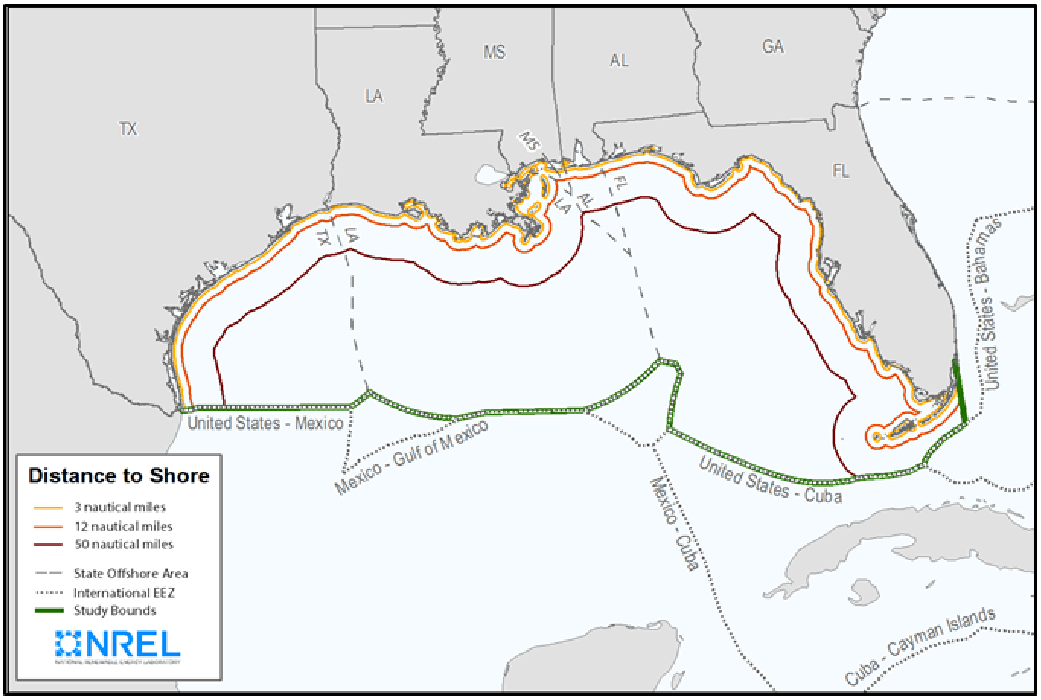

Figure 1. Map highlighting distance-to-shore zones for the GOM.

1.2.3 Water Depth Zones

Water depth plays a critical role in determining whether a resource is suitable for development (Figure 2). For offshore wind, water depth is crucial in determining the cost of energy. Almost all offshore wind installations to date have been built in water depths less than 50 meters (m) (164 feet [ft]) on fixed bottom foundations, but new floating technologies promise to allow installations at much greater depths. Though there is no hard limit, most industry experts agree that 1,000 m may be a practical cut-off when computing technical resource limitations (Musial et al. 2016). As such, 1,000 m was also used as the cut-off for other less mature technologies (e.g., ocean current, tidal, ocean-based solar) where no depth limit on resource has been established by the industry yet.

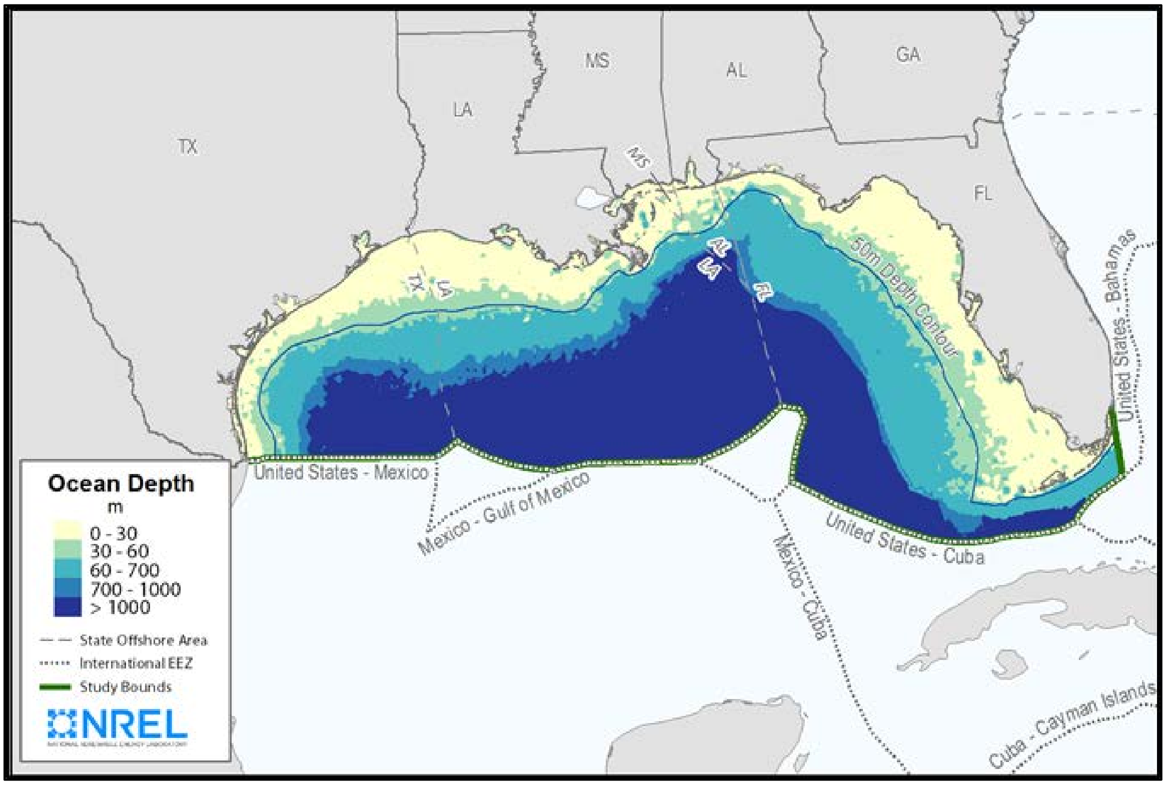

Figure 2. Bathymetry of the GOM out to the international exclusive economic zone (EEZ).

For OTEC and cold water source cooling, this depth limit was relaxed to avoid elimination of most of that technology's resource, as sufficient hot-cold water differentials tend to exist only where water depths exceed 900 m. Cold water sources also reside in greater depths, but the more limiting factor is that in the GOM these resources tend to be far from shore.

1.3 Constraints and Limitations

1.3.1 General Constraints

The analysis and conclusions for this study were based on existing literature and information that could be derived using desktop calculations and assessments. In some cases, it was necessary to apply internal expert judgements of the NREL team. Greater accuracy could be obtained with more rigorous research, analysis, and validation. However, the authors' conclusions about the relative feasibility and impacts of these technologies would not likely be significantly affected by larger investments in higher fidelity studies. It is possible that the specific cost and technology readiness conclusions could change due to advancements in specific technology types in later years. Therefore, periodic future assessments are recommended.

Certain renewable energy sources analyzed in this study are not regulated by BOEM based on its authority under EPAct 2005. For example, OTEC is regulated by the National Oceanic and Atmospheric Administration (NOAA) and the OTEC Act of 1980. Cold water source cooling is not mentioned in EPAct. Also, some of the renewable energy types are likely to be applicable only to state waters, such as tidal energy and ocean-based solar, but are included here in cooperation with the Gulf Coast States and to generate a more inclusive study. As such, all renewable energy types are included in the report to facilitate discussion across the wider Gulf community, but BOEM will regulate only the sources called out by EPAct.

1.3.2 Data Sources, Filters, and Uncertainties

1.3.2.1 Resource Data

Resource data for individual technologies were obtained from the best available existing sources. The general sources of these data are summarized in **Table 1** and their full citations are given in the reference section.

Table 1. Resource Data Sources for GOM Renewable Energy Technologies

Technology	Source
Offshore wind	AWS Truepower (2012) Draxl et al. (2015) **Musial et al. (2016)**
Wave energy	Kilcher and Thresher (2016) MHK Data Base (DOE, 2017)
Tidal energy	Kilcher and Thresher (2016) MHK Data Base (DOE, 2017)
Ocean current	Duerr and Dhanak (2012) Hamilton et al. (2015) Von Arx et al. (1974) National Research Council (2013) MHK Data Base (DOE, 2017)
Offshore solar energy	Denholm and Margolis (2007) IRENA (2012) NASA (2008)
OTEC	Ascari et al. (2012) Avery and Wu (1994)
Cold water source cooling	Ascari et al. (2012) Makai (2017)
Hydrogen conversion and storage	Abdel-Aal et al. (2010) Meier (2014) Ruth et al. (2017)

For each technology, the gross resource potential was determined from the data sources above, which is consistent with standard industry best practice, if best practices could be identified. However, in some cases best practices have not yet been fully established. For these technologies, NREL established metrics and filters, as described in **Table 2**.

Estimating a technology's resource potential is necessary to determine the amount of electricity generation potential for a given area. Gross resource was defined primarily by the geographic area within set boundaries that contain the legitimate legal resource contained in US waters through international agreements, using the 200 nm EEZ as the maximum outer boundary. These boundaries establish the theoretical resource area available for US deployments but do not suggest technical or economic viability.

To calculate the technical resource potential, filters are applied within the gross resource area to eliminate regions where technology challenges are judged to be too great to be considered for further deployment or study. For offshore wind, these are regions where the wind speeds are too low (below 7 meters per second [m/s] (15.7 miles per hour [mph]), or the water is too deep (greater than 1,000 m [3,281 ft]). For wave energy, the filters eliminate regions where the waves do not contain enough energy for practical energy extraction. Solar energy is abundant in the GOM, but technology filters eliminate all regions where extreme wave heights preclude the development of economical support structures. Tidal and ocean current filters are based on a minimum power density in the cross section of any current flow. OTEC filters are based on the water column containing a minimum thermal gradient to drive thermal engines. Finally, cold source cooling requires a low enough temperature source and proximity to a prominent load.

Table 2. Resource Filters for Each Renewable Energy Technology[3]

Technology	Gross Resource			Technical Resource			
	Max Distance from Shore (nm)	Max Water Depth (m)	Capacity Density (MW/km²)	Max Distance from Shore (nm)	Max Water Depth (m)	Resource Cut-Off	Max Wave Height (m)
Offshore wind	200	None	3	200	1,000	> 7 m/s (15.7 mph)	N/A
Wave energy	200	50m Isobath	50%	200	None	> 10 KW/m	N/A
Offshore solar energy	200	None	120	200	1,000	N/A	3
Tidal energy	200	None	None	200	1,000	> 500 W/m²	N/A
Ocean current	200	None	None	200	1,000	> 500 W/m²	N/A
OTEC	200	None	0.19	200	None	> 18° C Differential	N/A
Cold water source cooling	200	None	N/A	6	1,000	< 8° C	N/A

1.3.2.2 Technology Readiness

Data for technology readiness were derived from industry reports, websites, and personal conversations with technology developers. The data were used to document progress and to assess the maturity of the various technologies. We defined four technology readiness stages: 1) early stage R&D, 2) proof of concept, 3) pre-commercial demonstration, and 4) commercially proven. These readiness stages represent the full spectrum of technology maturity and provide a coarse readiness framework, especially when compared with other more detailed readiness scales, such as the DOE’s Technologies Readiness Levels (TRL) (DOE 2011). Each readiness stage and its rough TRL equivalent are described below.

1. **Early stage R&D** refers to technologies that are conceptual in nature and still require additional basic science and applied research to validate analytical predictions. This category is roughly equivalent to TRLs 1–3 (DOE 2011).

2. **Proof of concept** describes the stage where individual components and/or the entire system has been tested in a laboratory and gradually scaled up to prototype-scale technology with all the

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[3] Hydrogen is not included in this table because it is not a form of electricity generation, in this case.

capabilities of the eventual commercial model. This category is approximately equivalent to TRLs 4–6 (DOE 2011).

3. **Pre-commercial demonstration** technologies take the design validated in the proof-of-concept stage and assess the scaled-up system in field test- or real-world conditions. This category is equivalent to TRLs 7–8 (DOE 2011).
4. **Commercially proven** denotes a technology that has been deployed for commercial energy generation and is qualified to operate under a full range of real world operating conditions. This category is roughly equivalent to TRL 9 (DOE 2011).

1.3.2.4 Technology Cost

Cost data for nascent technologies is difficult to obtain because commercial costs must be extrapolated from earlier readiness stages where the costs are high. This type of cost calculation was not performed in this study. Instead, we relied on published industry data to report life cycle cost ranges. In general, the more mature technologies, such as offshore wind, had more accurate cost data. For several of the technologies, a lack of empirical data made it difficult to validate the cost assumptions, which may have introduced additional uncertainty in some cases. For most technologies, published industry cost data showed a wide range and were often dismissed from further analysis if the methodology could not be verified from the documentation or if the assumptions did not agree with conventional wisdom. For example, cost of energy for technologies that did not account for operation and maintenance were considered incomplete and could not be used. The sources that were used to determine ocean renewable energy cost data are summarized in **Table 3**.

Table 3. Cost Data Sources for Each Renewable Technology

Technology	Source
Offshore wind	NREL (2017a); Moné et al. (2017)
Wave energy	IEA-OES (2015); Neary et al. (2014); Lewis et al. (2014)
Tidal energy	IEA-OES (2015); Neary et al. (2014); Lewis et al. (2011)
Ocean current	IEA-OES (2015); Neary et al. (2014); Lewis et al. (2011)
Offshore solar energy	Ciel & Terre (2016); Bureau of Reclamation (2016); Barbusica (2016)
OTEC	Lewis et al. (2011)
Cold water source cooling	Vega (2016); Ascari et al. (2012)
Hydrogen conversion and storage	Ruth et al. (2017); Meier (2014)

1.3.3 Competing Uses and Environmental Exclusions

Historically, the ocean areas of the US have served multiple users and are home to many wildlife species. The GOM has a long history of energy extraction from the oil and gas industry; thus, some human use conflicts are unique to the GOM. Moreover, there may be collaborations with some of the oil and gas infrastructure, not only in terms of supply chain advantages but also with opportunities to use the existing oil and gas platforms to facilitate renewable energy generation or conversely, for suppling renewable energy sources to aid in oil and gas production (i.e., energy needed to run a platform and production processing equipment). Such collaborations are not examined quantitatively, but follow-on studies may be warranted in some cases.

In DOE's 2015 *Wind Vision* (DOE 2015), a Black & Veatch study of the continental US was used to identify areas of competing-use and environmental exclusions shown in **Figure 3** in red (Black & Veatch 2010). These areas include national marine sanctuaries, marine protected areas, wildlife refuges, shipping and towing lanes, and offshore platforms and pipelines.

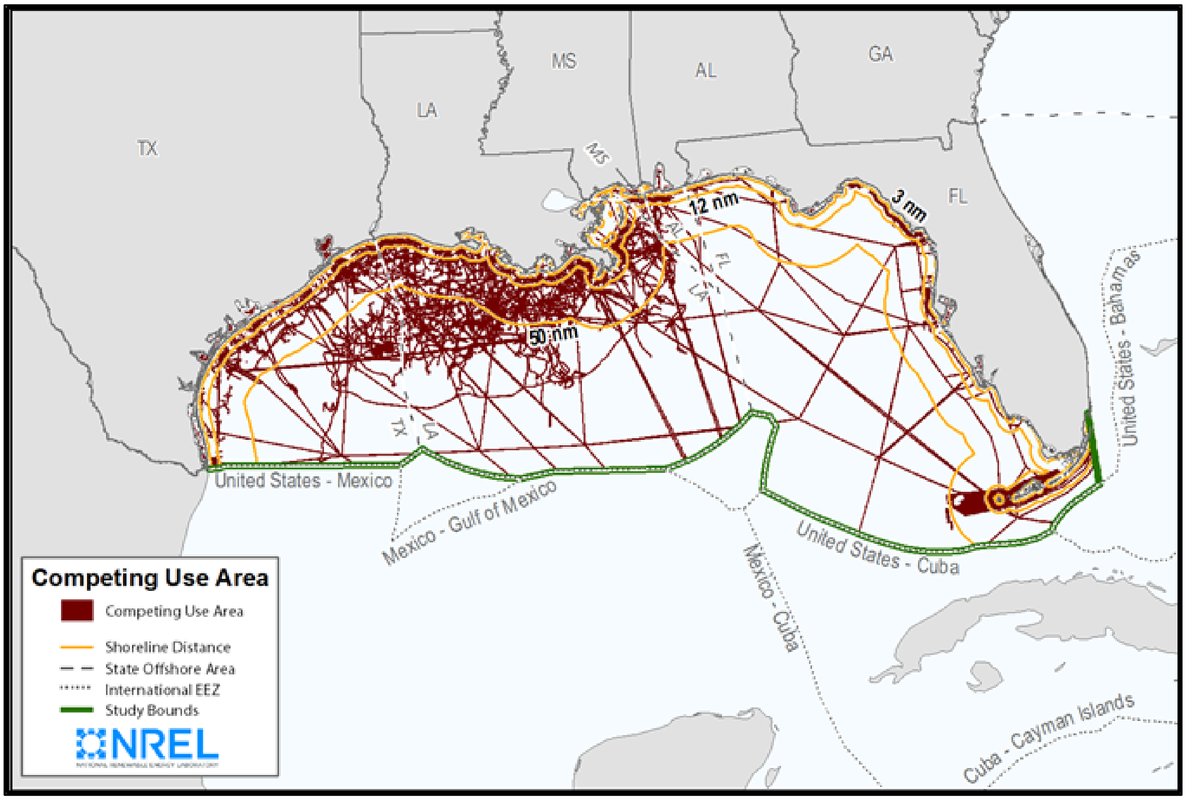


Figure 3. Areas with possible environmental and human use conflicts.

From a study conducted by NREL in 2016 (Musial et al. 2016), analysis was performed to calculate the percentage of excluded areas to arrive at the total technical resource potential on a national basis. This analysis was performed as a function of distance to shore and is shown in **Figure 4**.

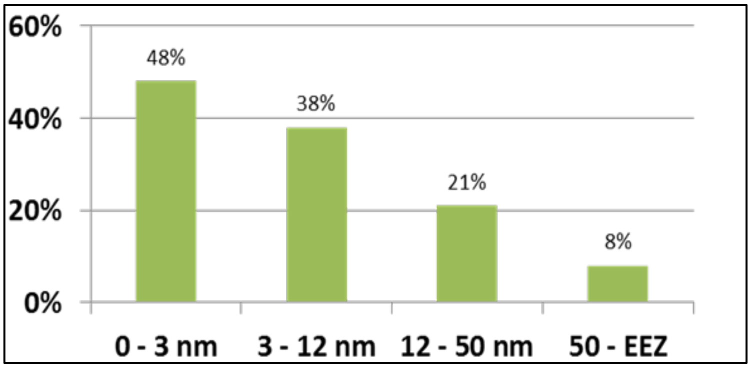


Figure 4. Excluded resource area percentages for the US based on Black & Veatch (2010) study.
(Musial et al. 2016)

For example, nearly half (48%) of the available area between 0–3 nm is not considered feasible for wind development in the technical potential calculations; likewise, 38% of the area from 3–12 nm was excluded from the viable wind resource, and so on. The percentages in **Figure 4** were applied to calculate the offshore wind technical resources presented in **Table 11** in Chapter 3. In Chapter 2, these exclusions are also applied to the data in Figure 10 on a state by state basis for the GOM.

These percentages likely do not include all exclusions that may be required during a more rigorous marine spatial planning process, and they may increase under more detailed analysis with full stakeholder participation. However, “excluded area” in this case includes areas of conflicting use or areas where coexisting use could be negotiated. Not all the area in dark red, in **Figure 3**, would necessarily be excluded for offshore renewable energy development.

2 Offshore Renewable Energy Technology Types

In the following sections, each technology type is examined in terms of its resource adequacy, technology readiness, and cost. To maintain objectivity and allow comparative analysis among the technologies, resource filters were applied in a manner consistent with documented industry practices following the methodology developed in Musial et al. (2016).

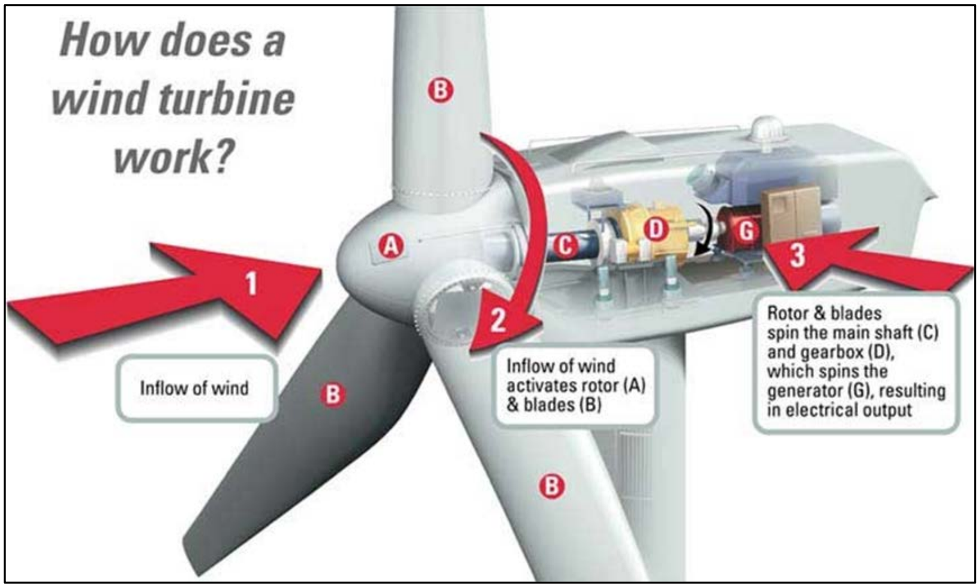
2.1 Offshore Wind Energy

Offshore wind is a renewable technology with increased global deployment and rapid cost reductions. At the end of December 2017, there were 16,312 megawatts (MW) of commissioned capacity including all operating offshore wind projects world-wide, most of them in European seas (Beiter et al. 2018). Offshore wind can provide coastal states with economic benefits such as job growth, energy diversity, reduced pollution, operational grid flexibility, and transmission congestion relief (Musial et al. 2016). Among the technologies investigated, offshore wind is at the highest technology readiness level. This section assesses the technical and economic viability of deploying offshore wind turbines in the Gulf of Mexico (GOM).

Most of the discussion around offshore wind energy, and the focus of this report, centers on bringing the power generated to land, for the power grid. However, on the outer continental shelf (OCS) under the Bureau of Ocean Energy Management's (BOEM) jurisdiction are thousands of offshore oil and gas facilities that are powered by diesel generators. The diesel fuel must be transported by ship or barge out to the oil and gas platforms. It may be more cost efficient for the oil and gas industry to use wind or wave devices to power multiple OCS platforms. This has been considered by BOEM in studies conducted by the University of Louisiana (Kaiser et al. 2011). Though this topic is beyond the scope of this report, it is potentially important for future feasibility assessments.

2.1.1 Offshore Wind Energy Technology Description

As passing wind collides with a wind turbine's blades, the wind's kinetic energy is converted into mechanical energy as the rotating blades spin a drive shaft connected to a gearbox. The mechanical energy in the drive shaft and/or gearbox is then converted to electrical energy using a generator (**Figure 5**). In many offshore wind turbines today, the wind turbines do not use gearboxes but instead are connected to a direct-drive generator spinning at the same speed as the rotor, which varies between 8 to 15 revolutions per minute (rpm), depending on the machine size and model. These modern machines eliminate the gearbox to reduce the number of moving parts and minimize maintenance costs.



Source: DOE: Wind Energy Technology Office

Figure 5. How a wind turbine generates electricity.

Offshore wind turbines have over twice the power output as land-based wind turbines and are still increasing in size as the industry matures. The average output capacity of an offshore wind turbine today is over 4 MW, but turbine sizes of 8 to 9 MW are being installed in some projects. Based on analysis conducted by the National Renewable Energy Laboratory (NREL), offshore wind may be cost competitive in the GOM by about the 2030 timeframe, and turbines could be 12 to 15 MW in capacity with rotor diameters exceeding 200 m (656 ft) (Beiter et al 2017)[4]. Mature offshore wind plants have turbines arranged in arrays of 400 MW to 800 MW per project for large scale power generation (40–80 turbines per wind plant). The turbines are connected to an offshore substation located near the wind farm, and the aggregated power is transmitted to shore via a high voltage subsea cable. A schematic of a typical offshore wind plant is shown in **Figure 6**.

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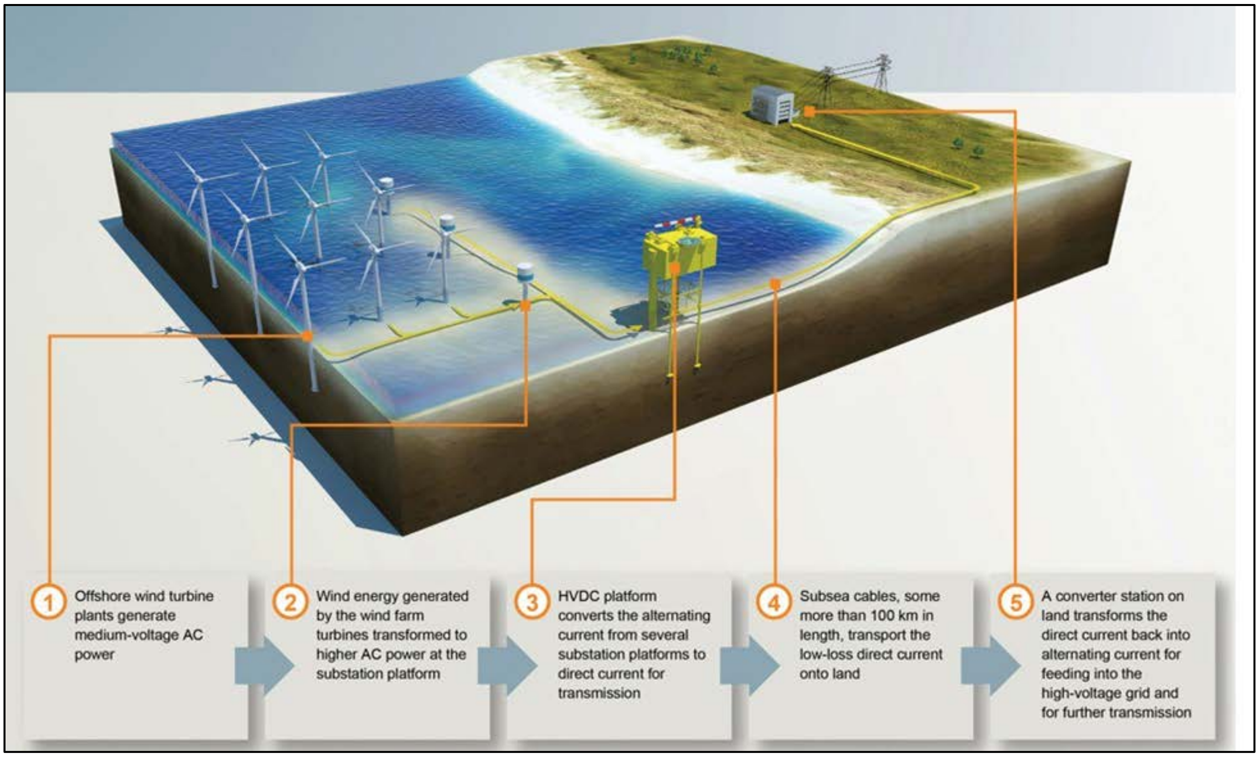
[4] A more detailed assessment of this potential will be conducted later as part of this study.



① Offshore wind turbine plants generate medium-voltage AC power

② Wind energy generated by the wind farm turbines transformed to higher AC power at the substation platform

③ HVDC platform converts the alternating current from several substation platforms to direct current for transmission

④ Subsea cables, some more than 100 km in length, transport the low-loss direct current onto land

⑤ A converter station on land transforms the direct current back into alternating current for feeding into the high-voltage grid and for further transmission

Figure 6. Schematic of a typical offshore wind farm.
Source: Siemens Gamesa Renewable Energy, Inc.

Offshore wind can be divided into two technology types that relate primarily to water depth; fixed-bottom systems and floating systems (**Figure 7**):

- **Fixed-bottom offshore wind systems** are usually deployed in waters shallower than 60 m (196 ft) and are attached to the seafloor using a rigid substructure. Substructure types and their respective share of the market include: monopole (80%), gravity base (5%), jacket (2%), tri-pile (3%), high-rise pile cap (4%), suction bucket (0%), and tripod (6%) (Musial et al. 2017). The costs, benefits, and technical risks of each substructure type depend on the project's location and environmental conditions. Currently, fixed-bottom offshore wind systems make up almost the entire commercial offshore wind market.
- **Floating offshore wind systems** are expected to be deployed in water depths between 60 to 1,000 m (196 to 3,281 ft). Turbines are mounted on a variety of buoyant platform types and secured to the seafloor using mooring lines and anchors. Although the first multi-turbine commercial floating wind plant was deployed off Scotland in 2017, approximately 10 other floating pilot projects with different platform technologies are under construction or planned for construction in the near future, totaling over 200 MW (Musial et al. 2017). In addition to accessing deeper water depths, floating wind technology potentially eliminates the need for developers to rent costly specialized lift vessels during the installation process because the systems can likely be constructed in port and towed to the project site by tugs.

Figure 7. Offshore wind technologies: fixed-bottom foundation (left) and floating foundation (right).
Photo Credits: Dennis Schroeder, NREL (left) and Senu Sirnivas, NREL Image Gallery number 27598 (right).

2.1.2 Offshore Wind Energy Resource Potential

NREL's *2016 Offshore Wind Energy Resource Potential for the United States* found that the GOM possesses approximately 15% of the U.S.'s gross offshore wind energy potential and 25% of the country's technical offshore wind energy potential (Musial et al. 2016). **Figure 8** illustrates average annual wind speeds over the gross resource potential area. The GOM's gross offshore wind capacity potential is the amount of power that could be produced in the GOM before technology filters, economic filters or siting considerations (e.g., areas where protected species migrate, shipping lanes) are applied. The gross resource potential is important to quantify because technology innovation and other factors in the future could change the technical resource filters, but the gross potential is likely to remain the same. There are 1,872 gigawatts (GW) of gross offshore wind resource capacity. The resulting gross energy production potential is 6,376 terawatt hours per year (TWh/yr) assuming a hub height[5] of 100 m (328 ft), a resource area extending 200 nm offshore[6], and a capacity array power density of 3 MW/km^2 (Musial et al. 2016).

Figure 9 displays the areas and wind speeds for the technical potential of the GOM after applying the technology filters. Consistent with Musial et al. (2016), exclusions applied to determine technical potential include filtering out wind speeds less than 7 m/s (15.7 mph) and water depths greater than 1,000 m (**Table 2**). Filters were also applied to reduce the technical resource potential for competing use areas. These filters were described earlier in Section 1.3.3 and **Figure 4**. Applying average wind speed[7], max water depth[8], and land-use/environmental considerations, the GOM's technical offshore wind resource potential by capacity is 508 GW, with a technical energy resource potential of 1,556 TWh/yr (Musial et al. 2016).

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[5] A 100 m (328 ft) hub height was selected because it reflects the typical system expected to be deployed in the United States (US) within the next five years and is consistent with the most recent resource assessments (Musial et al. 2016).

[6] 200 NMnm is the limit of the US Exclusive Economic Zone (EEZ).

[7] Areas with wind speeds lower than 7 m/s (15.7 mph) were excluded because current offshore wind technologies may not be able to economically generate electricity at lower wind speeds in the foreseeable future (Schwartz et al.2010).

[8] Although there is no hard technology limit, areas with water depths greater than 1,000 m (3,281 ft) were excluded because 1,000 m (3,281 ft) is assumed to be the current limit that floating platforms can be deployed.

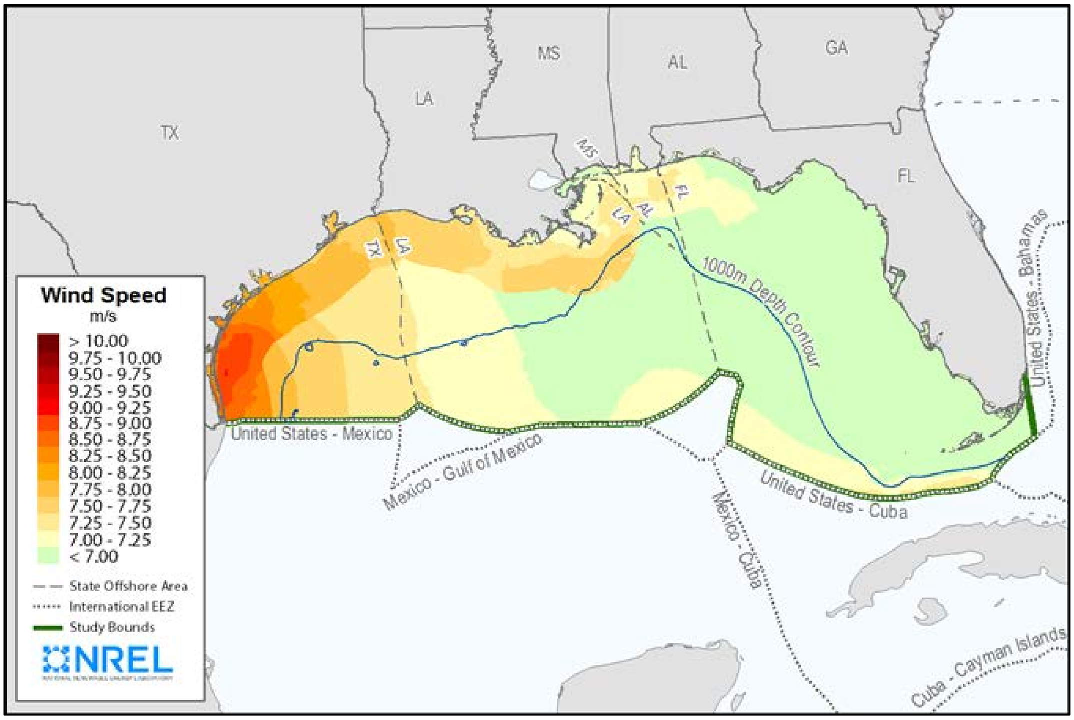

Figure 8. Average annual wind speeds at a hub height of 100 m (328 ft) in the GOM for the gross resource area.

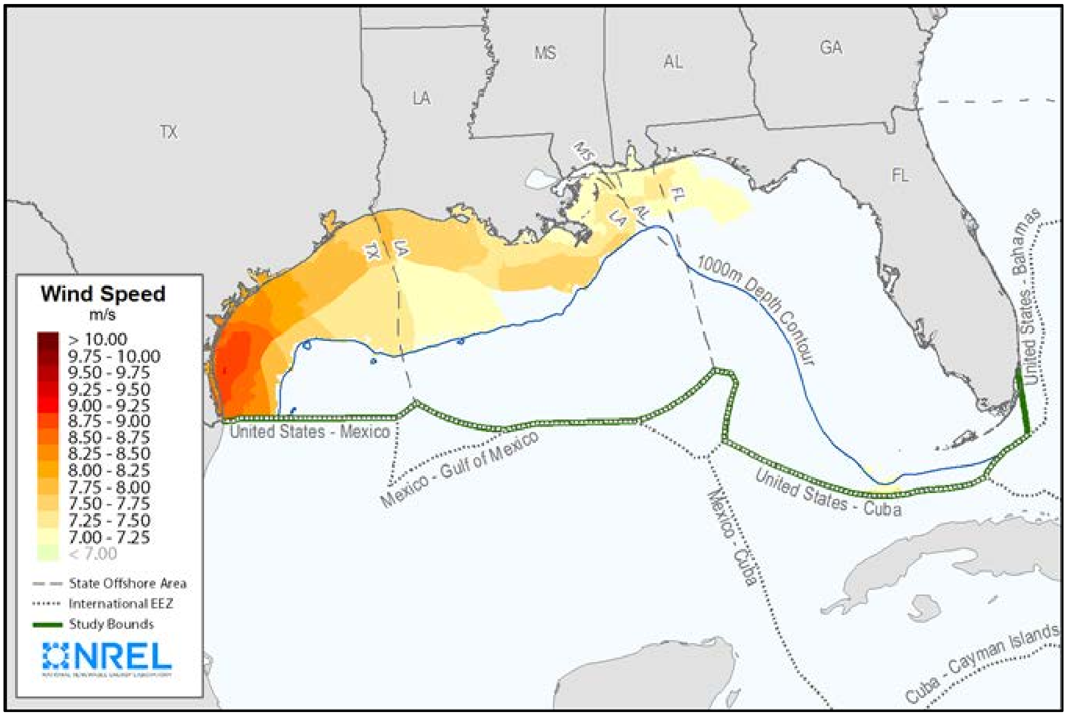

Figure 9. Average annual wind speeds at a hub height of 100 m (328 ft) in the GOM for the technical resource area.

A state-by-state breakdown of the GOM's technical offshore wind resource potential was divided into water depths greater than and less than 60 m (197 ft) to distinguish between technologies for fixed-bottom and floating wind (**Figure 10**). It is important to note that Florida, Texas, and Louisiana rank second, third, and fourth, respectively in national state by state offshore wind technical potential[9]. Note that the Florida offshore wind resource shown in **Figure 10** only includes the resource area on the GOM coast.

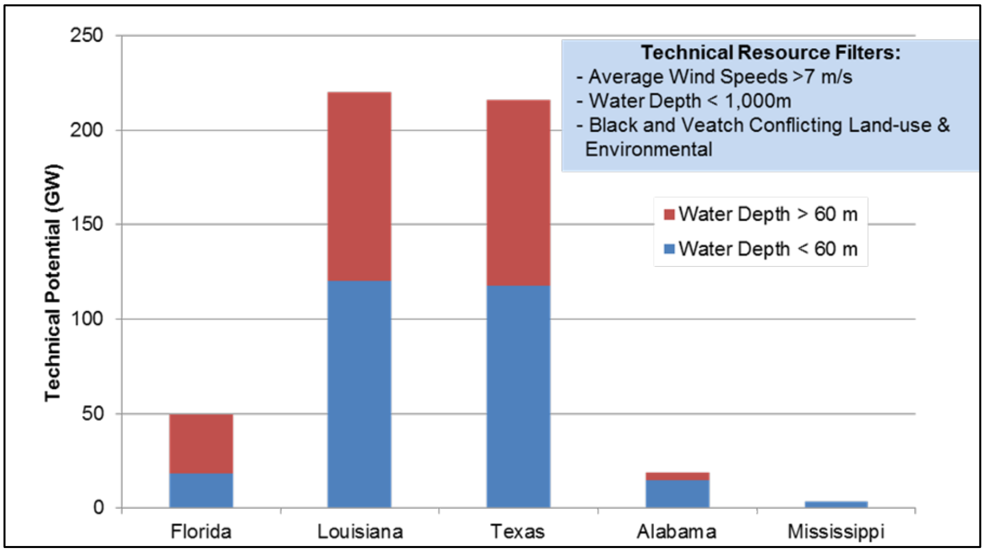

Figure 10. Technical offshore wind resource potential by state in the GOM.

2.1.3 Offshore Wind Energy Technical Readiness

Due to significant global deployment levels and industry experience, offshore wind is the most mature technology investigated in this study, yet it still carries several technical risks unique to the GOM that may require further technology development including:

- **Hurricanes**: The GOM regularly experiences hurricanes that bring increased wave height and extreme winds (Kaiser 2008). Offshore wind developers may have to create specialized designs that ensure turbines, towers, blades, and substructures can withstand these extreme weather events. Using the proven practices of the oil and gas industry, substructures for offshore wind turbines can be designed with a fairly high degree of confidence, although wind turbine designs may have to be adapted if local conditions exceed current design specifications given by the governing International Electrotechnical Commission (IEC) standards. However, the GOM is not a unique region for experiencing hurricanes, with the US Atlantic region also prone to such extreme storm events. Thus, advances in designs currently implemented in the Atlantic would likely apply to the GOM.
- **Lower Wind Speeds**: Relative to Europe or US offshore wind sites in the North Atlantic, the GOM has lower annual average wind speeds (similar to South Atlantic) that may lead to new turbine designs optimized to operate in these conditions. Features may include increased rotor diameters, lower solidity blades, and more intelligent control strategies for extreme load mitigation.
- **Softer Soils**: The OCS has softer soils compared to other regions where offshore wind development has occurred. This may increase the weight and cost of substructure design.

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[9] This rank holds true only if all the resource for Florida is counted, including the Atlantic resource, which is technically not part of the GOM.

Although these risk factors may be significant, other benefits, such as lower average sea states and warmer ocean waters, may increase turbine accessibility, lower operation and maintenance costs to help offset these factors.

2.1.4 Offshore Wind Energy Economics

Exact offshore wind project costs vary by location and are impacted by water depth, distance to shore, wind resource, wave regime, seabed conditions, prospective staging ports, inshore assembly areas, potential interconnection sites, environmental sensitivities, and competitive use areas (Beiter et al. 2016). Additionally, a project's potential profitability and/or viability are impacted by wholesale electricity prices, market marginal costs, capacity credit, and capacity payment.

For the GOM, NREL's geospatial cost model[10] was used to estimate levelized cost of energy (LCOE) for offshore wind. The LCOE represents on a per energy unit basis, a technology's lifetime costs (Capital, O&M, and Financial) divided by its expected lifetime energy production. In 2015, LCOE ranged from $140/MWh–$385/MWh. Ranges of $105/MWh–$206/MWh, and $90/MWh –$185/MWh were predicted in 2022 and 2027 respectively (Beiter et al 2016). **Table 4** shows the amount of cumulative offshore wind capacity that could be deployed at various LCOE thresholds in 2015, 2022, and 2027 as predicted using the NREL geospatial cost model.

Table 4. Offshore Wind Economic Potential in the GOM

Year	LCOE	Cumulative Capacity (GW)		
		Fixed-bottom	Floating	Total
2015	<$150/MWh	<10	0	<10
2022	<$150/MWh	120	30	150
	<$125/MWh	40	0	40
2027	<$150/MWh	200	300	500
	<$125/MWh	150	100	250
	<$100/MWh	40	10	50

The net value of an offshore wind project is defined as the difference between the LCOE and the Levelized Avoided Cost of Energy (LACE). LACE is the metric used to capture the value of electricity generation to the system (e.g., the grid) over the course of a technology's expected lifespan that measures how much "other" energy generation from other sources is avoided. Regional maps of the GOM show spatial values of LCOE and the net value of offshore wind (**Figure 11**). These results from Beiter et al. (2017) indicate that most modeled sites had a net value near or below zero dollars, meaning that project costs exceed the levelized avoided cost in 2027 necessary for economic competitiveness without subsidies. A project is generally considered to have economic potential if it has a net value greater than $0/MWh.

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[10] For more information on NREL's geospatial cost model, see Beiter et al. (2016)'s *A Spatial Cost-Reduction Pathway Analysis for U.S. Offshore Wind Energy Development from 2015–2030*.

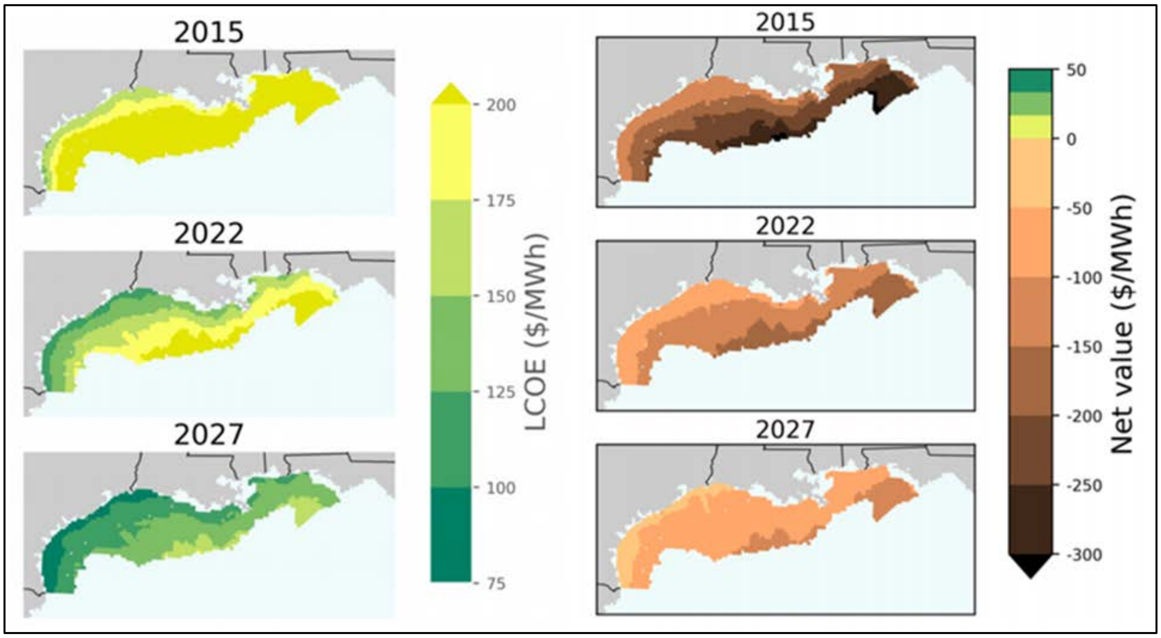

Figure 11. Regional map of levelized cost of energy (LCOE) (left) and net value (right).

The Beiter et al. (2017) findings reflect 2016 costs assumptions and do not fully capture recent cost reduction trends in Europe or the uncertainty of future cost declines. Cost reductions are being realized due to innovations such as larger rotors (low specific power), up-scaling of turbines and project size, maturing supply chains and infrastructure, and risk reduction resulting in lower financing costs due to industry experience. Therefore, offshore wind economics in the GOM could improve sooner than 2027, especially given the rapid global price declines. Under some aggressive technology development scenarios (e.g., 15 MW wind turbines) it is possible that some GOM sites could potentially reach economic viability by 2030.

For this study, an LCOE range from $0.095/kWh to $0.19/kWh was used, representing the expected cost of offshore wind for all regions of US for projects designed in 2018. But this range is probably wider than what near term commercial projects in the northeast are likely to realize.

2.1.5 Offshore Wind Energy Summary

Offshore wind is a relatively mature technology that could utilize the significant offshore wind resource capacity in the GOM, especially as offshore wind costs continue to decline. Depending on the location and site conditions, either fixed-bottom or floating technologies could be deployed while leveraging the GOM's existing manufacturing and offshore engineering expertise. Cost assessments for offshore wind are the most accurate of the technologies assessed because they are based on market trends from over 16 GW of offshore installations to date and models developed to assess the cost elements are derived from actual project data. These models indicate that costs are declining faster than expected, dropping more than 65% in just a few years. These global cost declines indicate similar cost reductions would be possible for the GOM with some adjustments for site conditions and geospatial differences. Indications are that cost may be approaching competitiveness without subsidies by 2030 but uncertainty about the rate of technology advancement and other market factors make the exact year difficult to predict. It should also be noted that the infrastructure and supply chains for offshore wind are compatible to the oil and gas industry already established in the GOM. Markets for offshore wind in the North Atlantic are now accelerating rapidly and it is likely the offshore wind industry will invest over $20 billion in the next decade, some of which will help bolster the GOM infrastructure in advance of GOM deployments.

2.2 Wave Energy

Wave energy is a new renewable technology with global interest, especially in Europe, the US, Asia and Canada. Wave energy can potentially provide coastal communities with economic benefits such as job growth, energy diversity, operational grid flexibility, and transmission congestion relief. However, its development is at a very early stage, and no commercial installations yet exist. Among the technologies investigated, wave energy is at a relatively low technology readiness level and low wave climates make its utility scale use in the GOM unlikely for the foreseeable future. This section assesses the technical and economic viability of deploying wave energy in the GOM.

Most of the discussion around wave energy focuses on bringing the power generated to land, for the power grid. However, there may be applications for wave energy to help power thousands of offshore oil and gas facilities on the OCS under BOEM's jurisdiction, that are currently powered by diesel generators. This possibility has been considered by BOEM in studies conducted by the University of Louisiana (Kaiser et al. 2011) and is beyond the scope of this report, but it is potentially important for future feasibility assessments.

2.2.1 Wave Energy Technology Description

Ocean surface waves are generated by wind passing over the ocean surface. The friction between the wind and ocean surface causes energy to be transferred from the faster moving air to the surface layer of the ocean. Wave development depends on the length of ocean, or "fetch," over which the wind blows in a constant direction. Longer fetches with higher wind velocities will produce larger waves. Waves can travel thousands of miles with little energy loss and can combine with waves from storms and other wind-driven events to create very energetic seas. The energy of ocean waves is concentrated at the surface and decays rapidly with depth.

The ocean water does not travel with the wave, but instead moves in an orbital motion as the wave passes (**Figure 12**). This creates two types of energy that can be harvested: 1) the kinetic energy of the particles moving in their orbits, and 2) the potential energy caused by the change in sea surface height. There are many unique characteristics to wave energy that could provide early forecasts to allow utilities to optimize power production including the fact that the relationship between wind and waves is known, that waves do not dissipate rapidly once they are formed, and finally that their speed and direction of propagation is deterministic.

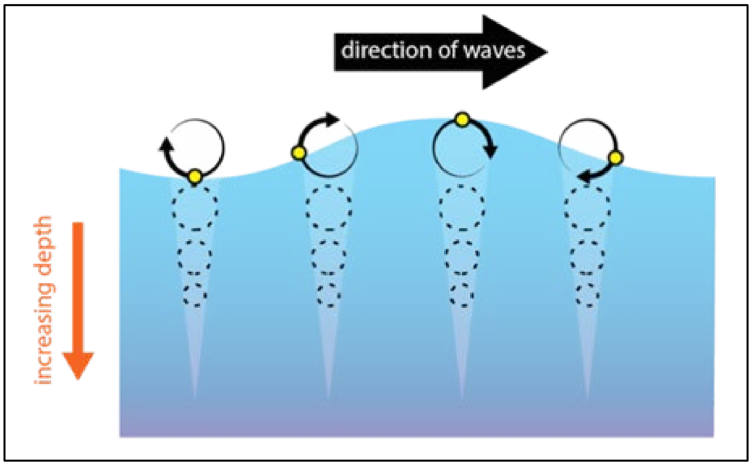

Figure 12. Behavior of water particles in a wave propagating in deep water.
Source: Exploring Our Fluid Earth (2015)

Unlike some renewable energy technologies, like wind energy, wave energy converters (WECs) have not converged to a common archetype for absorbing the wave energy or for converting the energy to electricity (i.e., power take-off [11]), and many variants exist. The following sections describe some of these variants:

- **Attenuators** are long in comparison to the incident wavelength and are composed of multiple rigid bodies connected at their ends by hinged joints (**Figure 13)**. The devices orient themselves in the direction of wave travel and extract energy by resisting the relative pitching between the device bodies. New concepts for wave attenuator technologies use continuous tubes that extract power from the deformation of the device body as waves pass over it (**Figure 14**).

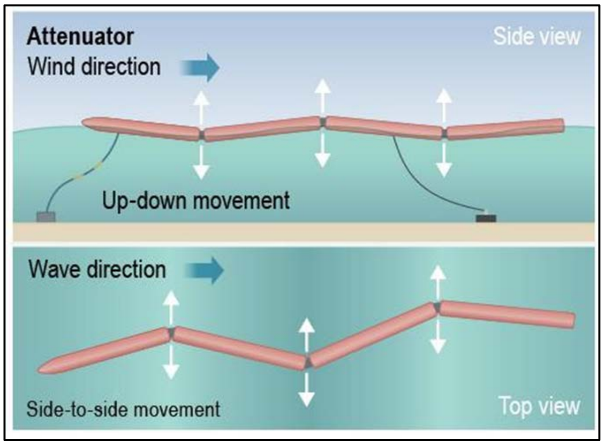

Figure 13. Multi-segmented, hinged wave attenuator technology.
Source: NREL (2018)

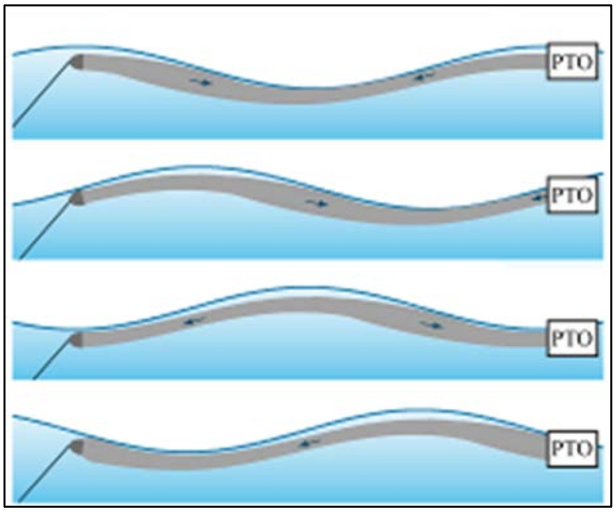

Figure 14. Continuous tube attenuator technology.
Source: NREL (2018)

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[11] The power take-off (PTO) of a wave energy converter is the mechanism with which the absorbed energy by the primary converter is transformed into useable electricity. Source: Heller et al. (2010).

- **Point absorbers** are smaller than the incident wavelength and can capture energy from a wave front larger than the physical dimension of the device (**Figure 15**). Point-absorbers typically extract energy through a heaving or pitching motion, or a combination of both. There are both floating and submerged point absorber concepts.

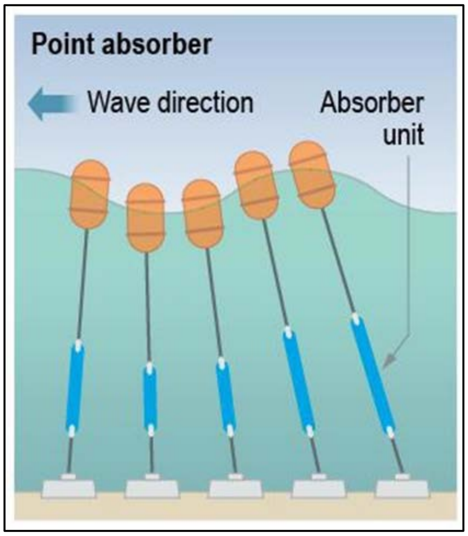

Figure 15. Wave point absorber technology.
Source: NREL (2018)

- **Oscillating water columns** use a partially enclosed volume of water that is driven upwards and downwards in a chamber by the external waves (**Figure 16**). Energy is extracted as the water column forces air within the enclosure in and out across a turbine**.**

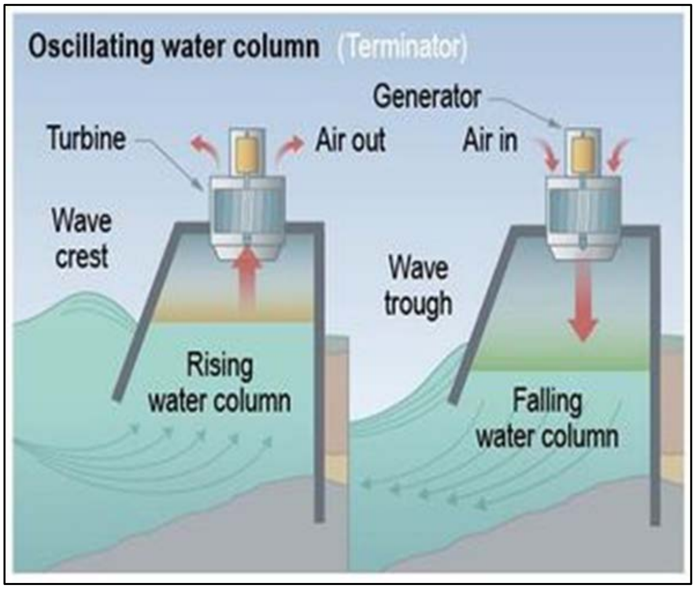

Figure 16. Oscillating water column technology.
Source: NREL (2018)

- **Overtopping technologies** use a structure to focus and amplify waves before overtopping into a reservoir (**Figure 17**). The reservoir fills above the ambient sea level. Gravity drains water from the reservoir through a turbine before being released back to the sea**.**

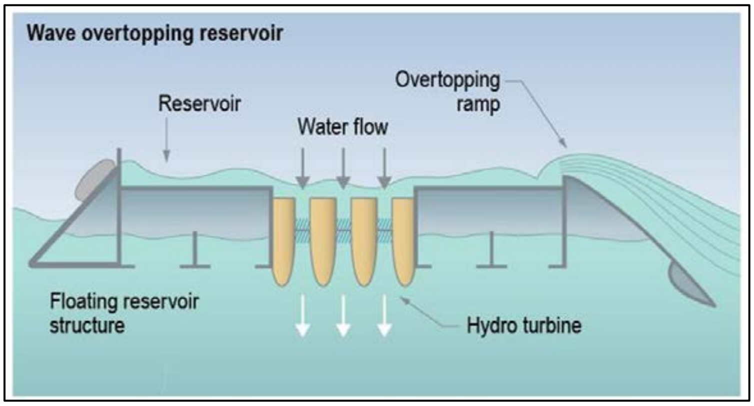

Figure 17. Wave overtopping technology.
Source: NREL (2018)

- **Pressure differential** devices are located below the waves and use the pressure difference between the crest and troughs of waves (**Figure 18**). On one side, the higher pressure of the crest causes a device to compress and on the other side, the lower pressure of the trough causes the device to expand. Power is extracted as air flows between the chambers**.**

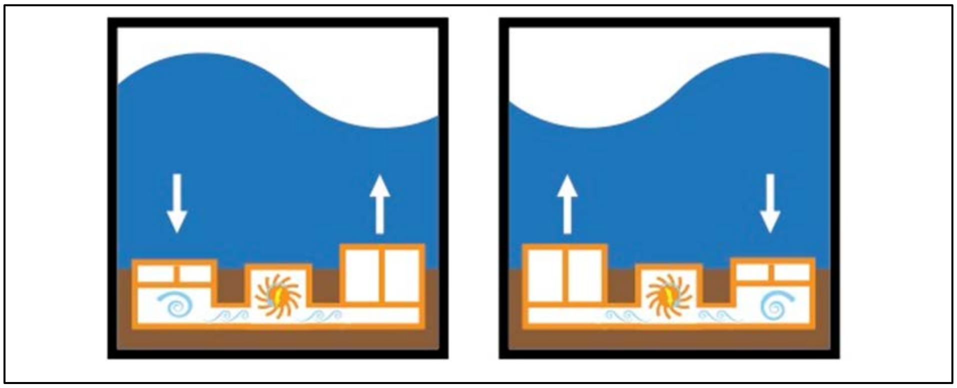

Figure 18. Wave pressure differential technology.
Source: Goodwin and Hildenbrand (2013)

- **Surge converters** are devices, typically flaps, which are oriented perpendicular to the direction of wave propagation and move forwards and backwards with the water motion (**Figure 19)**.

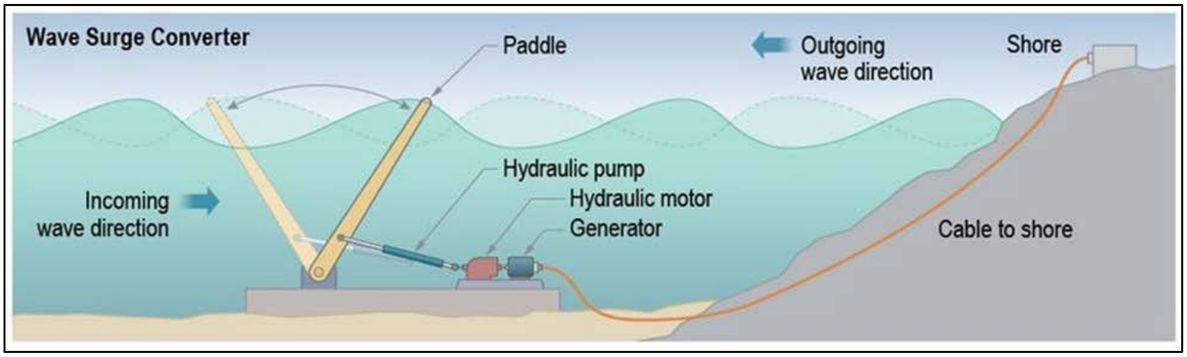

Figure 19. Surge converter technology.
Source: NREL (2018)

2.2.2 Wave Energy Resource Potential

The gross wave energy resource is specified as the annual average power per meter of wave crest width, which can be approximated as power per meter of coastline. This is the gross power contained in the waves themselves, but the actual energy that could be turned into electricity is substantially less due to efficiency limitations of the device, and conflicting use and environmental restrictions along the coastline.

Waves are relatively energy-dense. Typical commercial sites considered for development at this early stage of the industry have an average annual wave energy flux of 30–35 kW/m. Such sites can be found for example in the Pacific Northwest, could provide significant power to coastal communities (NREL 2017b). The global wave resource varies from less than 10 kW/m to over 120 kW/m, depending on location (**Figure 20**).

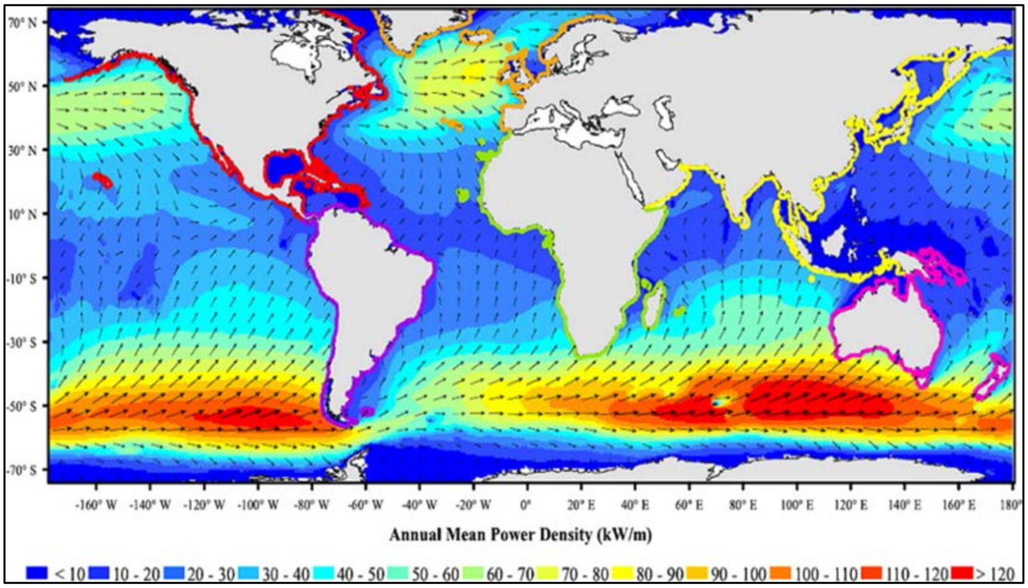

Figure 20. Global wave mean power density.
Source: Soares et al. (2014)

For the GOM, the wave flux from the Texas-Mexican border to the Florida Keys was determined using data from the NREL marine hydrokinetic (MHK) atlas (2017b) (**Figure 21**). Note that the map shows only the available data from the MHK data base (DOE 2017), which extends up to 50 nm from shore but does not cover the entire resource area that theoretically extends to the EEZ. However, this data limitation does not affect the estimation of gross wave resource potential. This is because the gross wave resource was calculated by multiplying the average annual wave energy flux along a state's coast by the length of the coastline at the 50m isobath, which is well within the data domain (**Table 5)**. The omni-directional wave energy flux is a sum of wave energy irrespective of direction and is always larger than the contour-normal wave energy flux which is the sum of the incident wave energy crossing perpendicular to a depth contour[12]. Both quantities are important depending on the type of wave energy technology being considered. The best wave resource is along the south Texas coast but does not exceed 8 kW/m. The wave resource decreases moving to the east in GOM and is the lowest off the west coast of Florida. Note that this gross potential is the total annual wave power contained in the wave resources but does not represent the energy that can be extracted. For the GOM, the total gross resource wave energy resource potential was determined to be approximately 3.1 GW, as calculated along the 50 m isobath.

The technical potential is calculated from the gross resource potential and includes only the resource that can reasonably be developed with existing technology. The wave energy industry estimates that a 10 kW/m resource is an appropriate minimum threshold (Kilcher and Thresher 2016). As technology improves and lower wave sites are exploited, it is possible that this limit could be lowered. Based on the 10 kW/m filters recommended, zero wave energy technical potential was found within the GOM (Kilcher and Thresher 2016), which indicates that the GOM's wave energy resource would not likely be economical using today's technology.

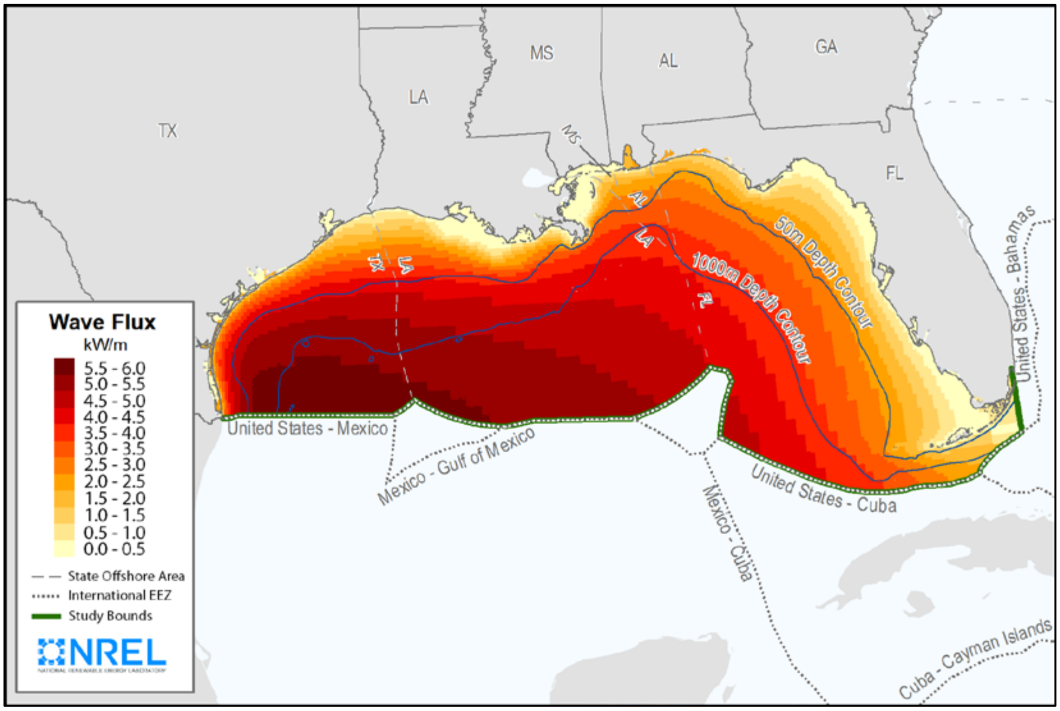

Figure 21. Gross Wave Resource in the GOM.

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[12] Note that the 50 m (164 ft) isobath does not cross the Mississippi state boundary which made the standard methodology used flux calculation impossible for this state. The wave flux for Mississippi was approximated to be 1.8 kW/m.

Table 5. Wave Resource Potential in the GOM

State	Length of 50 m (164 ft) Isobath (km/mi)	Average Annual Omni-Directional Wave Energy Flux (kW/m)	Average Annual Contour-Normal Wave Energy Flux (kW/m)	Gross Wave Energy Resource (MW)	Technical Wave Energy Resource >10 kW/m (MW)
Florida	829 (515 mi)	3.9	1.6	1,400	0
Alabama	83 (52 mi)	4.8	2.7	200	0
Mississippi	0	1.8	N/A	0	0
Louisiana	556 (345 mi)	5.4	2.9	1,600	0
Texas	536 (333 mi)	7.1	4.2	2,300	0
Total	2004 (1,245 mi)	5.24	2.7	5,500	0

2.2.3 Wave Energy Technical Readiness

Ocean wave energy technology development began in the mid-1970s in response to the oil crisis, but wave technologies today are still pre-commercial with respect to their technical maturity. This slow pace can be attributed to the harsh environment in which wave energy converters operate and the complex regulatory requirements imposed on device deployments. These limitations impact the speed of deployment and the rate of technology learning by the industry. Only a few technology deployments have achieved sustained operation of one year or longer and demonstrated predictable energy production. As a result, the technology for wave energy remains at a relatively low state of technology readiness and, much like in the early days of wind, there has been limited convergence in optimizing device architectures. Because new concepts are still being explored to find reduced cost designs and few technologies have operated for more than a year with meaningful energy production, it is difficult to assess critical aspects of reliability and performance. Therefore, wave energy technology needs significantly more experience to design better concepts, and to demonstrate predictable reliability and efficiency before it can be considered commercially ready.

2.2.4 Wave Energy Economics

Though wave energy holds substantial promise in many coastal areas where incident wave resource is adequate, wave technologies are still at the prototype stage, which means current costs are significantly higher due to its nascent stage of development. In addition, the cost of energy decreases with a higher wave energy resource potential. In some of the best resource areas (e.g., 30 kW/m), costs are estimated to be $0.70/kWh (Jenne et al. 2015), with some estimates exceeding $1.00/kWh (IEA-OES 2015; Neary et al. 2014). Research and development trends aim to significantly increase energy extraction efficiency and optimize mechanical designs through advanced controls, increased understanding of loads, and targeted innovations to increase energy production and reduce material costs. IEA-OES (2015) estimates that the first commercial array of wave energy convertors may be installed between 2020 and 2030 at a cost of energy between $0.12 to 0.48/kWh. However, for the GOM the cost would likely be much higher because of the low average wave energy flux potential.

2.2.5 Wave Energy Summary

Wave technology is at an early prototype stage with very few successful demonstrations of power performance or reliability. In addition, the wave climate in the GOM is poor compared to other regions of the US, with no states showing resource above the minimum recommended threshold of 10 kW/m of wave crest length. The combination of low maturity and poor resource make the cost of wave energy very high using the technologies that are available today. As such, it is likely that for the GOM, commercial viability is not likely for the foreseeable future. It is recommended that wave energy assessments be revisited periodically to evaluate possible changes to the technical resource.

2.3 Tidal Energy

Tidal energy is a renewable technology with global interest, especially in Europe, the US, Asia, and Canada. Tidal energy can potentially provide some coastal communities with energy diversity, operational grid flexibility, and transmission congestion relief. Due to the nature of the resource, tidal energy in the US is generally confined to state waters and is not usually under the jurisdiction of BOEM. Among the technologies investigated, tidal energy is at a higher technology readiness level than wave energy, but its limited resource potential makes broad utility scale use in the GOM states unlikely for the foreseeable future. This section assesses the technical and economic viability of deploying tidal energy in the GOM.

2.3.1 Tidal Energy Technology Description

Tides are characterized by the rise and fall of the ocean surface height primarily caused by the gravitational interactions of the earth, moon and sun and the rotation of the earth. Tidal current used for power production typically occurs between two bodies of water connected by a narrow land passage. Therefore, in the US, most tidal energy sites are found near shore and tend to be in state waters. As the sea surface changes on the seaward side of the passage, water flows through the passage to equalize the height of the other body of water, such as a bay, estuary, or river. Because tides rise and fall, currents flow in and out of the inland body of water. It is the kinetic energy in the tidal current that is generally considered the useful energy resource. As the speed of the tidal current increases, the energy extraction potential also increases. Tidal currents move inland during *flood* tides, seaward during *ebb* tides, and no current exists during *slack* tides, when the bodies of water have equal height. Tidal heights change daily, with up to two cycles per day, depending on geodetic location, coastline and other factors. Maximum and minimum tidal heights and tidal current speeds, change throughout the year based on the relative location of the sun and moon. Though tidal flows are cyclic in nature (**Figure 22**), they are extremely predictable, and flow rates and hence power production, can be forecast decades ahead.

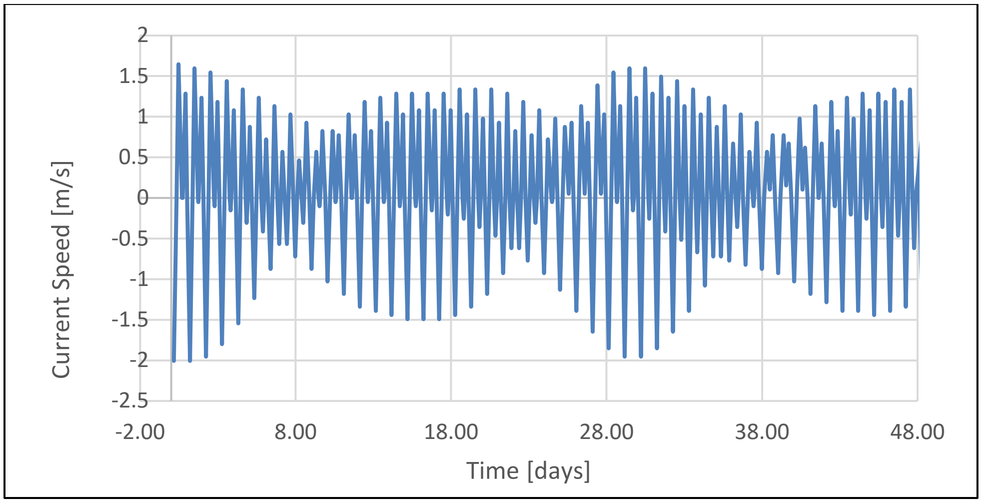

Figure 22. Example time series of tidal speeds for Boca Grande Pass, Charlotte Harbor, Florida.

Tidal current speed is primarily determined by the range of tidal height, size of the passage (width and depth), and size of the water bodies. Larger values of each of these variables results in higher current speeds. The primary method used to extract energy from a moving tidal flow is water current turbines located under the surface that convert the kinetic energy of moving water to electricity.

Tidal power has been used for centuries to produce mechanical power from paddle wheels to mill grain. In 1966, the first commercial scale tidal energy plant was installed in the estuary of the Rance River in Brittany, France (**Figure 23)**. It uses tidal *barrage* technology in which a dam-like structure is placed across the tidal flow, allowing water to flow into a bay from the sea during a flood tide. During ebb tide, sluice gates are shut, and water flow is diverted through turbines to generate power. Though it is possible to generate power during a flood tide, it is much less efficient. Because of the significant impact to the environment, tidal barrage technology has not been pursued in the US.

Figure 23. Tidal barrage in the Rance River in Brittany, France.
Source: Energy BC (2017)

Modern tidal power generating turbines operate on the same principles as wind turbines. As the moving water passes the current turbine's blades, the kinetic energy of the moving tidal current is converted into mechanical energy by rotating blades that spin a drive shaft. The mechanical energy in the rotating drive shaft is typically passed through a gearbox and converted to electrical energy using a generator. There have been many pre-commercial tidal turbine deployments in North America, Europe and Asia, but these have been limited to single units or small arrays. Some examples include Verdant Power's East River project in New York City (**Figure 24**) and Atlantis Resources project in Pentland Firth, Scotland (Rooney et al. 2013; MeyGen 2017).

The following two primary tidal turbine archetypes have been developed, and have direct analogues in wind energy.

- **Horizontal axis turbines** are similar to today's commercial three-bladed wind turbines. Turbine rotors, either with two or three blades, are mounted to a horizontal shaft that is aligned with the water flow. A central hub houses the gearbox and generator. Because tidal flows can reverse flow direction twice a day, the rotor must be able to rotate in both directions or yaw the entire nacelle to align with the direction of flow. Other models are designed to accommodate flow direction reversals by pitching the blades 180 degrees instead of yawing the nacelle. In many tidal flows, the ebb and flood tides are not exactly 180 degree apart because of curves in the channel geometry, thus limiting the use of the blade pitching technologies. Tidal turbines typically operate in restricted passages that limit the height and width of the turbines. Because the flow capture area of horizontal axis turbines is circular, horizontal axis tidal turbines do not scale well in shallow water flows but operate best in larger water channels that are at least 10 m deep**.**

- **Cross-flow turbines** are analogous to vertical axis wind turbines. In this archetype, blades are mounted lengthwise to a central shaft that is orientated perpendicular to the current. One or more sets of blades are connected to a pod that contains the gearbox and generator. Unlike horizontal axis turbines, cross flow turbines can generate power without re-orientating the blades flow reversals during flood and ebb tides, providing some simplicity in the design. However, a cross flow turbine's energy capture decreases when the ebb and flood flow directions are not aligned. Because cross-flow turbines can be scaled in both length and height, they can be tailored to fit both shallow and deep flows.

2.3.2 Tidal Energy Resource Potential

Gross tidal energy resources are characterized by the average annual energy in a flow past a fixed location in a channel, expressed as power per cross-flow area. However, the extractable tidal resource is substantially less due to various economic, environmental, and technical constraints. Commercial tidal developers look for a gross resource greater than 0.5 kW/m^2 over a cross sectional area with sufficient potential for utility scale generation of at least 10 MW (Kilcher et al. 2016). In the GOM, tidal height variations are small, there are few tidal channels, and connected bodies of water tend to be small. Six sites in the GOM were found to have more than 0.5 kW/m^2, including one site in Texas and five sites in Florida, mostly in the Florida Keys (**Table 6; Figure 24).**

Table 6. Tidal Energy Resource Potential for GOM Sites

Site Description	State	Maximum Power Density (W/m2)	Net Technical Resource Potential (MW)
Matagorda Bay	Texas	900	0.8
Charlotte Harbor	Florida	1,100	8.8
Boca Grande Channel	Florida	560	27.9
Key West Channel	Florida	1,000	13.6
Spanish Harbors	Florida	1,000	7.9
Seven Mile Bridge	Florida	2,300	26.6
Total	-	-	85.6

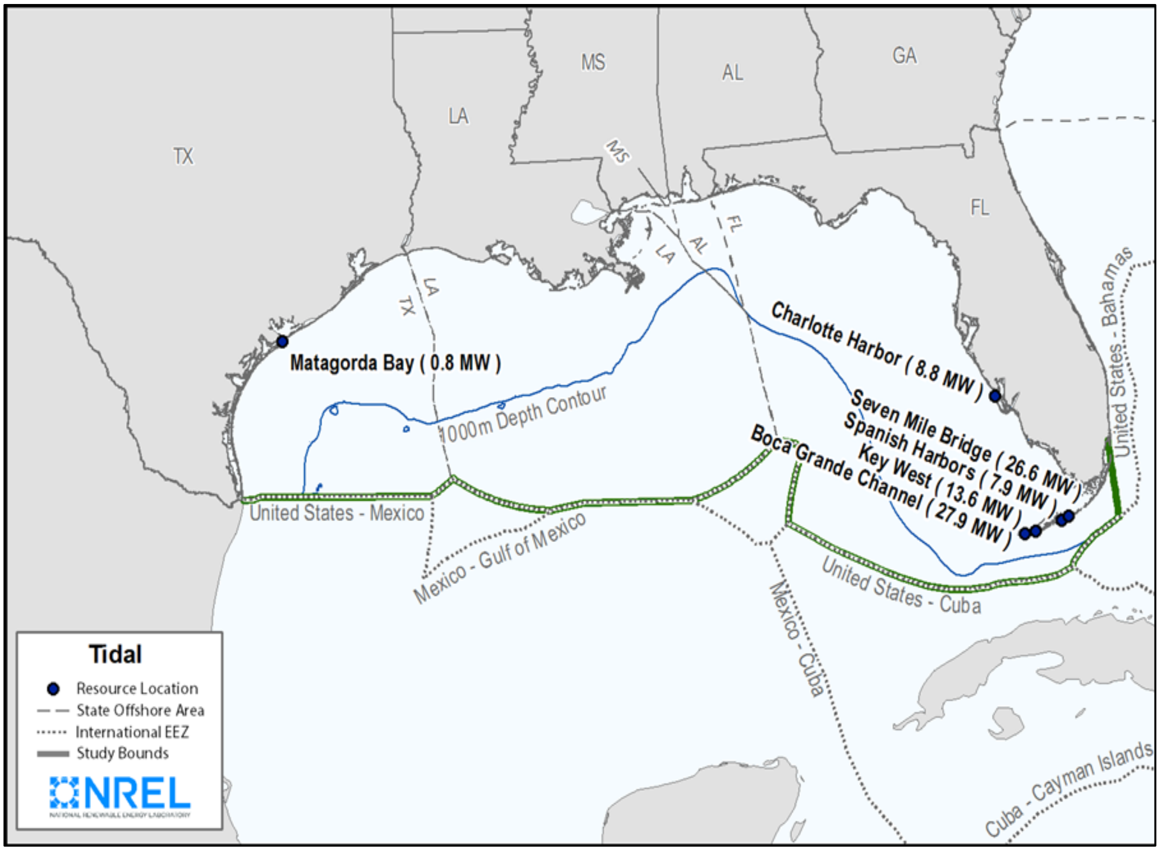

Figure 24. Potential tidal energy sites within the GOM and Florida Keys.

2.3.3 Tidal Energy Technical Readiness

Tidal energy technologies remain predominantly at a pre-commercial prototype level but are advancing faster than wave technologies toward commercial scale. In the United Kingdom, the first commercial scale project is under development in the Pentland Firth, with 269 turbines and a total installed capacity of 398 MW. The first Pentland Firth turbine is expected to be deployed in 2020 (MeyGen 2011; Power Technology 2017). Deployments of pre-commercial systems in the US have been limited to tidal flows in the East River in New York and Cobscook Bay, Maine. Much like the first wind turbines, tidal technologies need to overcome reliability issues in early designs to achieve expected lifespans and lower operation and maintenance costs. Poor accessibility is an added challenge in tidal flows because slack tides are short and offer limited windows for maintenance. With experience, better design tools and validation, more robust designs are expected to be developed.

2.3.4 Tidal Energy Economics

The cost of tidal turbines is driven by many factors, including the size of the machines, the number of machines, and the availability of quality resource. Early estimates indicate that a 10 MW array could have an LCOE of approximately $0.22/kWh and a 100 MW array could have an LCOE of around $0.15/kWh. However, these costs can only be achieved with sufficient industry deployment to gain experience and to take advantage of economies of scale. It is estimated that at least 1,000 MW of installed tidal power would needed to gain this experience, which is likely more than a decade away (IEA-OES 2015; Neary et al. 2014).

2.3.5 Tidal Energy Summary

Within the study domain, only six suitable tidal energy sites have been identified with a total potential of 85.6 MW; most are in the Florida Keys. Based on current industry information, these sites are not likely to be cost competitive with conventional electric generation for at least 10 years. Small scale projects may be possible, but the potential for significant commercial scale tidal generation within the GOM and the Florida Keys is unlikely, primarily due to low overall resource availability.

2.4 Ocean Current Energy

Ocean currents can be a renewable energy source that uses technology similar to underwater tidal turbines but is less constrained by channel geometry. It has been researched primarily in the US, where potential resource has been identified in the Florida Straits, in the Gulf Stream east of Miami. Ocean current energy can potentially provide significant power to a few coastal communities where the resource potential corresponds with the load. Currently its development is at a very early stage, with no installed projects. Logistics and regulatory concerns present significant challenges to initial implementation. As such, ocean current energy is at a low technology readiness level. This study focuses on whether there might be other opportunities not yet identified for deployment in the Loop Current and the Florida Current south of the Florida Keys. It assesses the technical and economic viability of deploying ocean current energy in these GOM currents and focuses on bringing the power generated to land, for the power grid. It is beyond the scope of this study to consider using ocean current turbines to power some of the thousands of offshore oil and gas facilities on the OCS under BOEM’s jurisdiction.

2.4.1 Ocean Current Energy Technology Description

Harnessing the Florida Current was first seriously considered in the 1970s when DOE sponsored the Coriolis Program that aimed to extract power using a very large ducted fan turbine (Lissaman and Radkey 1979). Because of these large water depths, ocean current energy converter concepts have shifted away from ducted turbines towards horizontal axis turbines that can vertically maneuver within the water column from a fixed mooring position (VanZwieten et al. 2006). These turbines use buoyancy or lifting surfaces to suspend them above the sea floor and eliminate the need for costly support structures.

This technology (**Figure 25**) operates on the same energy generation principle as a horizontal axis wind turbine. As the moving water passes the turbine's blades, the current's kinetic energy is converted into mechanical energy as the rotating blades spin a drive shaft connected to a gearbox. The mechanical energy in the drive shaft and/or gearbox is then converted to electrical energy using a generator. Though the concept in **Figure 25** has undergone small scale testing in tow tanks, it has not yet been demonstrated in the ocean. Because the density of seawater is approximately 850 times greater than air, an ocean current turbine operating in a water current with a speed of 1 m/s (2.2 mph) can produce the same power as a similar size wind turbine operating at a wind speed of 9 m/s (20.1 mph) (National Research Council 2013).

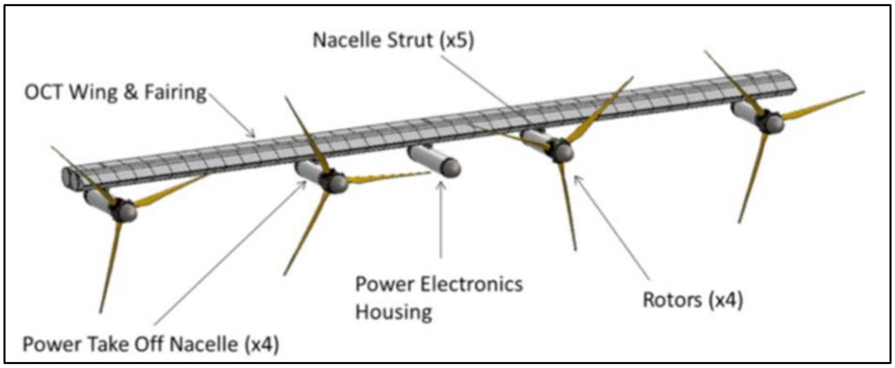

Figure 25. Horizontal axis ocean current turbine using lifting surfaces for position in the water column.
Source: Neary et al. (2014)

2.4.2 Ocean Current Energy Resource Potential

The Loop Current is the only open-ocean current within the GOM that has current velocities high enough to support electric power generation. The Loop Current is part of the North Atlantic Gyre circulation, which is primarily driven by the trade winds. It is the most westerly portion of the North Atlantic gyre and accounts for about 20% of the mass flow of the Gulf Stream. The Loop Current enters the GOM through the Yucatan Channel, where it flows northward then turns clockwise and follows the continental slope offshore Florida as it flows southward until it turns east and exits through the Straits of Florida where it forms the Florida Current. The highest speeds of the Loop and Florida Currents occur near the ocean surface and decrease with depth (Raye 2002). A snapshot of the current velocity forecast for Sept 14, 2017, provided by NOAA, shows the variability of the Loop Current (**Figure 26**).

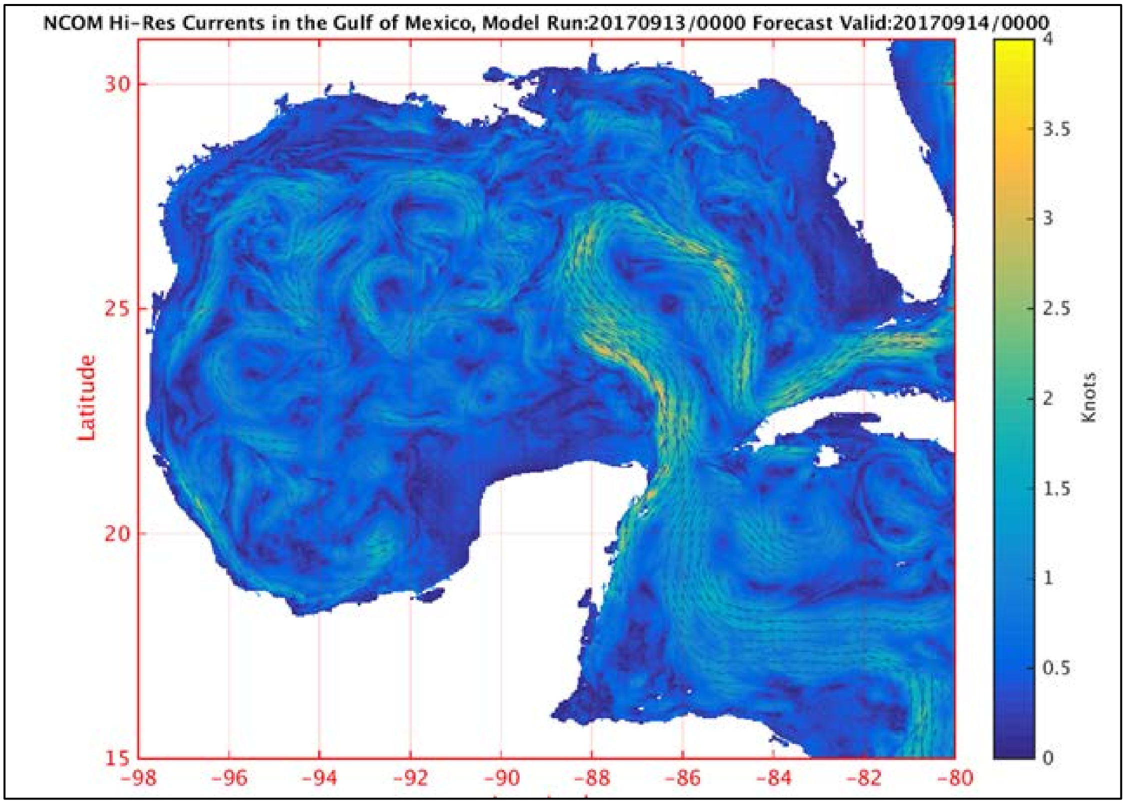

Figure 26. GOM Loop Current forecast by NOAA on September 14, 2017.
Source: National Weather Service (2017).

The Loop Current has a volume transport in the range of 24 to 30 million m^3/s (Athié et al. 2012), which is about 24 times the total freshwater river flows of the world. No studies were found that estimate the energy production potential from the Loop Current. Estimates for the Florida Current in the Straits of Florida provide some insight, assuming the energy flux is conserved between the GOM and the Straits of Florida. Based on field measurements and ocean circulation models, it is estimated that the total power flux of the current in the Straits of Florida is between 14 GW (National Research Council 2013) and 25 GW (Von Arx et al. 1974; Duerr and Dhanak 2012). Because the Florida Current is an extension of the Loop Current, it provides a good basis to estimate the gross energy potential within the GOM. Within the Straits of Florida, estimates of technical resource potential vary widely from 1 GW (Von Arx et al. 1974), 1–2 GW (National Research Council 2013), 1–4 GW (Duerr and Dhanak 2012), to 4–6 GW (Haas et al. 2013). Estimating the net power potential from the Florida Current is difficult because it is a low-friction flow that relies on a balance of the mass flow and thermohaline structures to maintain its position close to the coast of Florida. Blockages and mixing due to placement of ocean current turbines could potentially divert flow toward the Bahamas (National Research Council 2013). Estimates of extraction depend on assumptions such as device type, depth limits, and device spacing.

Within the Florida Straits and Yucatan Channel, the current is geographically constrained, and meandering is limited. However, in the GOM, the Loop Current is not geographically constrained, and it exhibits higher spatial variability than the Florida Current. As a result, the annual average flow speeds at fixed locations within the current area are much lower than the current maxima (Hamilton et al. 2015) and do not increase again until the current enters the Straits of Florida near the Florida Keys.

The extent that the Loop Current reaches into the GOM changes frequently. It has a quasi-steady meander that can reach as far north as the continental slope near the Mississippi Delta or can turn directly east toward the Straits of Florida after it enters the GOM through the Yucatan Channel. The northern extent of the current can change rapidly when an eddy is shed (**Figure 27**) (Hamilton et al. 2015). This schematic roughly shows the northern and southern extents of the current along with a shed eddy. Though the Loop Current is a continuous flow, it exhibits large inter-annual and spatial variability that limits the potential energy capture for a given location. Because of the high spatial variability of the Loop Current, the estimated current energy density does not exceed 500 W/m^2 (threshold for technical viability) in any part of the defined resource area containing the Loop Current.

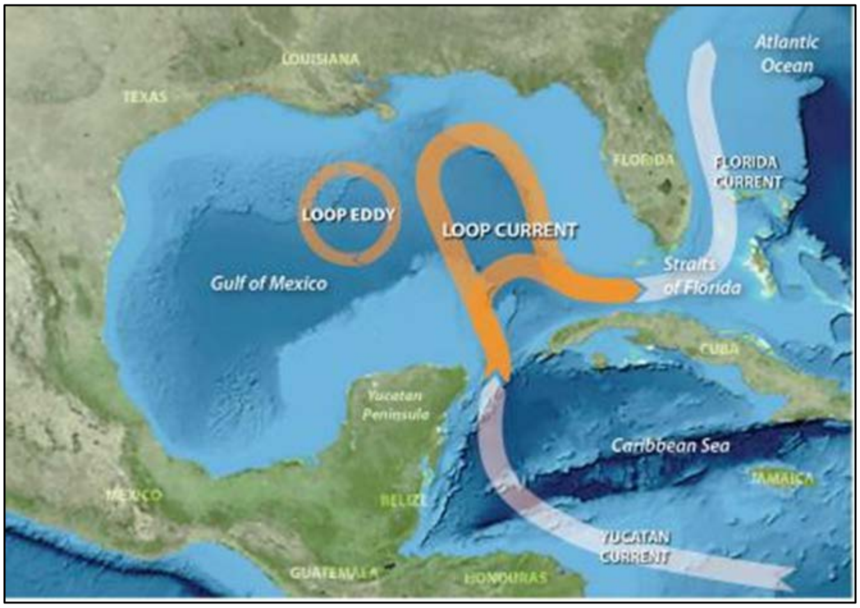

Figure 27. GOM Loop Current.
Source: UCAR (2011).

Figure 28 shows a map of the average annual ocean current energy densities for the GOM region. The data were plotted using GIS data and coordinates from the MHK data base (DOE 2017). When the 1,000 m (3,281 ft) depth limit and 500 W/m^2 energy threshold are considered, virtually all the Loop Current resource is eliminated from the viable ocean current resource within the GOM. Note that the spatial domain for the data plotted does not go all the way to the EEZ. However, the majority of this area exceeds the 1,000 m depth constraint (shown in **Figures 30** and **31**) and would be excluded from the technical resource potential.

When the Loop Current enters the Straits of Florida along the Florida Keys, it is more constrained and exhibits less spatial variability as it flows to the northeast. At this point, the average annual energy flux does exceed the technical threshold of 500 W/m^2. The highest current energy flux occurs on the eastern boundary of the study area where the gross potential is about 3.6 GW. This estimate included a decrease in the current velocity with depth (Raye 2002) with a maximum depth of 150 m (Raye 2002; Duerr and Dhanak 2012). A conservative estimate of production potential is about 10% (Von Arx et al. 1974; National Research Council 2013; Duerr and Dhanak 2012) which yields a value of 358.7 MW technical resource potential as shown in **Figure 29**.

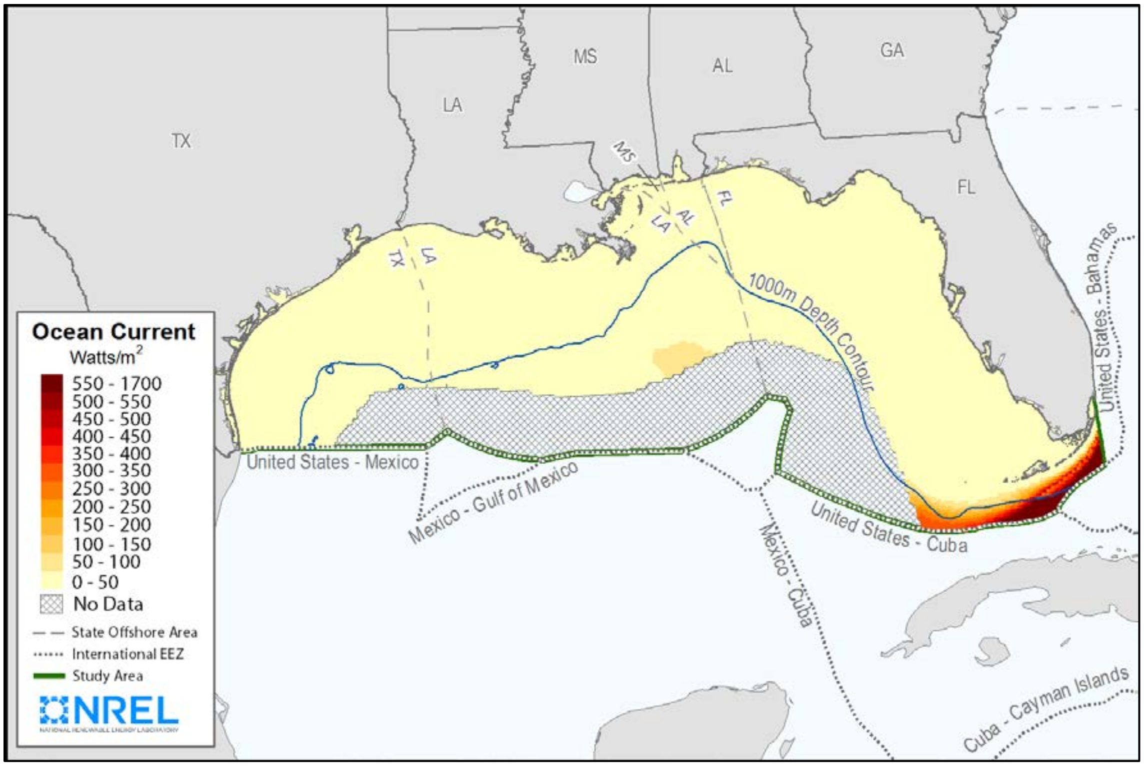

Figure 28. Average annual *power* density of the Loop Current.

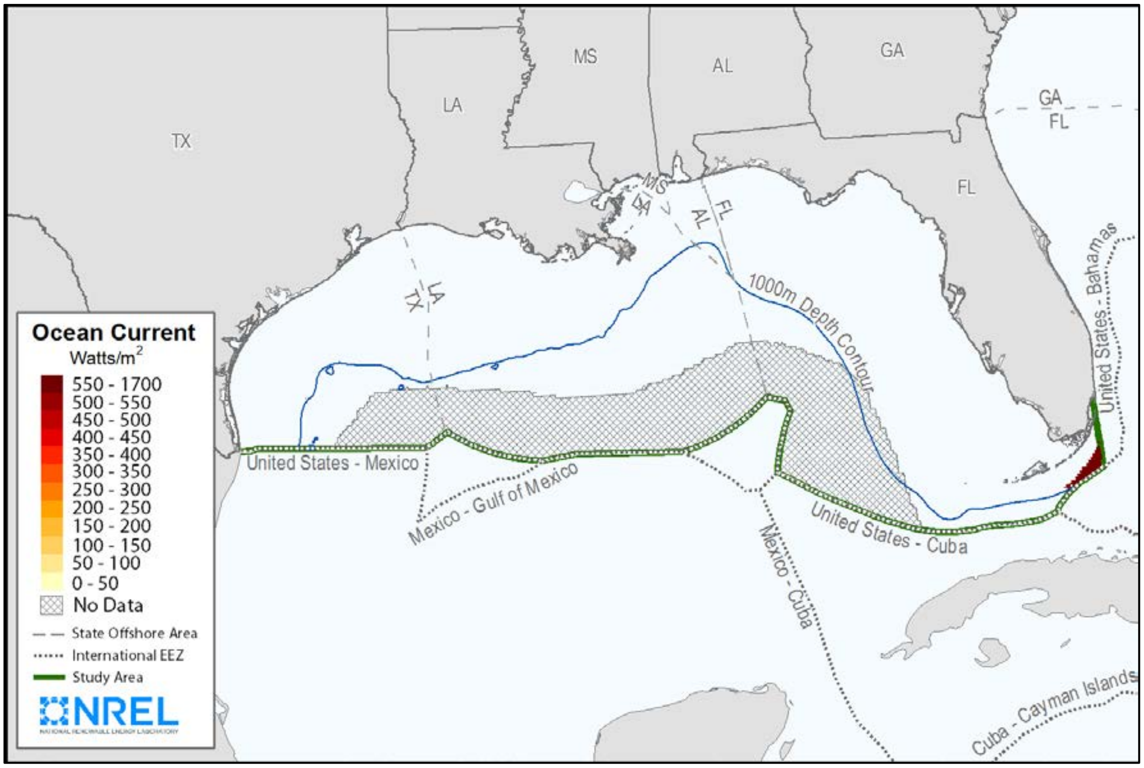

Figure 29. Average annual *power* density of the Loop Current (technical potential showing only areas above 500 W/ m²).

2.4.3 Ocean Current Energy Technical Readiness

Ocean current turbines are still nascent technologies with no open-ocean prototype deployments yet. Concepts have advanced to model testing at sub-scale, but many of the technical risk areas have not been addressed, such as long mooring and electric transport cables, deployment and maintenance in a high current, fatigue of the structure and blades, stability during slow current and mitigation of local current reversals. Because the Florida Current has less spatially variability, higher annual average energy flux, and is closer to load near Miami and Ft. Lauderdale, these areas are more likely to see deployments of ocean current turbines. The Loop Current in the GOM is not likely to be considered a viable site to deploy ocean current turbines in the foreseeable future.

2.4.4 Ocean Current Energy Economics

LCOE estimates of ocean current energy are poorly established because of the nascent state of the technology. NREL's reference model project estimated that a mature ocean current sector (achieved after multiple deployments) could achieve LCOE values near $0.18/kWh for a hypothetical 50 unit 200 MW capacity project and $0.15/kWh for a 100 unit 400 MW capacity project (Neary et al. 2014). This level of technical maturity is unlikely in the near-term even in the Florida Straits. For the Loop Current, the economics would be more costly because of lower power densities, intermittent currents, very deep water, and very large distances to shore. With no experience designing, building, deploying, operating and recovering ocean current turbines, these LCOE estimates have a high degree of uncertainty.

2.4.5 Ocean Current Energy Summary

The Loop Current in the GOM exhibits large spatial and temporal variability that leads to lower values of average current speeds when compared to locations in the Florida Straits off the east coast of Florida. Within the Loop Current in the GOM, the average current energy flux does not exceed the 500 W/m^2 threshold. Therefore, the resource is not considered viable in the foreseeable future considering the current state of technology and technology forecasts. Within the Straits of Florida, 360 MW of ocean current technical resource potential was identified. However, there are many local and global climatic and environmental questions about the impacts of harnessing energy from an ocean gyre that must be answered before this resource is considered viable. As a result, this technology is not likely to be viable for commercial scale deployment in areas within the GOM or along the Florida Keys within the next 10–20 years.

2.5 Offshore Solar Energy

Offshore solar energy has an enormous renewable energy potential but deployment is likely to be inhibited by extreme wave conditions at most exposed ocean sites; this would likely make the cost of support structures prohibitive. Offshore solar energy can potentially provide significant power to coastal communities in state waters where sheltered bays and estuaries would limit extreme waves. Currently its development has been limited to small enclosed water bodies where extreme wave heights are small. Advanced support structures may be able to significantly increase the survival thresholds using better engineering methods that merge offshore wind and petroleum industry know-how with solar to provide more robust substructures. Logistics and regulatory concerns may also present significant challenges to initial implementation, especially in congested waterways where other uses may compete. This study did not investigate the numerous bays and inlets of the GOM; therefore, it is likely that the resource for offshore solar energy is much greater than what is reported. It is also beyond the scope of this study to consider using offshore solar energy to power some of the thousands of offshore oil and gas facilities on the OCS under BOEM's jurisdiction.

2.5.1 Offshore Solar Energy Technology Description

Offshore solar energy systems are an emerging application in which photovoltaic (PV) systems are installed directly over bodies of water. Floating solar photovoltaic is a subset of that technology in which PV panels are mounted on buoyant substructures (**Figure 30)**. PV panel technology is similar to traditional ground-mounted PV, except the panels rest on a platform of plastic (typically high density polyethylene [HDPE] tubes) and stainless steel designed to float on water (Krishanaveni et al. 2016). Floating PV platforms are linked together in arrays with designated walkways and are anchored to the shore or bottom. The main electrical conversion equipment resides on the shore where electricity is transmitted from the floating PV system to the grid or load via underwater cables.

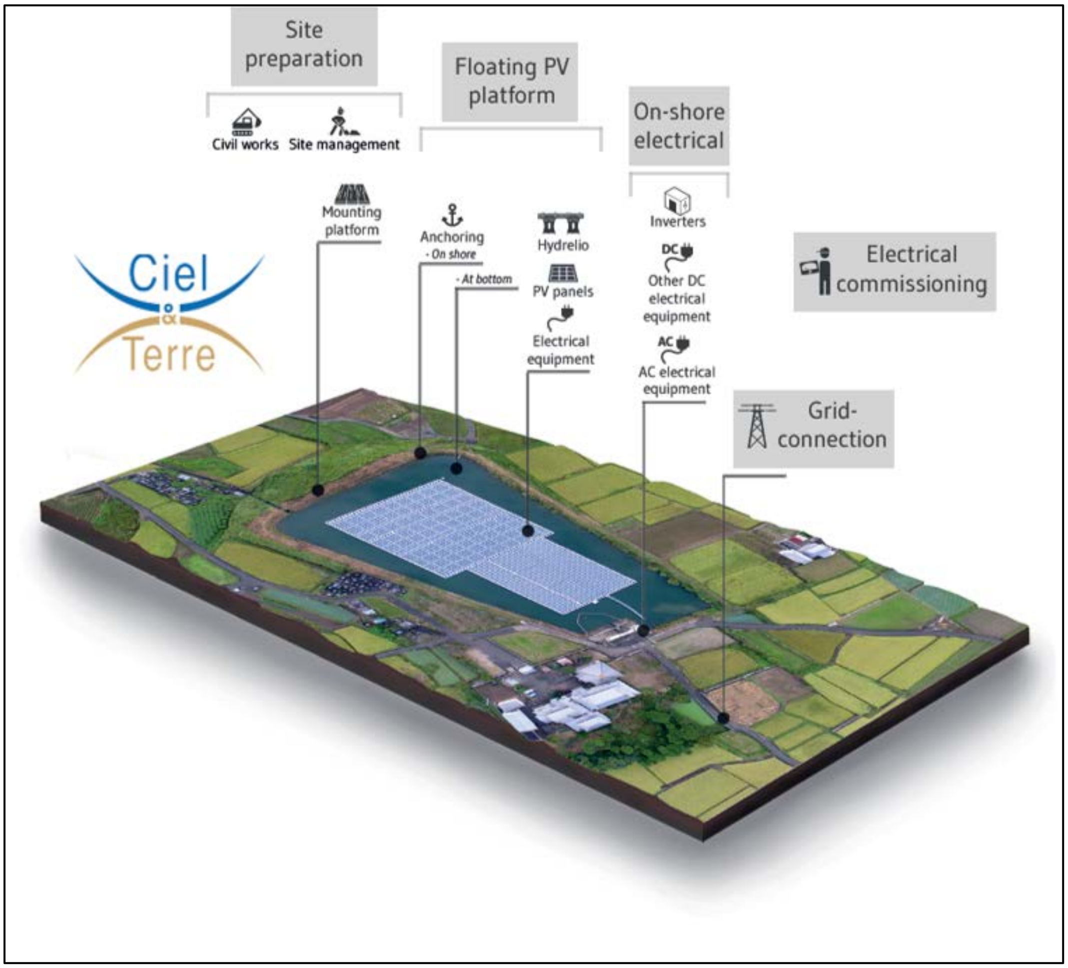

Figure 30. Schematic of a floating solar system.
Source: Ciel & Terre (2016)

To date, floating solar has been installed predominantly on human-made bodies of water such as wastewater storage ponds, reservoirs, remediation and tailing ponds, and agricultural irrigation or retention ponds. Systems must be designed to withstand fluctuating water levels, wind and wave loads, and other extreme weather conditions. Saltwater applications pose additional challenges due to corrosion and extreme wave conditions, with the latter exceeding practical design limits, seemingly in all open ocean locations.

The first floating solar installation came online in 2007 at the Far Niente Winery in California, yet the vast majority of existing systems (98%) became operational between 2014 and 2016 (**Figure 31)**. As of 2016, global installed capacity was approximately 94 MW, with additional projects expected to come online in early 2017. Japan is home to the majority of floating solar installed capacity (60%), including 70 of the largest systems in the world.[13] Floating solar systems have also been installed in more than a dozen countries throughout Southeast Asia, Europe, North America, and the Middle East. System sizes vary dramatically, ranging from 4 kW to 20 MW. The US has installed only a small amount of floating solar to date.

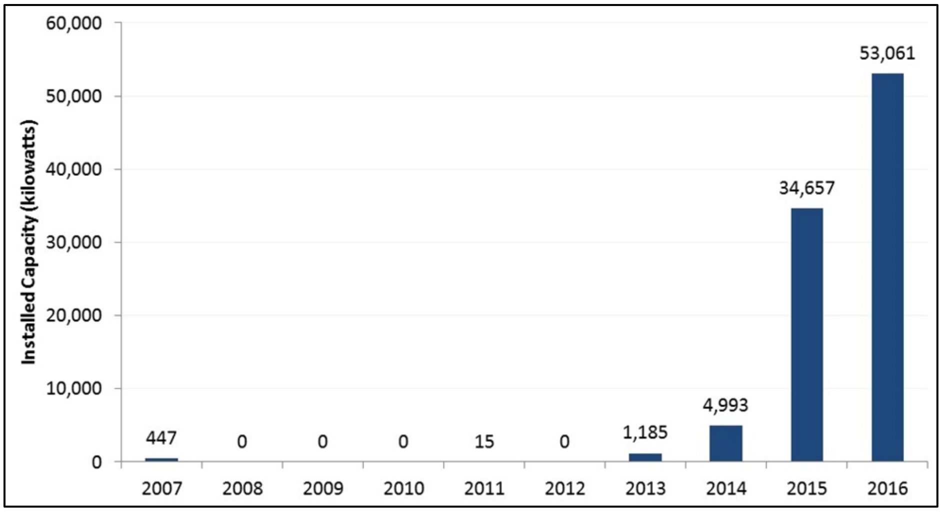

Figure 31. Reported global floating PV capacity installed by year.
Source: Adapted from Minamino (2016).

A 2017 report indicated the floating solar market is expected to grow globally from $13.8 million in 2015 to $2.7 billion by 2025 (Grand View Research 2017). Research surrounding system performance is relatively immature but has increased recently due to anecdotal claims of benefits for both water and energy operations.

Reported benefits of floating solar systems include:

- PV system efficiency gains due to lower ambient temperatures underneath the panels. Empirical research corroborates claims of efficiency gains (Choi et al. 2013).
- Reductions in unwanted algae growth
- Reduced rates of evaporation
- Lower land acquisition and site preparation costs
- Avoidance of land-energy conflicts (e.g., fuel and food)
- Conversion of unused space into a space that generates revenue
- Minimal risk to wildlife

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[13] Ciel & Terre is a developer of floating PV projects in Japan.

2.5.2 Offshore Solar Energy Resource Potential

2.5.2.1 Offshore Solar Energy Gross Resource Potential

The gross potential resource analysis method followed a series of steps which emulate the procedure for offshore wind described by Musial et al. 2016. First, the gross offshore PV resource domain area was defined as the area from the shore, including state waters, to the 200 nm international EEZ and the Florida Keys. Using GIS tools, the total area was calculated to be 715,100 km^2.

The gross offshore PV resource capacity was calculated by multiplying the gross domain area by the array power density. Power densities for horizontal PV arrays are driven by cell conversion efficiency, cell packing density, and module spacing, as explained in Denholm and Margolis 2007. PV array power density is equal to PV array power deployable per unit of land area. The array consists of individual PV modules, and the nameplate (or peak) direct current (DC) power rating of an individual module is a function of module efficiency and the module collector area. The module efficiency is defined under standard test conditions (STC) of 1,000 W/m^2 solar irradiance and 25 ˚C. Typical commercially-available silicon PV modules have efficiencies of about 10–15%, resulting in about 100–150W of peak DC output per square meter of collector area. Module efficiencies vary by technology, with current thin-film modules producing efficiencies of about 6–12%, while advanced silicon modules (also commercially available) can produce efficiencies of more than 15% (US Department of Energy 2007)[14]. Module efficiencies are expected to increase over time, which will increase the module power density and decrease the solar electric footprint.

The total array power density depends on the array spacing as well as the individual module efficiency. If deployed horizontally with no spacing between modules, the array power density would be equal to the module efficiency (100–150 MW/km^2 for silicon modules). Assuming a 120 MW/km^2 power density, the total gross resource capacity for the GOM is estimated to be 85,800 GW.

Offshore solar energy potential ranges from ~4.3 to 5.8 kWh/m^2-day in the GOM, with energy potential increasing towards the southeast near the Florida coast (**Figure 32**). Solar resource data for the GOM was sourced from the NASA surface meteorology and Solar Energy (SSE) dataset (NASA 2008).

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[14] Not considered in this analysis is the use of commercially-available concentrating PV modules which have demonstrated efficiencies of 20–26%.

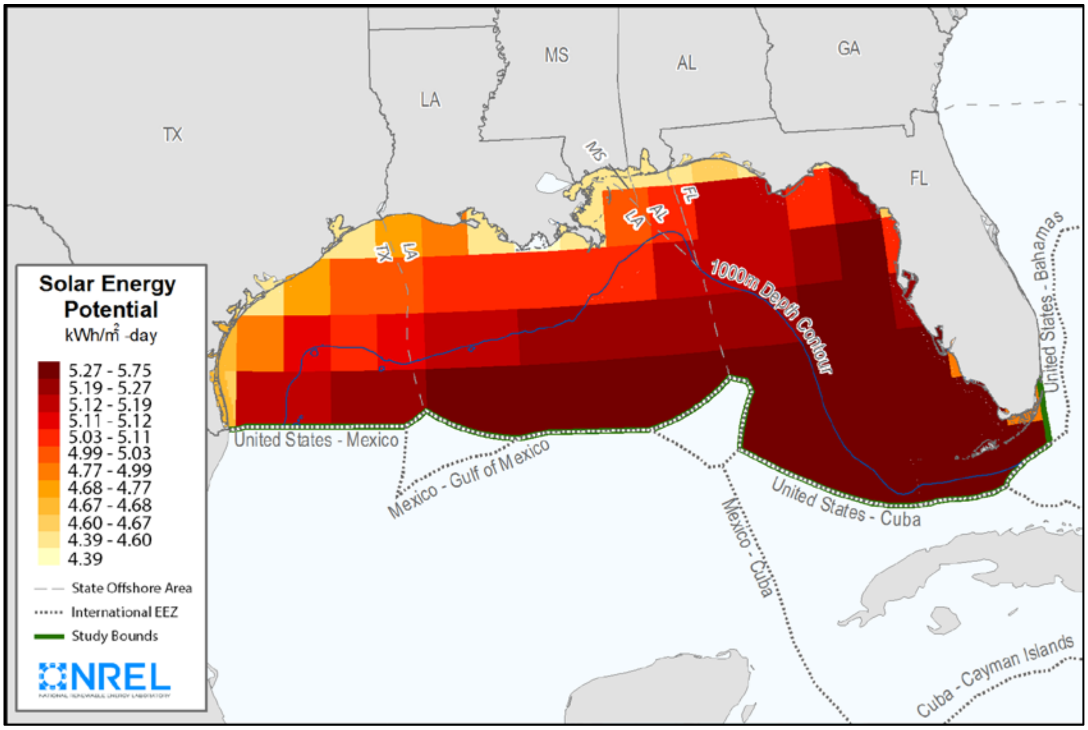

Figure 32. Gross long term average GOM horizontal solar radiation resource.
Solar Insolation Data Source: NASA (2008).

2.5.2.2 Offshore Solar Energy Technical Resource Potential

The technical resource potential of offshore PV captures the subset of gross offshore PV resource potential that can be considered recoverable using available technology within reasonable limits. It considers the technical limits of offshore PV, including conflicting use, environmental constraints, and technology limits.

Generally, technology exclusions are applied to the gross resource potential to restrict the resource area to geographic locations suitable for the technology based on industry experience to date. Because the floating solar industry is still in its infancy, exact technology specific exclusions are not yet available for floating PV but it is expected that siting will gradually expand to locations with more challenging physical conditions as industry experience grows. From NREL’s assessment, the primary technology limitation for ocean-based solar is wave loading in extreme sea states. An offshore solar array must be designed to withstand the extreme weather events and resulting loads where it is deployed as the possibility of furling the panels under extreme conditions is limited. Designing solar support-structures to survive extreme wind and wave events will drive system cost up rapidly and may prove to be cost prohibitive in areas some areas. Existing floating solar installations in Japan have been designed for cyclonic winds and 1 m extreme wave heights. This 1 m wave height design threshold was initially considered for a baseline. However, in such a nascent industry as offshore solar, we considered this design constraint to be too conservative for a technology resource threshold, given the potential for maturation without requiring any significant technology breakthrough. As such, we chose an arbitrary threshold of 3 m (9.8 ft) for this study; however, it is recommended that this threshold be examined more carefully as the industry gains experience.

Statistics for GOM extreme wave heights have been estimated by the American Petroleum Institute (API) (2007). It was estimated that all open ocean locations in the GOM have maximum wave heights much greater than 3 m (9.8 ft), with 3 s wind gust values over 55 m/s (123 mph) for a 100-year return period. The western region in general has the lowest values for maximum wave heights in the GOM, varying from 6.5 to 9.8 m (21.3 to 32.1 ft) for 10 year and 100 year return periods, respectively (API 2007).

Based on the 3 m (9.8 ft) extreme wave height criterion, we estimate that there is currently 0 MW of technical potential for offshore solar in federal waters of the GOM. Determining the associated costs for floating solar technologies under extreme wind and wave conditions is beyond the scope of this study because such technology does not exist yet. However, with any new technology, research and development may considerably change the site suitability of this technology. Currently, the leading developer and installer of floating solar does not recommend installing floating solar arrays in saltwater or ocean environments due to extreme waves. The best potential for ocean-based solar may be over more sheltered bodies of water that are found in state waters but estimating the magnitude of extreme wave events for these areas was beyond the scope of this study. As the potential resource for near-shore solar may be large, it is recommended that ocean based solar in sheltered bays and enclosed inland lakes be the subject of future resource and technology studies in GOM states.

2.5.3 Offshore Solar Energy Technical Readiness

Floating solar has typically been deployed in enclosed bodies of water near developed areas where land is in high demand with easy access to load centers. The deployment of floating solar systems in the open ocean is a significantly more challenging technology step, which resulted in a lower value assessment of the readiness level for offshore solar technology in this study. Generally, there are no insurmountable technological barriers to the advancement of floating solar technologies into deeper water with larger wave extremes. However, it is unknown how the system cost and reliability would be impacted for designs capable of surviving larger wave and wind events.

2.5.4 Offshore Solar Energy Economics

Recently installed floating solar systems (MW scale) on inland reservoirs in California cost $1.7–1.8/W (Ciel & Terre 2016). This cost is similar to many ground-mounted solar arrays and may represent a large technical and economic potential for existing reservoirs, waste water treatment plants, or areas where land is costly or unavailable. Deploying a floating solar array offshore will likely have significantly increased costs due to the need to design the arrays to withstand much stronger wind and wave loads but not cost data were available for this study.

2.5.5 Offshore Solar Energy Summary

Due to the extreme wave events in the GOM, ocean-based solar is not likely to be cost effective in the open ocean or any body of water that is not significantly sheltered from extreme weather events. Floating PV technology is relatively new and current industry experience has been mostly limited to small bodies of water where adjacent land area is more expensive.

There may be potential for fixed bottom PV to be installed in sheltered bays or semi-enclosed bodies of water where extreme wave heights are much lower. Extreme wave height estimates in bays or other sheltered areas must take into account the interaction with hurricane winds, rainfall, extreme wind direction, fetch, and surge. Future solar developers may find sheltered sites where support structures can be designed to withstand the extreme wave conditions. It is recommended that further study of technology and resource of ocean based solar in sheltered bays and enclosed inland lakes be conducted in GOM state waters.

2.6 Ocean Thermal Energy Conversion (OTEC)

Ocean thermal energy conversion (OTEC) technology converts solar energy stored in the thermal layers of the tropical and subtropical oceans. Thermal heat engines use the temperature difference between the sun-warmed surface water and cold water in the deep ocean. This technology requires the movement of large volumes of water to convert a small portion of the available energy, yielding about 2.5%–3.0% of stored solar energy as net power after pumping and other power requirements are met (Avery 1994). Because the gross potential resource is large, OTEC could potentially provide substantial amounts of carbon-neutral baseload power. Under funding from DOE, open-cycle OTEC was successfully demonstrated with positive net energy production (up to 103 kW from 255 kW gross) from 1993 to 1998 at the Natural Energy Laboratory of Hawaii Authority (NELHA) facility at Keahole Point on the island of Hawaii (SERI 1989). OTEC has significant gross and technical potential in the GOM but remoteness of the resource, cost, logistics and environmental concerns may present significant challenges to initial implementation.

2.6.1 OTEC Description

The deeper tropical and subtropical oceans have steep temperature depth gradients, with warm water overlying cold deeper water. The temperature difference between surface waters and deeper water can reach over 25 ˚C in summer months, although usually this temperature difference exists only over water with depths of 1,000 m or greater. However, there are some places in the world with high thermal gradients, such as in the Florida Straits where these temperature differentials can be reached at depths less than 300 m.

OTEC systems use the temperature difference between warm surface water and cold-deep water to generate electricity. OTEC systems were first envisioned in the 1880s with the first proof of concept demonstration project built in Cuba in 1930. Presently, the 100 kW OTEC facility on Kume Island, Okinawa, Japan is the only operational OTEC facility in the world and is considered a sub-scale demonstration project. Commercial-scale OTEC facilities would probably require a capacity of approximately 100 MW to achieve minimum plant cost according to industry scaling studies (Ascari et al. 2012). To date, there have been no commercial scale systems built.

Many different OTEC archetypes have been investigated; some on floating offshore platforms and some built onshore with pipelines to transport the water to and from the ocean (Vega 2016; Meyer et al. 2011; Avery and Wu 1994). Each system uses one or a combination of thermodynamic processes to turn the temperature difference into mechanical energy.

The closed-Rankine cycle is an example of a closed-cycle OTEC system (Ascari et al. 2012; **Figure 33**). Warm water is pumped from near the surface and used to heat a working fluid, such as ammonia, which vaporizes at a low temperature. The vapor expands and drives a turbine as it passes from the hot to the cold side where it condenses using cold water pumped from the deep ocean. Both the warm and cold water supply must be sufficient to supply the large volumes needed by an OTEC plant. Based on the Lockheed 100 MW conceptual OTEC plant design, to produce approximately 1 GW (ten 100 MW plants), a combined flow rate of 8,260 m^3/s is needed, or about half the flow of the Mississippi River at New Orleans (Ascari et al. 2012).

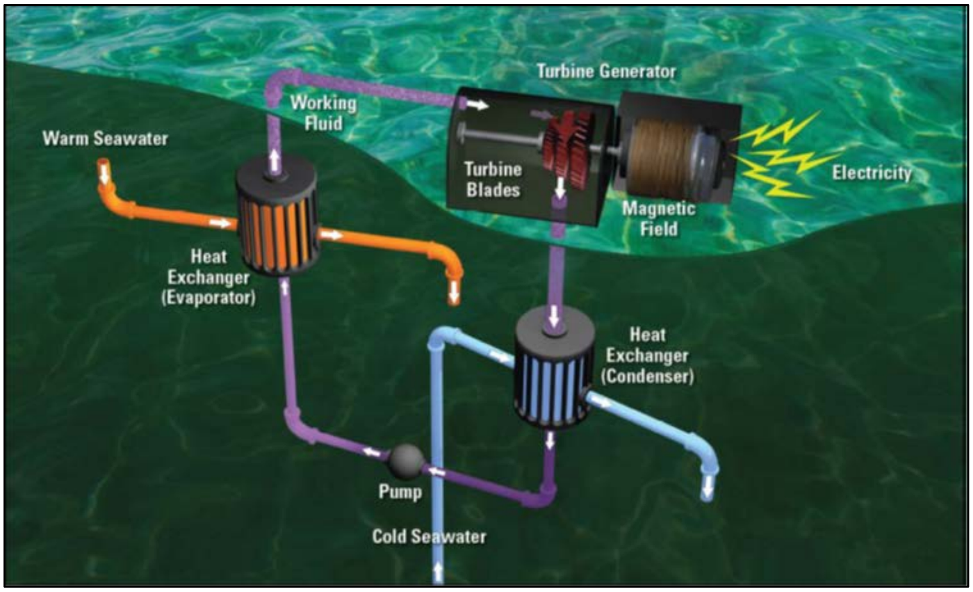

Figure 33. OTEC example schematic.
Source: Ascari et al. (2012)

OTEC systems can be classified as closed cycle or open cycle systems (**Figure 34)**. The open-cycle system pumps warm sea water into a low pressure chamber where it vaporizes, expands through a turbine, and condenses on the cold side. In contrast, the closed cycle system pumps the warm sea water through a heat exchanger to warm the working fluid. Both the open-cycle and closed-cycle plants use cold water pumped from the deep ocean to condense the working fluid. An ancillary benefit is that the condensate is freshwater that can have other uses such as agriculture and potable drinking water.

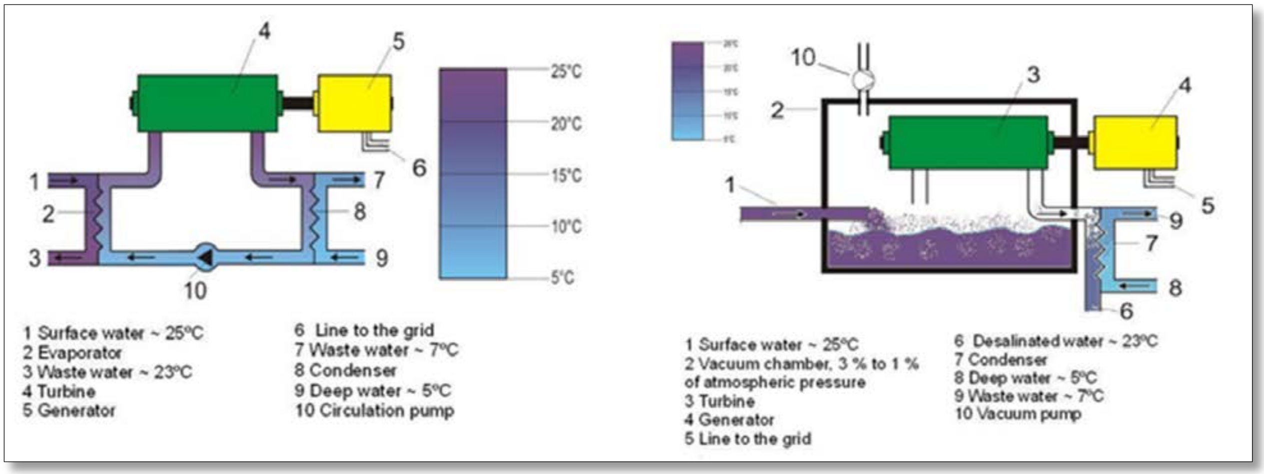

Figure 34. Schematics of closed-cycle (left) and pen-cycle (right) OTEC systems.
Source: Wikipedia (2018).

2.6.2 OTEC Resource Potential

OTEC resource quality depends primarily on water temperature differences in the water column, but also on the availability of both warm and cold sources, often determined by the rate of replenishment at the plant location via local ocean currents. Thermal differences that are higher than 18˚C (64°F) are considered suitable for OTEC, with optimal differences of around 25˚C (77°F) or higher. OTEC plants require access to both a large volume of warm surface water that is at least 22˚C (72°F) and a cold deep water source (Ascari et al. 2012; Avery and Wu 1994). Within the GOM, average annual temperature differences of at least 20˚C (68°F) are readily found but tend to be far offshore in water depths that are typically greater than 1,000 m (3,281 ft) (Avery and Wu 1994; National Research Council 2013).

The gross OTEC resource in the GOM can be approximated by calculating the area where there is sufficient thermal difference between the surface water and the deeper water and multiplying this area by a maximum power extraction density. The GOM ocean thermal energy resource with a temperature differential of 18 ˚C (64.4°F) or greater was calculated to have a gross resource area of 321,600 km^2 (79,469,091 ac) (**Figure 35**). This density was estimated to be 0.19 MW/km^2 (Avery and Chih 1994). This results in a gross OTEC resource potential of 61.1 GW.

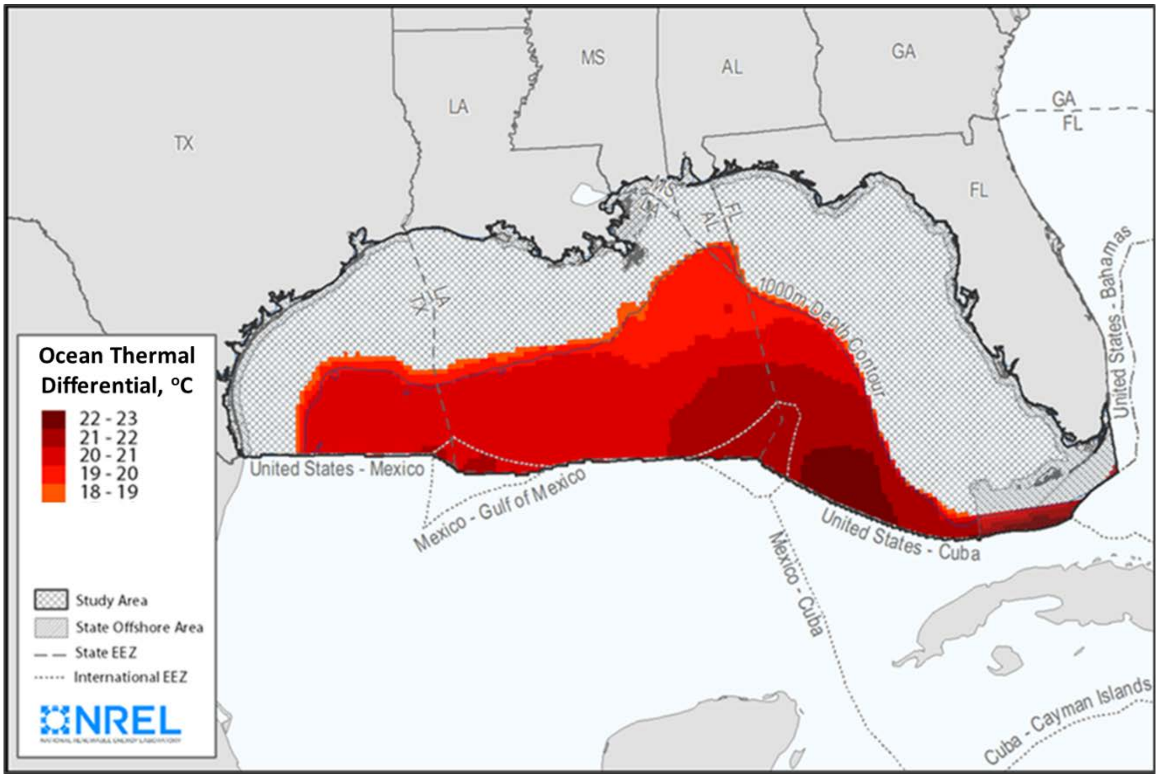

Figure 35. Ocean thermal energy gross and technical resource showing 321,600 km^2 area where temperature differential is 18˚C (64.4°F) or more.

The technical resource potential has the same resource area as shown in Figure 35 but is further limited by two factors: 1) the supply of cold water to and from the GOM, and 2) the local currents in the OTEC resource area. The replenishment rate of the cold water reservoir is limited by the flow rate of cold water into and out of the GOM through the Yucatan Channel and the Florida Straits, respectively. The technical resource potential would also be limited by large warm water discharge rates from the OTEC plants diluting the local cold water resource, which would require significant spacing between adjacent plants. Local currents within the gross resource area are typically small, except for transient phenomena, such as eddies spun off from the Loop Current. Conservatively, water current speeds between 0.1 and 0.5 m/s (.2 and 1 mph) may be available to disperse the warm water discharge from the plant. Assuming the Lockheed Martin 100 MW design was used, plant spacing in the GOM would be limited to approximately 50 km (31 mi) (Ascari et al. 2012). Taking these limitations into account, we estimate the maximum technical potential for OTEC in the GOM to be 8.1 GW. However, this value may be optimistic; studies by the National Research Council found reduced thermal gradients during winter months in the GOM that may further limit the OTEC resource (National Research Council 2013).

2.6.3 OTEC Technical Readiness

OTEC is not a new concept, but it has yet to be demonstrated at commercial scale. Several subscale plants have been built to demonstrate the principles, including:

- 100 kW OTEC facility presently operating on Kume Island, Okinawa, Japan
- 210 kW Open Cycle OTEC experimental apparatus which operated in Hawaii from 1993 to 1998
- 100 kW closed-cycle OTEC plant on the island of Nauru, Japan which operated from 1981 to 1982
- 50 kW Mini-OTEC plant offshore Hawaii which had a gross production of 50 KW and a net yield of 15 KW in 1979 (Rafferty and Mero 2011)

Because a commercial scale plant has not been built, key design components such as the cold water pipe and the large volume heat exchangers have not been developed or validated at full scale.

In the GOM, 20˚C (68°F) temperature differentials, sufficient for an OTEC plant to operate, exist in water depths mostly greater than 1,000 m (3,281 ft); therefore OTEC plants will need to be built on floating platforms, moored and anchored to the seabed. A large vertical cold water pipe will be needed to bring water up to the platform. This cold water pipe poses a difficult challenge as it is very large and expensive and may be susceptible to damage from extreme lateral currents.

Though currents in the GOM are small on average, floating OTEC platforms placed in the Loop Current or Florida Current would intermittently experience current velocities in the range up to 2.5 m/s (5.6 mph) or greater which is perhaps one of the greatest technology challenges for OTEC in the GOM. In the Florida Keys, cold water is located closer to shore and in shallower water which may possibly enable shore-based OTEC facilities. However, in these areas, the large discharge must be carefully considered, first to avoid impacting the quasi-stable baroclinic structure of the offshore waters which could potentially disturb the path of the Florida Current. Second, the large discharge water volume can potentially contaminate the local warm and cold water resources. Finally, there may also be ecological and/or biological concerns about de-stratifying thermal layers if large enough volumes of cold water are pumped from the bottom of the ocean.

Mooring an OTEC facility in water depths greater than 1,000 m (3,281 ft) is feasible, though it adds cost when depth increases, but the bigger challenge is the cost of bringing the power to shore. Most of the potential OTEC sites are located far from shore (50 to 200 nm) and would require a significant grid export system. The technology for this exists but the cost would be significant, especially at the 100 MW scale or less.

2.6.4 OTEC Economics

Recent OTEC cost studies have been performed for floating plants and all studies have concluded that the cost of power strongly improves with plant size (Vega 2016; Ascari et al. 2012). The studies suggest that a 100 MW plant size may be optimum with an estimated LCOE of between $0.14 and 0.20/kWh. For smaller plants, approximately10 MW size, LCOE doubles and is estimated to be between $0.35 and 0.45/kWh (Vega 2016). These studies however, assumed the OTEC plant was relatively close to shore (0 km), and that the transmission export cable accounted for approximately 10% of the total capital costs. In the GOM, with sites nominally 50 to 200 nm offshore, higher LCOEs would be likely. No cost studies have been performed for land-based OTEC plants within the last 25 years. However, earlier studies indicate that for a very near shore cold water source, the LCOE would be $0.98/kWh for a 10 MW plant when adjusted for inflation (Vega 1992). A side product of some OTEC cycles is the production of fresh water which can be used to augment revenue streams.

2.6.5 OTEC Summary

The OTEC processes have been demonstrated for sub-scale systems (50 to 200 kW) during several multi-year deployments, but no full-scale systems (50 to 100 MW) have been deployed to demonstrate the efficiencies, reliability and costs. Because the development pace is slow and the resource in the GOM is marginal in the winter and located relatively far from shore, the cost of energy would be higher in the GOM relative to sites where OTEC demonstrations have already occurred. There are many sites within the US with better resource and higher costs of electricity that are more suitable for OTEC development. These locations include Hawaii, the Mariana Islands (including Guam), Puerto Rico, and the US Virgin Islands (National Research Council 2013). Based on the nascent stage of the global industry, higher regional costs, marginal resource quality, and site-specific issues, it is unlikely that OTEC will be deployed in the GOM in the foreseeable future.

2.7 Cold Water Source Cooling

Cold water source cooling is not an energy source, but it can enable significant energy savings by providing cooling, primarily for regions with high air conditioning loads. It is considered a potentially viable option if cold water from the ocean exists in close proximity to large load centers. Unlike OTEC, cold water source cooling requires only a cold water source, it does not need a thermal gradient. Its economics are largely determined by the infrastructure cost needed for implementation, which are difficult to obtain for a generic application. Because of the high thermal capacity of water, cold ocean water has the potential to reduce energy demands of cooling processes in commercial and industrial applications, especially in populated regions of the GOM where air conditioning is a primary load.

2.7.1 Cold Water Source Cooling Technology Description

Cold water source cooling uses cold water in the chiller of an air conditioning (A/C) system instead of an electricity-driven compressor (**Figures 36 and 37)**. Using cold water reduces the electricity use of A/C systems by up to 85% to 90% (Makai 2017). This provides a significant benefit because electricity used in A/C is often from periods of peak generation and is the highest cost.

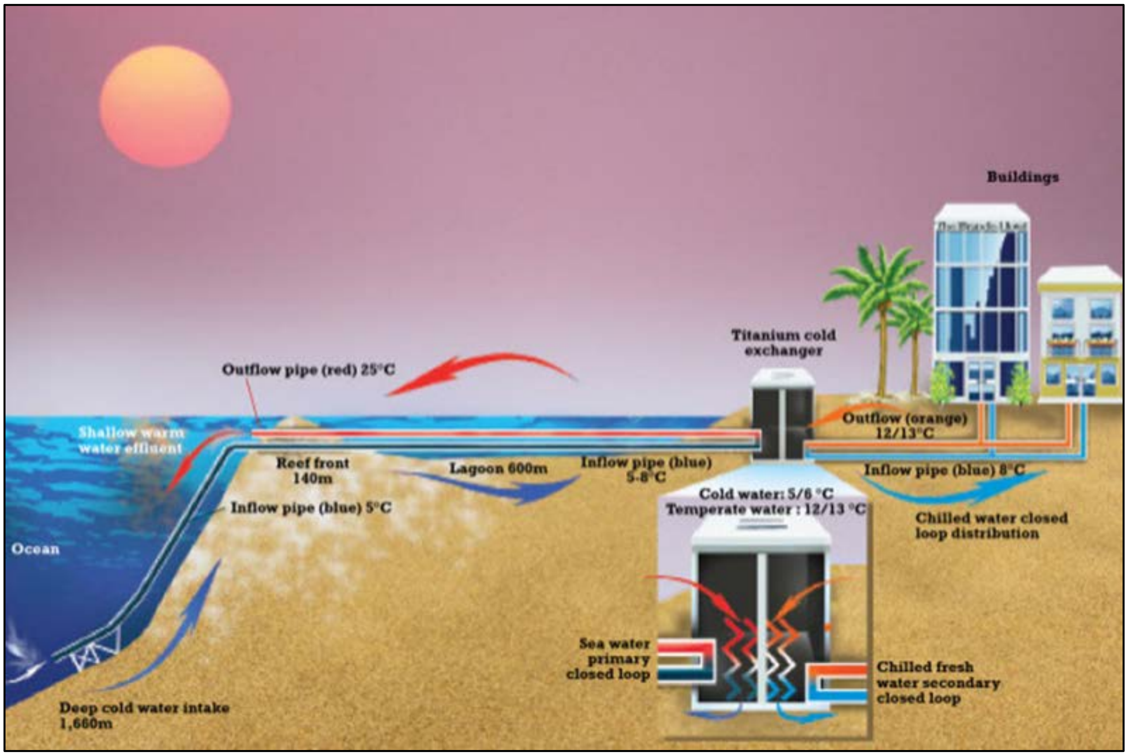

Figure 36. Cold water source cooling diagram.
Source: IRENA (2014)

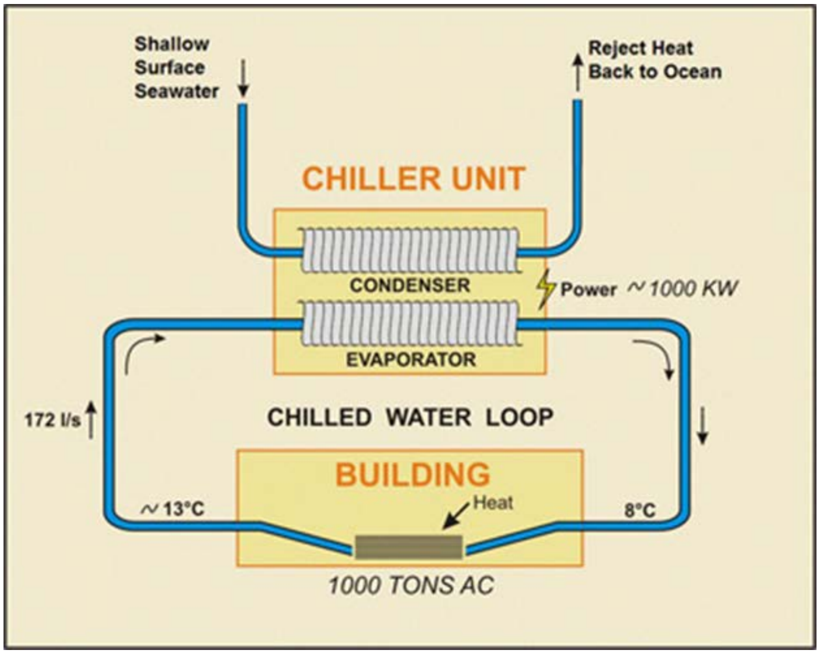

Figure 37. Cold water source cooling schematic.
Source: Makai 2017

The most effective form of cold water source cooling is district cooling. District cooling is much like district heating, but rather than having a central source of heat, a central source of cold is used to chill a cooling fluid. This cooling fluid is then circulated among buildings and is used for air conditioning (War 2011; Makai 2017). For this to work, cold-water is pumped from ocean sources that are usually deeper than 300 m and brought to shore. A general threshold is that seawater sources can be as warm as 8˚C (46.4°F) (Ascari et al. 2012; Makai 2017), but colder water sources yield higher efficiency and require less water.

It is also worth noting that the chiller efficiency for an A/C system is related to the temperature of the ambient sink to which the heat from the hot refrigerant is dumped. This is typically air or an evaporative cooling tower. Cooler water near shore can thus be used to increase the efficiency of conventional A/C systems with gains between 10 and 25% (personal correspondence with Makai Ocean Engineering).

2.7.2 Cold Water Source Cooling Resource Potential

Ocean surface water flows into the polar regions, cools and becomes more saline as ice is formed and water evaporates. This denser water sinks to the deep basins of the ocean and slowly flows towards the equator. Unlike fresh water that has a maximum density at 4˚C (39.2°F), sea water maximum density occurs at its freezing point of -1.8˚C (28.8°F); thus, cold water is found in all deep water areas of the oceans.

The GOM has a large volume of cold water which is continually replenished by the cold deep water flowing in from the Yucatan Channel. Cold water is also found in the Straits of Florida, which is in shallower water and closer to shore because of the baroclinic-barotropic structure under the Florida Current.

The GOM holds an enormous volume of cold water that is suitable for cold water air conditioning that is less than 8˚C (46.4°F). Though the cold waters in the GOM have the potential to meet much of the A/C cooling requirements of the large coastal load centers, the distance from shore to the cold water source is generally too far to feasibly transport the cold water using present technologies. The locations of cold water below 8˚C (46.4°F) in the GOM were determined (**Figure 38**; NREL 2017b). These are computer modeled data that have not been validated, but the general trend shows that significant cold water resources are not present until depths of at least 300 m (984 ft). These locations are further from shore than is practical for transport to shore due to the cost of the piping systems as well as the unwanted heat transfer that would raise the temperature of the water before it reached the load unless special pipe insulation was used.

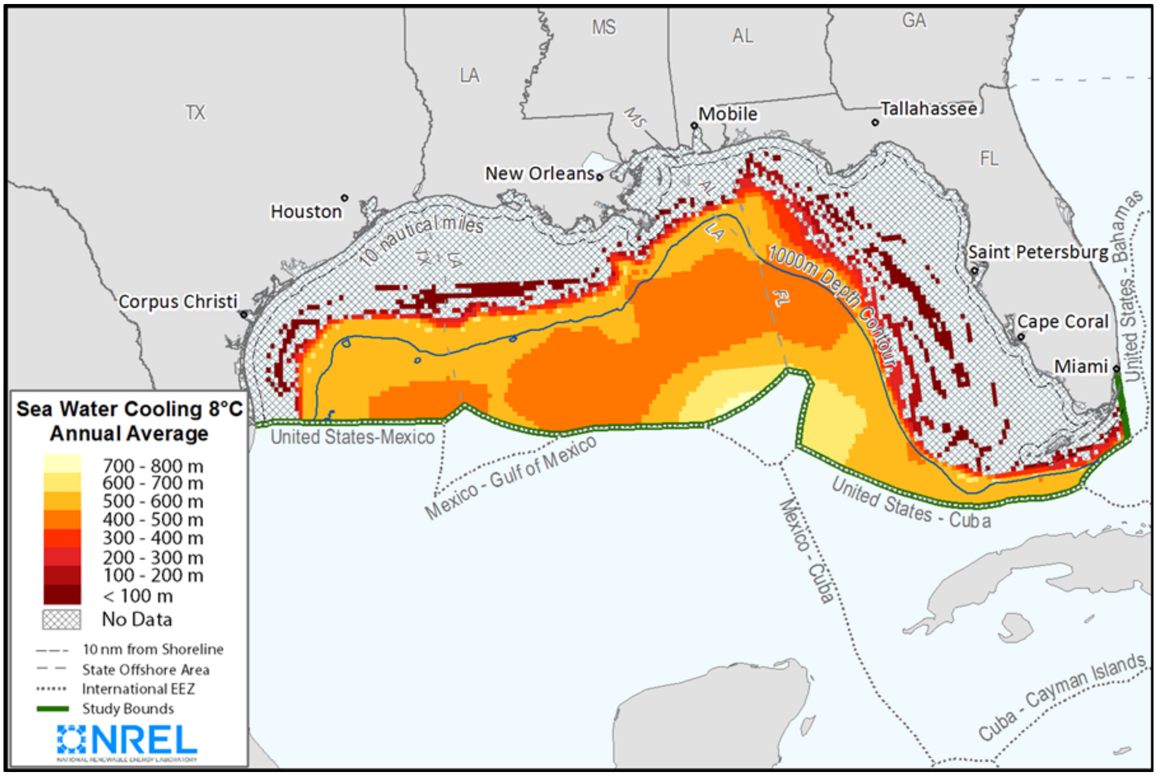

Figure 38. Locations of cold water resource (<8˚C [46.4°F]) in the GOM averaged over a typical year.

2.7.3 Cold Water Source Cooling Technical Readiness

Cold water source cooling systems are not common, but they have been implemented in several commercial applications, including

- City of Stockholm (>100,000 tons[15]),
- City of Toronto (75,000 tons),
- Cornell University (20,000 tons),
- Purdy’s Warf, Nova Scotia (1,000 tons),
- Intercontinental Hotel, Bora Bora (450 tons)
- Natural Energy Laboratory of Hawaii Authority (50 tons)

Though there are no large technical risks in cold water source cooling, the primary technology hurdle within the GOM is developing a low cost offshore pipe that can transport water to shore with minimal heat transfer to the cold water and low power pumping.

2.7.4 Cold Water Source Cooling Economics

In the states that border the GOM, a large proportion of the electricity use goes to air conditioning. For example, the percent of electricity used for air conditioning, based on an annual average in the residential sector is up to 27% (EIA 2009). On a seasonal basis, this number is much higher in the summer when air conditioning use is the greatest. Also, it is often the most expensive electricity (peak generation) that

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[15] Ton is a standard term used in air conditioning to rate A/C units. It is a measure of how much heat the system can remove and relative to how much ice it would take to accomplish that same impact.See https://www.energyvanguard.com/blog/55629/Why-Is-Air-Conditioner-Capacity-Measured-in-Tons.

supplies air conditioning. Replacing or increasing the efficiency of conventional electricity-based A/C systems has the potential to significantly reduce energy use along the GOM. However, the primary costs of a cold water source cooling system are in the pipe used to transport the water to shore, pumping system and the cold water distribution system.

Favorable economics for cold water source cooling depend on the following factors:

1. A source of cold water close to shore, ideally within 10 km,
2. A concentrated air conditioning load (e.g., dense city core) near the source, and
3. High electricity costs.

When the cold water source is close to shore (within 10km), the heat exchanger and pumping stations can be located on shore where they are easier to install and service, with minimal heating of the cold water as it is brought to shore. For further offshore installations, costs will increase due to the need for larger diameter pipes and intermediate underwater pump stations, both major cost drivers. Additionally, heat gain through long runs of pipe through warm water can be significant. For these reasons, cold water source cooling systems have not been considered when an intake pipe exceeds 10 km (6.2 mi) (personal correspondence with Makai Ocean Engineering). For new installations, the trenching and tunneling work to run pipes can be very expensive if infrastructure does not already exist.

2.7.5 Cold Water Source Cooling Summary

Cold water source cooling has potential to offset electricity used for air conditioning in some areas of the GOM. In most locations, the cold water resources are generally too far from shore to economically transport (i.e., pipe and pumping costs) while maintaining the cold temperature. In addition, the cost of upgrading the infrastructure within the large urban areas to install a cold water distribution system would be high. Thus, cold water source cooling systems will not likely be a suitable option in most GOM locations. For the GOM, the best opportunity for cold source cooling is in the outer Florida Keys, where the deeper cold water entering the Florida straits might be close enough to warrant further investigation.

2.8 Hydrogen Conversion and Storage

Hydrogen (H_2) is an environmentally clean energy medium that can be created to store energy. As a stored fuel it can be used to manufacture other chemical commodities, power fuel cell vehicles, or generate electricity. Hydrogen produced by an integrated offshore wind-electrolyzer system could be moved to shore by ship or pipe, either newly laid pipe or possibly by injection into existing underwater natural gas infrastructure. It is estimated that the GOM has approximately 13,135 mi (21,139 km) of active natural gas pipelines in federal waters. There are also more than 15,000 mi (24,140 km) of abandoned pipeline that could be potentially leveraged to transport hydrogen to shore (Bureau of Safety and Environmental Enforcement [BSEE] 2018). However, use of existing pipelines could be hindered by embrittlement due to the flow of hydrogen, unless a means is found for first treating the pipelines. If use of existing pipelines was not deemed feasible, new pipelines could also potentially be laid for transporting the produced hydrogen, and likely at a lower cost than laying subsea cables for transporting electricity.

The primary purpose of this section is to evaluate the technical and economic viability of integrating an electrolyzer into an offshore wind system in the GOM that leverages existing oil and gas pipeline infrastructure to transport hydrogen to onshore markets. Specifically, it focuses on the economic trade-off between producing hydrogen offshore through electrolysis and transporting it to shore using the existing undersea pipeline infrastructure, and the conventional method of transporting offshore electricity from each wind turbine to shore by undersea cables.

2.8.1 Hydrogen Conversion and Storage Technology Description

Electrolysis is the process of using electricity to split water molecules into hydrogen and oxygen molecules in an electrochemical unit called an electrolyzer, which is made up of an anode and a cathode separated by an electrolyte (**Figure 39)**. Assuming the electrolyte is pure water, when electricity is passed through the electrodes, the water molecules split causing the positively charged hydrogen ions to travel towards the negative cathode to combine into hydrogen gas and the negative oxygen ions to gravitate towards the positive anode recombining to form oxygen gas. When powered by electricity from offshore wind, an electrolyzer will produce hydrogen without emitting any greenhouse gases. Other hydrogen production processes (i.e., thermochemical, direct solar water splitting, and biologically produced) are not considered because they are technically and/or economically impractical to install in an offshore setting.

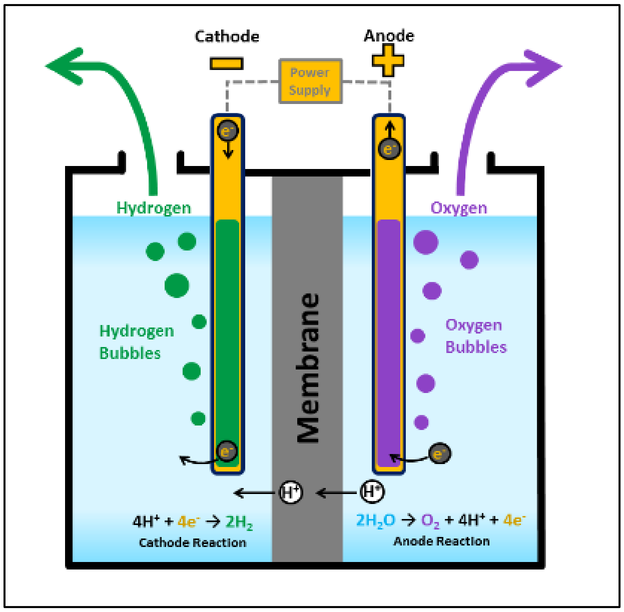

Figure 39. Overview of proton exchange membrane electrolyzer.
Source: DOE, Fuel Cell Technologies Office

The two main categories of electrolyzers are High Temperature Electrolyzers (HTE) and Low Temperature Electrolyzers (LTE).

- An HTE, like a solid oxide electrolysis cell, requires an additional heating system to turn the water into steam, thus adding additional capital costs and system complexity to a hypothetical integrated offshore wind-electrolyzer system.
- Alkaline electrolyzers and proton exchange membrane (PEM) electrolyzers are the two most common LTEs used in the hydrogen market today. Alkaline electrolyzers have been commercially available for decades but require a potassium hydroxide electrolyte that needs to be transported and stored offshore, making this technology less than optimal for offshore applications (Meier 2014). PEM electrolysis cells require only water as an electrolyte and are compatible with intermittent power flows from renewable electricity sources, potentially making them the most practical choice for offshore applications. Siemens has commercially deployed a 6 MW PEM electrolyzer at Energiepark Mainz in Germany powered by wind energy (Siemens 2015).

2.8.2 Hydrogen Conversion and Storage Resource Potential

The two main feedstocks required for electrolysis are water and electricity. The GOM has a plentiful supply of salt water. However, electrolysis using ocean water has only been conducted at laboratory scale (Abdel-Aal et al. 2010). Existing commercial electrolyzer technologies require purified water. In an offshore setting, this requires installing a desalination system that will add capital costs and require periodic disposal of salt and other contaminants. Based on the resource assessment in Musial et al (2016) NREL estimates that the GOM has the net technical potential[16] to generate 1,556 TWh/yr using offshore wind technology, equivalent to approximately 25% of the U.S.'s net technical offshore wind potential. Assuming Ruth et al.'s (2017) estimate that a low temperature electrolyzer requires 50.2 kWh[17] to produce one kilogram (kg) of hydrogen and operates at 66% efficiency[18] , the GOM's technical offshore wind resource has the potential to produce approximately 23.7 billion kg H_2/yr[19].

2.8.3 Hydrogen Conversion and Storage Technical Readiness

Electrolytic hydrogen production faces four main technical risks in an offshore setting:

1. **Hydrogen conversion efficiency and system economics**: Energy conversion losses associated with the production and storage of hydrogen most likely cost more than the cost of the electrical grid infrastructure that is avoided. This is the primary disadvantage to hydrogen conversion and storage. A conventional offshore wind system experiences losses converting wind energy into mechanical energy, converting mechanical energy into electrical energy, and transporting electrical energy over distance. In total, losses due to electrical transmission from offshore wind turbines are about 3.4% of total power production (Moné et al. 2017). In a scenario where an electrolyzer replaces an offshore wind system's electrical substation and export infrastructure, these electrical losses would be eliminated. However, overall energy losses increase to about 33% in converting the electricity to hydrogen. In a typical offshore wind plant, the electrical infrastructure comprises approximately 20% of the total capital cost but all the revenue is made from the energy sold. Without accounting for the added cost of the electrolyzers, a rough assessment indicates that a loss of over 25% of the energy revenue could not be recovered by the savings gained by avoiding the grid infrastructure.
2. **Cost and maturity of electrolyzer technologies**: Electrolyzer technologies are relatively nascent, are just beginning to be commercially deployed at scales larger than one megawatt and have only been deployed on land. Manufacturers are still searching to find optimal electrolyzer materials and configurations for different types of commercial applications. This technological uncertainty and a lack of large-scale deployment means that electrolyzer costs are still significantly higher than conventional hydrogen production techniques like steam methane reformation (SMR), which uses a series of chemical reactions to split methane molecules into hydrogen and carbon dioxide. Because the offshore environment is more demanding to operate in, an offshore electrolyzer would need to be built to a higher standard, demand more maintenance, and require novel materials and subsystems all of which would substantially increase the system's overall capital and operating costs. The potential added costs and technological requirements of an offshore electrolyzer decrease the probability of cost effectiveness when married to an offshore wind turbine, because the electrolyzer, hydrogen storage, and hydrogen transport mechanism would have to cost less than the offshore wind

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[16] Net technical offshore wind energy potential refers to the total amount of electricity that could be generated from offshore turbines given technical and siting limitations.

[17] This energy consumption estimate uses a low temperature electrolyzer and is based on DOE's H2A Production Analyses.

[18] Electrolyzer efficiency is highly dependent on a number of factors. Future PEM electrolyzer technologies could experience efficiencies of up to 80% (Harrison et al. 2009).

[19] Note that this estimate is hypothetical and does not include constraints on the number, size, or operational characteristics of a potential electrolyzer deployed in the GOM.

system’s electrical substation and electrical cable infrastructure, in addition to gaining significantly in conversion efficiency.

3. **The transport and storage of hydrogen**: In the GOM, hydrogen produced offshore will have to be transported to markets onshore via specialized transport vessels or pipelines. Moving hydrogen by ship is technically challenging and potentially very costly. The vessel would require specialized compression and refrigeration subsystems to prepare hydrogen molecules for transport and no such vessel yet exists. If treated first for embrittlement by hydrogen, using the GOM’s substantial existing undersea pipeline infrastructure could provide significant cost savings and offset an electrolyzer’s substantial capital costs. While many assume that blending low concentrations of hydrogen into natural gas pipelines with methane is safe, it requires additional downstream separation technologies to separate the hydrogen from the methane on land (Melanina et al. 2013). Using existing pipeline infrastructure to move pure hydrogen is untested and presents unique economic and safety concerns caused by hydrogen molecules’ small size and increased propensity to leak out of standard pipes and seals (Pellow et al. 2015). To avoid the potential complications of using existing undersea pipeline infrastructure, specialized pipes and seals that can handle higher pressures and other tolerances could be used but would make the project uneconomical. Connecting an offshore hydrogen production system with existing pipeline infrastructure is unproven and would require additional engineering and safety assessments.

2.8.4 Hydrogen Conversion and Storage Economics

There is significant uncertainty surrounding future hydrogen markets, prices, and costs. Furthermore, it is extremely difficult to accurately predict the future costs of a large integrated offshore wind-electrolyzer system because no large-scale electrolyzers or offshore systems have ever been deployed. Meier (2014) estimated the costs of deploying either an HTE or LTE powered by offshore wind in Norwegian waters and found that neither system would be profitable under any of the scenarios considered, even excluding transportation costs (**Table 9**). The study found that the above-surface platform for the electrolyzer, desalination subsystem, and a potential steam generation subsystem dramatically increased the system’s capital costs.

Table 9. Base Case Economics of an Offshore Wind-Powered Electrolyzer

Type pf Electrolyzer	Electrolyzer Size	Price/kg H_2	Total Investment Cost
HTE	100 MW	18.85 €	641 million €
LTE (PEM)	100 MW	20.61 €	716 million €

In a best case scenario, the costs for onshore electrolyzers could be transported to an offshore setting. Ruth et al. (2017) conducted a techno-economic analysis of onshore integrated energy systems producing hydrogen in Texas using modeled electrolyzers and SMR using DOE’s H2A Production Analyses (**Table 10**).

Table 10. Modeled Hydrogen Production Costs Without Transport Costs

Technology	Plant Capacity	Capital Costs[20]	Fixed O&M Costs[21] per year	Electricity Requirement	Thermal Energy Requirement[22]	Price/kg H_2
HTE	50,000 kg H_2/day	$662/kW	$58.69/kW	35.1 kWh/kg H_2	11.15 kWh/kg H_2	$3.09
LTE	50,000 kg H_2/day	$616/kW	$42.73/kW	50.2 kWh/kg H_2	N/A	$3.87
SMR	379,387 kg H_2/day	$429/kg H_2/day	$6,427,000	N/A	156,000 BTU/kg H_2	$1.47

Leveraging existing GOM infrastructure could reduce the cost of an integrated offshore wind electrolyzer system by removing the electrical subsystems[23] that move electricity to shore, saving roughly $397/kW for a fixed bottom system and $698/kW for a floating system.

While the electrolyzer costs modeled by Ruth et al. (2017) are significantly lower than offshore electrolyzer costs estimated by Meier (2014), both studies' electrolyzer cost estimates are at least twice as high as the cost of SMR, which currently produces 95% of hydrogen globally. NREL's H2@Scale research team estimated that existing electrolyzer costs will need to be reduced by approximately 75% and electricity costs reduced by 70% (Ruth et al. 2017) to become competitive with SMR. Therefore, electrolysis (conducted either onshore or offshore) will be economically uncompetitive for the foreseeable future if the primary purpose is to produce hydrogen and carbon pricing has not been implemented.

2.8.5 Hydrogen Conversion and Storage Summary

Current electrolyzer technologies have not been commercially scaled to absorb the electrical output of a commercial wind farm or designed to operate in offshore settings. The analysis did not find any application that would warrant the use of hydrogen in conjunction with a renewable energy system due to the following primary reasons:

- Even in an optimistic or best case scenario, hydrogen production using electrolysis is economically uncompetitive with hydrogen production technologies that use SMR.
- Replacing an offshore wind farm's electric substation and undersea cable infrastructure with an electrolyzer that feeds hydrogen into existing undersea pipeline infrastructure is less economically attractive. The added capital costs and energy conversion losses would likely decrease the system's revenue compared to selling electricity to shore via undersea cables.

For the foreseeable future, electrolytic hydrogen production in the GOM will remain challenging because of significant technical and economic obstacles.

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[20] All costs are reported in 2012 dollars because the uncertainty in the estimate is greater than the cost differential between years.

[21] Operation and Maintenance (O&M) costs include feedstock costs.

[22] Heat upgrading costs are not considered in Ruth et al. (2017)'s calculations.

[23] Moné et al. (2017) estimate that a 4.14 MW fixed bottom offshore wind plant's total CapEx is $4,615/kW with its electrical infrastructure equivalent to 8.6% of capital costs. A 4.14 MW floating offshore wind plant's total CapEx is $6,647/kW with its electrical infrastructure equivalent to roughly 10.5% of its capital costs.

3. Gulf of Mexico Offshore Renewable Energy Summaries

This section summarizes the findings from the individual offshore renewable energy technology assessments presented in Section 2. Section 3.1 describes each technology's gross and technical energy potential and identifies the geospatial and technical filters used for resource calculations. Section 3.2 provides an overview of each technology's readiness level. Section 3.3 identifies the levelized cost of energy (LCOE) ranges reported for each technology.

3.1 Resource Comparisons by Technology

In aggregate, we estimated the Gulf of Mexico (GOM) to have 87,752 GW of gross offshore renewable energy potential. When applying the technical and geospatial filters identified in **Table 11**, the GOM was estimated to have 517 gigawatts (GW) of technical offshore renewable energy potential in aggregate. Cold water source cooling and hydrogen conversion were not included in either the gross or technical potential calculations because neither technology generates energy.[24]

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[24] Neither cold source cooling nor hydrogen conversion are energy generation technologies. Cold source cooling is an efficiency technology that could potentially reduce the amount of energy that costal Gulf cities use to cool buildings. In this study hydrogen conversion merely converts the energy captured by offshore wind turbines into a different medium that could be potentially transported to shore using existing oil and gas undersea pipeline networks.

Table 11. Offshore Renewable Energy Resource Limit Criteria for the GOM

Technology	Gross Potential Criteria					Technical Potential Criteria					
	Max Distance from Shore (nm)	Max Water Depth (m)	Capacity Density (MW/km^2)	Gross Resource Area/Length (km^2 / km)	Gross Resource Capacity (GW)	Max Distance from Shore (nm)	Max Water Depth (m)	Resource Minimum	Technical Resource Area (km^2)	Max Wave Height	Technical Resource Capacity (GW)
Offshore wind	200	None	3	624,100	1,872	200	1,000	> 7 m/s (15.7 mph)	169,333	N/A	508
Wave energy	200	50m Isobath	50%	2,004 km	3.1	200	None	> 10 KW/m	0	N/A	0
Tidal energy	200	None	None	N/A	0.13	200	1,000	>500 W/m^2	N/A	N/A	0.06
Ocean current	200	None	None	715,100	3.6	200	1,000	>500 W/m^2	N/A	N/A	0.359
Offshore solar energy	200	None	120	715,100	85,812	200	1,000	N/A	0	3 m	0[25]
OTEC	200	None	0.19	321,600	61.1	200	None	> 18 °C Differential	321,600	N/A	8.1
Cold water source cooling	200	None	N/A	321,600	N/A	6	1,000	> 8 °C	0	N/A	N/A

nm: nautical mile; MW: megawatt

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[25] Though the technical potential reported in this chart is zero, there may be sites in protected bays in the GOM that could support offshore solar photovoltaic (PV) deployment.

A breakdown of the GOM's total gross and technical offshore renewable energy potential by technology resulted in a large range of values (**Figure 40**). Given this large range of values, it was necessary to use a log scale on the vertical axis to show values on one chart. In making this conversion, the resource numbers are shown in megawatts (MW). Note that 1 GW equals 1,000 MW. In terms of gross energy potential, the analysis estimated that offshore wind has 1,872 GW, wave energy has 3.1 GW, tidal energy has 0.13 GW, ocean current has 3.6 GW, offshore PV has 85,812 GW, and OTEC has 61.1 GW. After applying the constraints from Table 11, offshore wind has a technical potential of 508 GW, wave energy has 0 GW, tidal energy has 0.086 GW, ocean current has 0.358 GW, offshore PV has 0 GW, and OTEC has 8.1 GW.

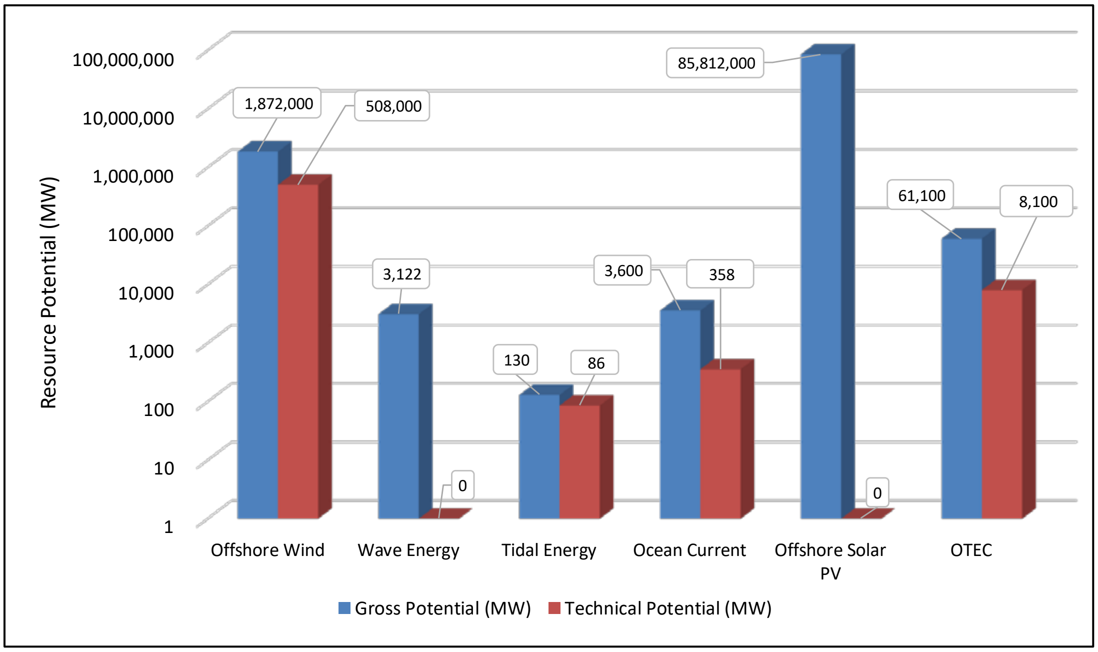

Figure 40. Gross and technical offshore renewable energy potential for the GOM by technology.

3.2 Technology Readiness by Technology Type

Technology readiness refers to a given offshore renewable energy technology's ability to be commercially deployed. This analysis identified four technology readiness stages: early stage research and development (R&D), proof of concept, pre-commercial demonstration, and commercially proven as described in section 1.3.2.2. These readiness stages represent a simplified hierarchy when compared with other more detailed readiness scales such as the DOE's Technologies Readiness Levels (TRL) (DOE 2011). Early stage R&D refers to technologies that are conceptual in nature. Proof of concept describes the stage where individual components and/or the entire system has been tested in a laboratory and gradually scaled up to prototype-scale technology that has all the capabilities of the eventual commercial model. Pre-commercial demonstration technologies take the design validated in the proof-of-concept stage and assess the scaled-up system in advantageous test- or real-world conditions. Commercially proven denotes a technology that has been deployed exclusively for commercial purposes that is qualified to operate under a full range of real world operating conditions. Each offshore renewable energy technology was assigned a range of readiness levels (**Figure 41**).[26]

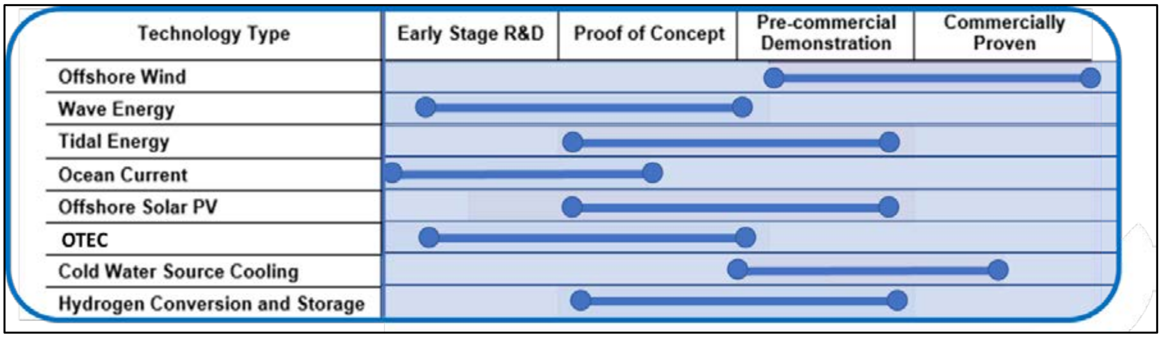

Figure 41. Technology readiness for GOM renewable energy technologies.

The rationale for each technology's readiness level is listed below:

- Offshore wind ranges from pre-commercial demonstration to commercially proven because although fixed-bottom offshore wind technologies are commercially deployed around the globe[27], additional technology development is needed to demonstrate and validate hurricane designs and to optimize rotors for lower wind regimes.
- Wave technology readiness spans from early stage R&D to pre-commercial demonstration because while multiple demonstration projects have been deployed, the industry has yet to sustain the operation of any concept for a duration long enough to demonstrate commercial operation or predictable energy production profiles. The industry is still actively engaged in new concepts at an R&D scale without significant convergence.
- Tidal energy has had some success and is approaching commercialization in some projects, partly due to adaptation of wind energy technology.
- Ocean current technology has been validated at the laboratory/prototype scale and could benefit from tidal energy successes and similarities, although no prototypes have yet been deployed.
- Ocean-based solar PV benefits from proven technology on land where it has achieved vast commercial success. This success has been extended commercially to deployment over sheltered lakes and reservoirs. However, it has yet to be commercially deployed or tested in open-ocean conditions where the challenges are immense due to extreme waves.
- OTEC requires larger (100 MW) power plants to demonstrate commercial costs and technological success. Deployments to date have been at a scale 1/100th of that size. Therefore, the technology has not demonstrated economic or performance feasibility, and significant technical challenges are still unsolved. The technology requires significant additional research, prototyping and demonstration before it can be deployed commercially.
- Cold water source cooling has successfully been used in multiple locations around the world, but its application in the GOM is limited to the Florida Keys and may require additional technology to overcome longer pipe lengths.
- Hydrogen conversion using electrolysis has been proven and significantly larger demonstration projects continue to be deployed. Successful deployment in an offshore ocean application will require a significant amount of additional testing but does not appear to be economically feasible under any scenario investigated.

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[26] Note that technology is constantly evolving, and that these "readiness" demarcations reflect our best assessment as of September 2017.

[27] For more information about offshore wind deployment levels, see DOE's *2016 Offshore Wind Technologies Market* Report (Musial et al. 2017).

For a more detailed description of each technology's readiness level please refer to individual technology assessments located in Section 2.

3.3 Cost Comparison by Technology

A large range of estimated LCOEs is observed across the technologies examined in this report (**Figure 42**). For some of the technologies, the wide ranges incorporate high uncertainty because developers have yet to converge on an optimal configuration, develop operational parameters, or demonstrate the technology at a commercial scale. As a result, costs and cost ranges are difficult to compare because some technologies, like offshore wind, have established costs based on present day market data that can be verified. Other technology costs are based on projections of future costs for a mature version of the technology that has not yet been developed. Therefore, cost information may favor nascent technologies that are characterized by future cost scenarios that may be optimistic in some cases. Costs are not provided for cold water source cooling because it is not considered an energy source but an energy efficiency measure that is difficult to compare with actual energy sources.

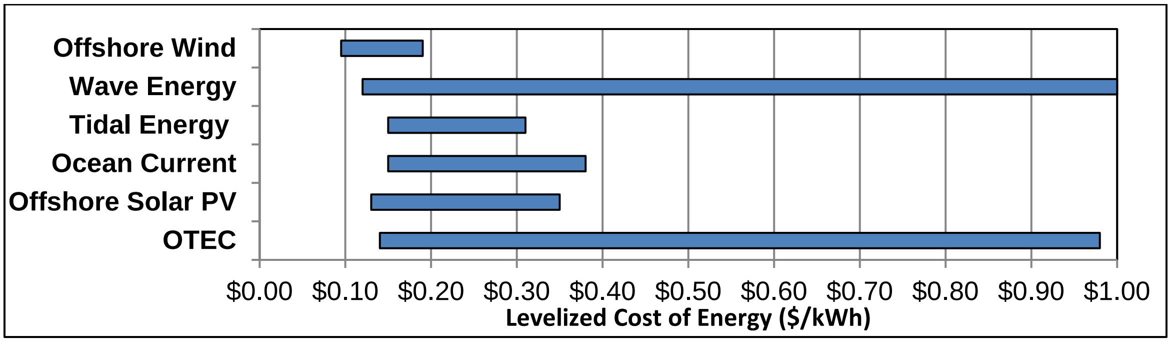

Figure 42. Levelized cost ranges for renewable energy technologies.

Offshore wind energy is estimated to have a current LCOE range of $0.095/kWh to $0.19/kWh in U.S. markets (**Figure 42**), based on recent sources of information (**Table 12**). Wave energy is expected to be able to achieve an LCOE range of $0.12/kWh to $1.00/kWh; the extreme amount of cost variation is driven by uncertainty of the ultimate design and scale of deployment but none of these costs have been validated yet. Tidal energy has an estimated LCOE range of $0.15/kWh to $0.31/kWh. Ocean current energy may be able to achieve an estimated levelized cost range of $0.15/kWh to $0.38/kWh. Offshore solar PV has a projected LCOE range of $0.13/kWh to $0.35/kWh. OTEC has a projected LCOE range of $0.14/kWh to $0.98/kWh. Offshore electrolytic hydrogen production is expected to cost between $3.09/kg H_2 to $127.16/kg H_2 on a levelized basis.

Table 12. Technology Cost Sources

Technology	Sources
Offshore wind	NREL (2017); Moné et al. (2017)
Wave energy	IEA-OES (2015); Neary et al. (2014); Lewis et al. (2014)
Tidal energy	IEA-OES (2015); Neary et al. (2014); Lewis et al. (2011)
Ocean current	IEA-OES (2015); Neary et al. (2014); Lewis et al. (2011)
Offshore solar energy	Ciel & Terre (2016); Bureau of Reclamation (2016); Barbusica (2016)
OTEC	Vega 2012; Ascari et al. 2012
Hydrogen conversion and storage	Ruth et al. (2017); Meier (2014)

4. Down-selecting to One Technology

The primary purpose of this study was to examine the range of ocean-based renewable technologies in the context of the Gulf of Mexico (GOM), assess their viability, and provide Bureau of Ocean Energy Management (BOEM) with information on offshore renewable energy potential for near-term as well as long-term planning. The following section narrows the renewable energy technologies above to a single technology to be examined in more detail in follow-on tasks for this project.

4.1 Down-select Criteria

Based on information presented in Section 3, each technology was evaluated based on the resource adequacy, technology readiness, and cost competitiveness, on a scale from 1 to 5. The highest score (5) represents the highest resource adequacy, the most mature technology, and the lowest cost potential relative to the other technologies, respectively. For each technology, a score was given in each of these categories, with equal weighting for each category. The sum of these three numbers was the given score for each technology (**Table 13)**. Some of the scoring was subjective as it was necessary to consider the global industry progress and the status of each technology relative to each other. The results conclude that offshore wind received the highest composite score of 13 out of a possible 15.

Table 13. GOM Technology Scoring Assessment Results

Technology Type	Resource Adequacy	Technology Readiness	Cost Competitiveness Potential	Total Score
Offshore wind	5	4	4	13
Wave energy	1	2	2	5
Tidal energy	2	3	3	8
Ocean current	1	2	2	5
Offshore solar energy	3	3	3	9
OTEC	3	2	2	7
Cold water source cooling	1	4	N/A	-
Hydrogen conversion	N/A	3	1	-

Across technologies, total scores ranged from a low of 5 to a high of 13 (out of a total 15; **Figure 43**). Offshore wind was the top ranked technology, ranking significantly above ocean based solar which scored 9 out of 15. Based on these results it is recommended that offshore wind be selected as the technology to be continued for deeper analysis in this study.

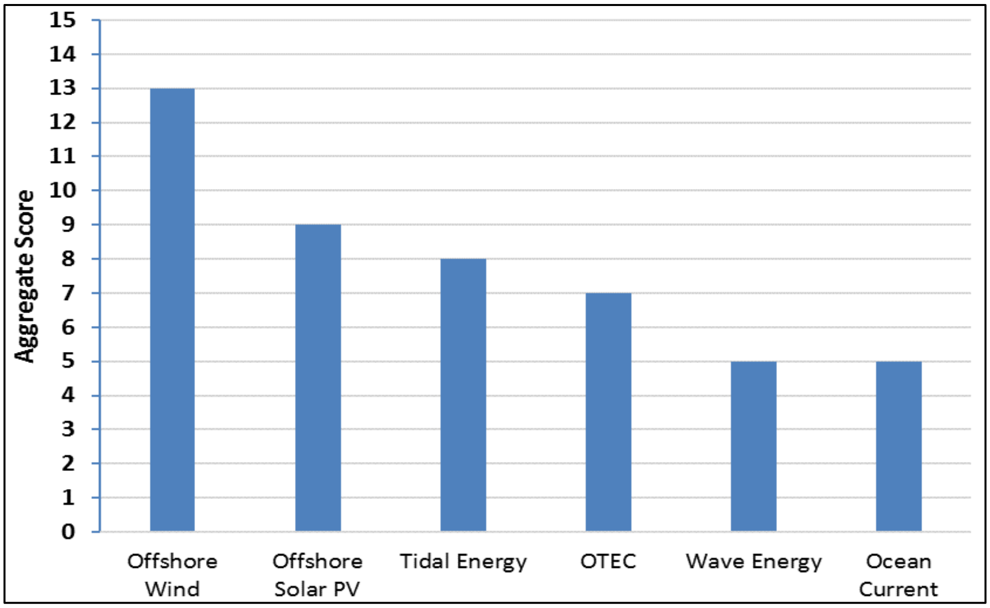

Figure 43. GOM technology scoring in rank order.

4.2 Down-select Conclusion

Based on the criteria established for resource adequacy, technology readiness, and cost competitiveness, NREL's recommendation is to focus the next tasks in this study on offshore wind as the primary technology. The technical resource potential for offshore wind was 508 GW, the largest of any of the technologies examined. Its deployment and ability to serve a significant percentage of the load in the GOM is primarily dependent upon improving the economics over the next decade. Based on global trends, the economics for offshore wind are improving rapidly, making economic deployment of offshore wind turbines in the GOM likely by 2030 (Beiter et al 2017) when costs may be approaching acceptable market levels. During this timeframe, there will be a need to develop offshore wind new technologies to optimize energy capture in the lower wind regimes of the GOM, to increase understanding of hurricane risk, and to design machines suitable for hurricane-prone areas.

Ocean-based solar has an enormous gross resource potential in the GOM but is severely constrained by extreme wave conditions on the ocean surface that would likely damage conventional photovoltaic (PV) systems and support structures. However, state waters in the GOM have sheltered bays and water bodies closer to urban load centers that could better take advantage of solar resources and may present a future opportunity. In addition, new technology concepts for floating solar may be developed in the future.

Other renewable energy technologies surveyed in this study may present opportunities for energy generation on a limited basis. Tidal energy has very little resource in the GOM. However, specific sites that were identified in this study in Texas and Florida have potential for small distributed systems. Cold water source cooling is limited in the GOM because the best resource is located far from shore where it cannot be easily accessed. A few sites near Key West may be accessible for this purpose but will not make a major contribution to the GOM electricity needs. Wave energy, ocean thermal energy conversion (OTEC), and ocean current all have challenges that may preclude their implementation in the GOM in the foreseeable future. However, longer term technological and economic improvements are possible.

The potential for developing offshore wind to serve loads in the GOM is real in the shorter term and will be explored further in later tasks.

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