Challenges and Opportunities for ROICE (Repurposing Offshore Oil and Gas Infrastructure for Clean Energy) Projects in the Gulf of Mexico, United States

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Abstract

The Gulf of Mexico (GOM) in the United States (US) has around 1500 oil and gas structures that have reached or will soon reach the end of their oil and gas phase and will need to be decommissioned within the next few decades. In this context, the authors of the present work developed a project, named ROICE (Repurposing Offshore Infrastructure for Clean Energy), to evaluate the feasibility of repurposing these structures as well as the thousands of miles of pipelines for clean energy in the near future. A ROICE project involves installing fixed or floating wind turbines around an existing oil and gas platform, with the power exported to shore or used to generate green hydrogen (H2) while reusing the existing platform jacket to house the new topsides required for either power export or H2 generation. H2 generation by electrolysis will be supported by seawater desalination to provide a self-sufficient and constant fresh water supply. Of the different components of the oil & gas structure to be repurposed, it is likely most cost-effective to reuse the jacket (main support structure) and the deck (flooring above the structure) for ROICE projects. The remaining equipment will need to be decommissioned as per normal practice - removal of oil & gas topsides, abandonment of all wells, and any pipelines that will not be used to transport hydrogen.

A comprehensive model was developed named the ROICE LC Model, which calculates the levelized cost (LC) for wind power and hydrogen generation for new build and repurposed projects. Details of the levelized cost calculations and estimates of LC for a few typical locations are provided in a companion paper, a link to which can be found on the ROICE Website. This paper reports out on the use of the ROICE LC Model to generate Geospatial Levelized Costs (GSLC) maps for the GOM, and the estimation of LC values for each of the nearly 1600 asset locations. These maps were then used to analyze LC trends and to identify challenges and opportunities to make such projects profitable. Key findings are discussed here.

The estimated LC is a complex function of various variables such as wind speed, water depth, distance to shore, project size, and new build versus repurposing. The LCOE (Levelized Cost of Electricity) for the repurposed wind projects in the GOM ranged from $82 to $231/MWh and the equivalent new build projects ranged from $82 to $437/MWh. The LCOH (Levelized Cost of Hydrogen) for repurposed hydrogen generation projects ranged from $4.76 to $8.44/kg and for the equivalent new build projects ranged from $4.77 to $19.64/kg. The calculated LC does not include any federal or state incentives, and does not assume any projections on cost reductions and technology improvements. These LC's are higher than equivalent onshore low-carbon renewables, and are even more challenged versus high-carbon alternatives. However, projects at the lower end

of the range of LC across the GOM have the potential to be competitive with onshore through efficient design, cost reductions, and the use of all available federal and state incentives.

Opportunities to reduce the LC and improve project economics include repurposing, optimal site selection, project size optimization and comparing profitability between hydrogen and power export. Of the different components of the oil & gas structure to be repurposed, it is likely most cost-effective to reuse the jacket (main support structure) and the deck (flooring above the structure) for ROICE projects. The remaining equipment will need to be decommissioned as per normal practice - removal of oil & gas topsides, abandonment of all wells, and any pipelines that will not be used to transport hydrogen. Such repurposing has the dual impact of reducing Capital Expenditure (CAPEX) and shortening the project implementation schedule .

Shallow water/near-shore locations appeared to have the lowest LC for all cases - new build or repurposed, power or hydrogen production – due to several reasons such as higher wind speeds, lower structural costs, lower cable costs, etc. LC can be reduced by 5 to 10% for shallow water locations. Further away from shore, in deeper waters, repurposing can reduce the LC by up to 25% for larger-scale and up to 60% for smaller-scale projects. A hydrogen generation project trades off power export cables and an onshore substation for electrolyzers, desalination units, and hydrogen pipelines. This tradeoff can reduce CAPEX by 10 to 15% in many cases and in other cases result in no more than an ~10% increase in CAPEX. The incremental economics on the additional CAPEX for hydrogen generation is likely to be promising, especially considering the healthier federal incentives for hydrogen production vs wind power generation.

In conclusion, this work has demonstrated that a sizeable fraction of infrastructure can be reused for clean energy given the right structural and geospatial conditions, technology improvements, and federal and state incentives of the United States.

Keywords: ROICE LC Model, Levelized Costs, Offshore, Repurposing, GOM, CAPEX, OPEX, Wind Power, Green Hydrogen, GSLC Maps

1. Introduction

Energy needs and environmental effects are intimately correlated issues. Fossil fuel delivers most of the present energy demands. According to one of the published International Energy Agency (IEA) reports, oil, coal/peat, and natural gas cover approximately 27%, 32%, and 21% of the total energy demand respectively (Van de Garaf and Westphal, 2011). Extreme energy demands in the forthcoming will likely increase greenhouse gas releases under business-as-usual settings and the nonconventional oil and gas reserves will likely have a higher environmental footprint. The increase in greenhouse gas emissions with its potential for global warming and its detrimental effects on the quality of life will remain a significant challenge for decades to come. In the present scenario, the energy sector accounts for almost 90% of the greenhouse gas emissions in the United States and transportation, electricity, and heat represent nearly 60% of the energy demand (Herzong et al., 2005). Energy proficiency along with clean and renewable sources of energy presents sustainable solutions to lowering reliance on polluting and dwindling fossil sources.

Several clean power generation equipment is at this time being used at the demonstration or commercial stage, which comprises solar, wind, and bioenergy (Bensebaa, 2013).

A fundamental structural change is happening globally in the energy sector, a significant energy transition correlated to energy sources, structures, economics, scale, and energy policy (Brandoni et al., 2016; Dall Aqua et al., 2017). An important type of energy transition can be potentially characterized by the re-use of offshore oil & gas platforms at the end-of-life phase. Oil and gas offshore platforms and installations have a reduced life of operations. At this time, there are around 6500 offshore Oil and Gas production installations worldwide, located on the continental shelves of about 53 countries, roughly 950 in Asia, 700 in the Middle East, and 600 in Europe, the North Sea, and Northeast Atlantic (Ferriera and Suslick, 2001; Truchon et al., 2015). Worldwide, plenty of oil & gas offshore structures are to be decommissioned in the coming years for the reason exploration and production of fossils is ending (Parente et al., 2006).

Over the last 75 years, roughly 7000 platforms have been installed in the Gulf of Mexico (GOM). Additionally, the GOM infrastructure includes 14,000 wells and 10,000 miles of pipelines (Figure 1 a-b). These assets, once they reach the end of their fossil energy purpose, are "decommissioned," usually meaning plugged and abandoned (wells), removed or preserved in place (pipelines), taken apart and brought back to shore, or sunk to the ocean floor (platforms and structures). As of 2023, about 5500 platforms have been decommissioned, and as of June 2023, about 1533 structures remain on the GOM Outer Continental Shelf (OCS), with 356 of them having submitted applications for decommissioning. Seven of these have submitted applications for re-use, 74 are proposing to use the "Rigs to Reef" provision, and the rest (275) are expected to be brought back to shore (BSEE, 2023). One of the recent articles quotes that over the past decade, the offshore energy industry has averaged 200 platform removals per year. It also states that decommissioning in the GOM is expected to grow at a compound annual growth rate of about 6.89% from 2020 through 2030 (Presley, 2023). The Bureau of Ocean Energy Management (BOEM) of the US conducted a study of potential offshore renewable energy sources in the GOM to quantify their feasibility relating to resource adequacy, technology maturity, and the potential for competitive cost. Of all the technologies, offshore wind had the largest quantity of technical resource potential with 508 gigawatts (GW). Shallow water oil and gas production platforms could potentially be used to site integrated offshore wind-electrolyzer systems (Musial et al., 2020).

The wind speed distribution across the Gulf of Mexico ranges from 7 to 9 m/s. While noting that these speeds are lower than in other geographical regions such as the US Atlantic Coast (7.4 to 9.3 m/s) and the United Kingdom North Sea (8 to 14 m/s) (Peevey & Lenoir, 2022; Hahmann et al., 2022), . the GOM still has the potential of anchoring a profitable power generation and "power to X" projects. A recent BOEM and National Renewable Energy Laboratory (NREL) study showed that when the full range of economic factors are considered, the Texas Gulf Coast appears to have some advantages for economical wind development (Musial et al., 2020). The potential for hydrogen generation from wind power is also evident in the number of pilot and small-scale projects that are underway elsewhere in the world. Previously, the Center for Houston Future and the University of Houston led the assessment of opportunities for expanding clean hydrogen (H_2 value chains in Texas and developed a vision and roadmap to enter and expand new markets for hydrogen (Sariyeva et al., 2020). The Texas Gulf Coast region and the Gulf of Mexico have significant potential for such clean hydrogen supply projects, underpinned by the area's potential to be a driver and a hub for an increase in demand for hydrogen. With a population of more than 7 million, it simultaneously represents a strong demand and skill pool. The area's 30-plus refineries, and over 100 chemical and other plants represent approximately 40% of the total chemical and refining capacity of the nation. The industrial infrastructure and demand centers thus serve as ready customers for a sustainable and scaled-up offshore wind-hydrogen concept. By harnessing these advantages, leveraging the extensive oil and gas infrastructure for repurposing, and leveraging learnings from ongoing projects elsewhere in the world, the US GOM can be positioned to be ready with profitable ROICE research projects. To realize this potential, many challenges facing such ROICE projects will need to be addressed and a key one is project economics. Along with the well-known challenge of the levelized cost differential between low-carbon electric power (**Error! Reference source not found.**) and the current fossil-based power generation, and between low-carbon hydrogen and current industrial hydrogen (**Error! Reference source not found.**), moving the systems offshore adds additional costs.

Table 1: Levelized Cost of Electricity (LCOE) for Various Generation Pathways * (Lazard, 2023)

Generation Pathway*	**Min**	**Max**
Solar PV - Utility Scale	$24	$96
Solar PV + Storage - Utility Scale	$46	$102
Solar PV – Utility Scale (ITC)	$16	$80
Solar PV – Utility Scale (PTC)	$0	$77
Solar PV + Storage - Utility Scale (ITC)	$31	$88
Wind – Onshore	$24	$75
Wind + Storage – Onshore	$42	$114
Wind – Onshore (PTC)	$0	$66
Wind + Storage – Onshore	$12	$103
Gas Peaking	$115	$221
Nuclear	$141	$221
Coal	$68	$166
Gas Combined Cycle	$39	$101

Table 2: Levelized Cost of Hydrogen (LCOH) for Various Hydrogen Pathways ** (Bartlett & Krupnick, 2020)

Hydrogen Pathway	**Min**	**Max**
SMR**	$1.05	$1.50
SMR with 89% carbon Capture**	$1.75	$2.20
Electrolysis Solar**	$3.40	$6.80
Electrolysis Wind**	$2.50	$4.50

Other technical challenges include ensuring structural integrity and the remaining life of the offshore installations (for repurposing projects), reducing the costs of large-scale electrolysis and wind power through economies of scale, finding other cost reductions such as saline water electrolysis technologies, repurposing hydrocarbon pipelines for hydrogen transportation, etc. In addition, the regulatory framework, commercial and liability considerations, and public acceptance aspects need to be addressed (IRENA, 2020).

The basic ROICE concept in these cases is to install a set of floating or fixed wind turbines around a repurposed offshore platform. The resulting power is either transmitted back to shore as an electric power project or used for a hydrogen project to desalinate seawater, electrolyze the resulting fresh water into hydrogen and oxygen, and transport the hydrogen via existing pipelines to shore. In a power project, the offshore structure is used to house power transmission infrastructures such as converters, substations, and supporting infrastructure. In a hydrogen project, the offshore structure will also house desalination units, electrolyzers, and other balance of plant. The main objective of this research work is to use the ROICE LC Model to generate Geospatial Levelized Costs (GSLC) maps for wind power and hydrogen generation, compare the repurposing and new build cases, and generate the LC values for each asset in the GOM. Furthermore, this research work will be very significant in developing detailed modeling in the future for those valuable assets.

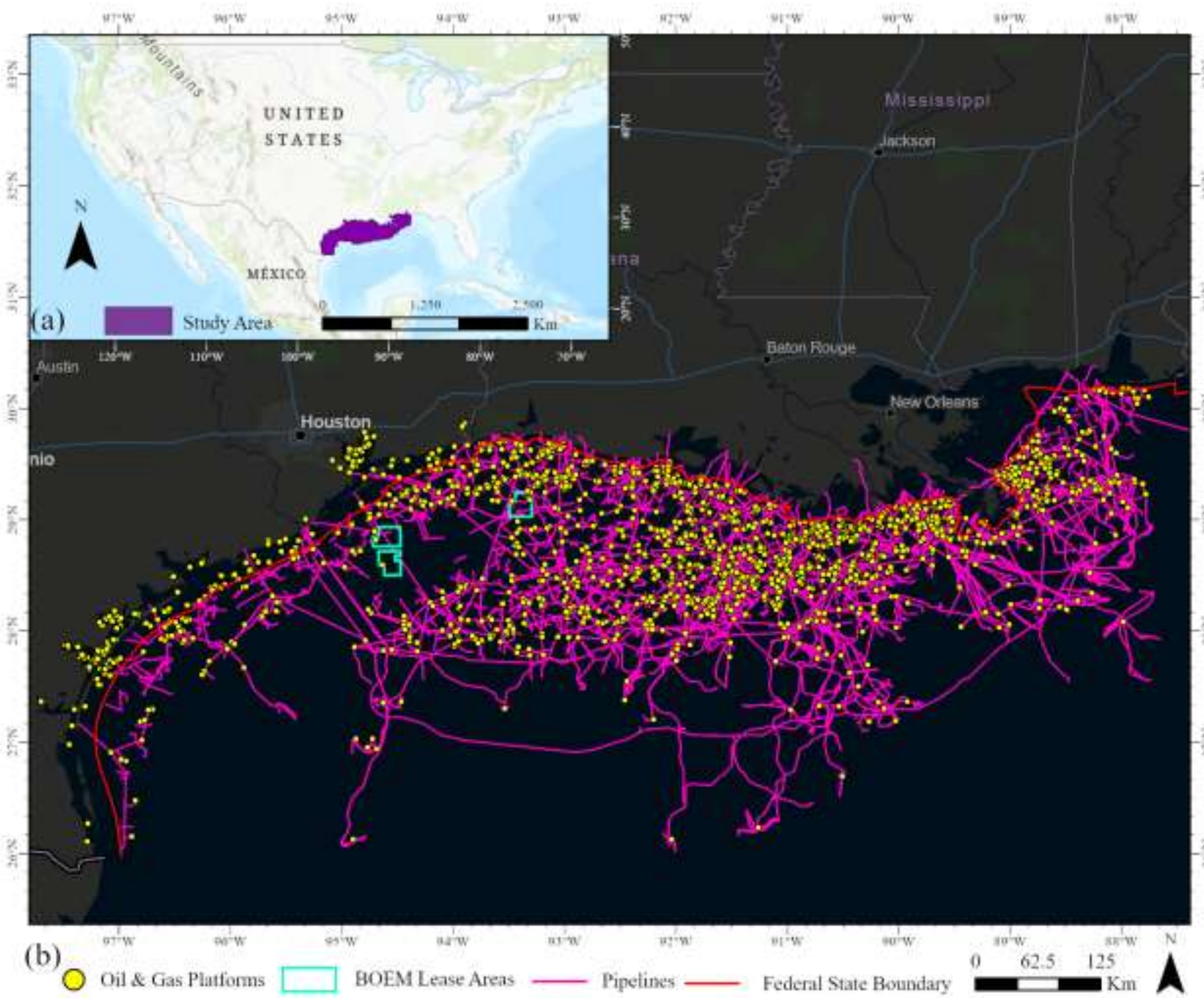

Figure 1: (a) Location of the study area (b) Oil and gas Platforms, BOEM lease areas, and pipelines in the Gulf of Mexico.

2. Data and Methodology

2.1. Data

2.1.1. Wind Speed and Bathymetry

Wind energy has been the fastest electricity-generating technology in recent years (Kaygusuz, 2009). Worldwide the potential of offshore wind energy is massive and it could meet the US energy demand four times over or the European energy demand seven times over (Wang et al., 2015). The Gulf of Mexico region has a vast offshore wind energy potential due to its favorable wind resources and proximity to coastal areas with high electricity demand. Wind power along the Gulf of Mexico for hydrogen generation offers a sustainable pathway to decarbonize the region's energy sector, reduce greenhouse gas emissions, and foster economic growth. The average wind speed ranges in the US GOM ranges from 6.9 to 8.6 m/s with the best wind speeds occurring at the southern coastal part near the Corpus Christi region (Figure 2). The other significant advantage of the US GOM is the relatively shallow water depths. The shallow water, near shore areas along the Gulf Coast, contains significant oil and gas infrastructure that can be repurposed for clean energy. For purposes of this study, only areas with water depths under 1000 meters were considered since floating wind solutions for deeper waters are not currently available (Figure 3). Besides, these locations are unlikely to prove profitable.

Bathymetry is the study of seabed settings, especially the ocean depths (Wathar and Shelke, 2016). Water depth is a critical factor in the planning of offshore wind projects. impacting not only the initial investment but also the maintenance cost (Nezhad et al., 2021; Costoya et al., 2021). Accurate bathymetry helps in optimizing cable routes, reducing costs, and minimizing potential environmental impacts as well. It should also be noted that the federal jurisdiction for offshore waters starts at nine US nautical miles for the Texas and Florida coast, three US nautical miles for Louisiana, and three international nautical miles for the other coastal states, which is shown in many of the maps provided in this report.

These geospatial inputs are crucial for identifying suitable locations for offshore wind farms and helping to determine areas with optimal wind resources and favorable conditions for wind turbine installation.

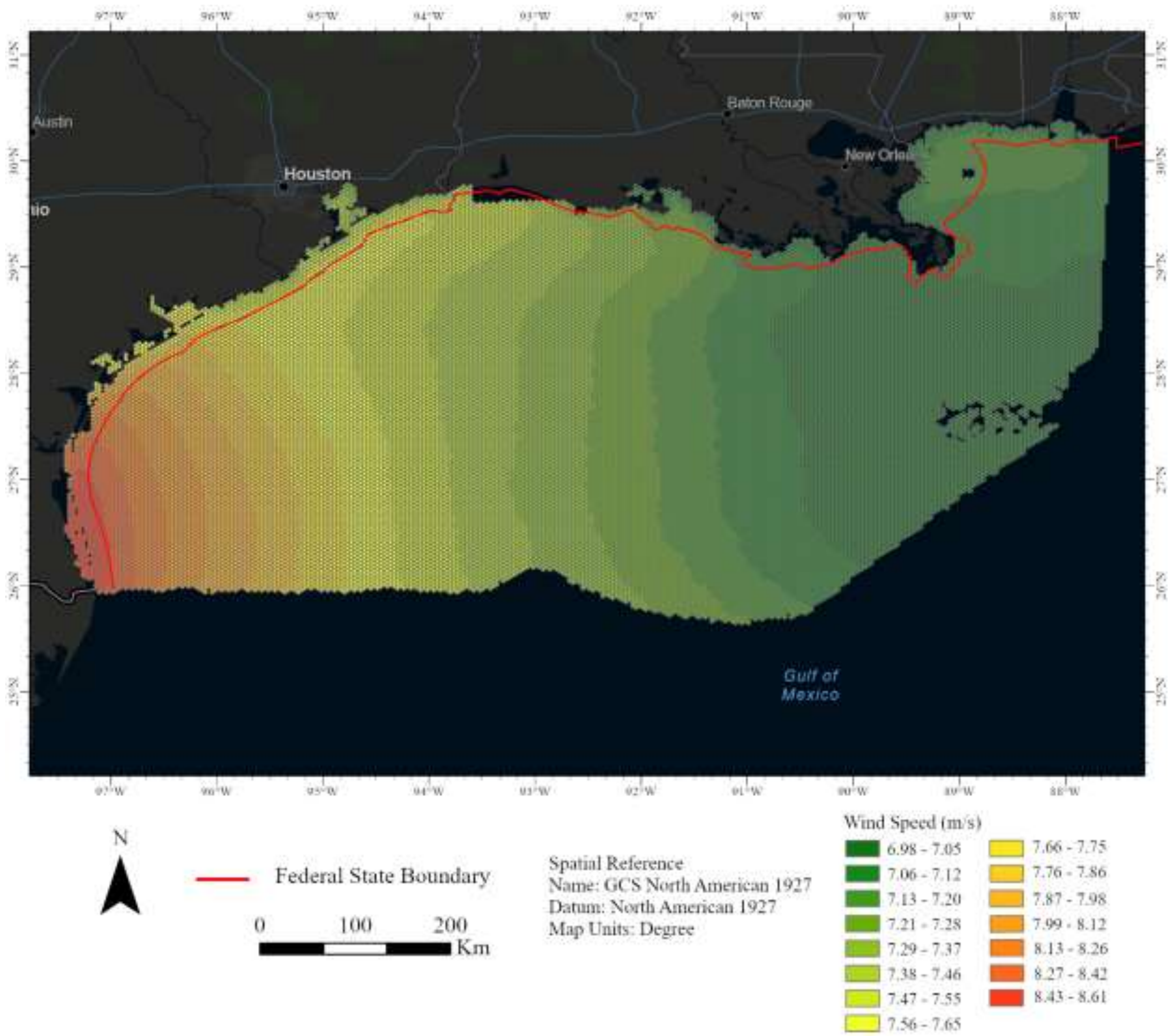

Figure 2: Average wind speed along the Gulf of Mexico United States.

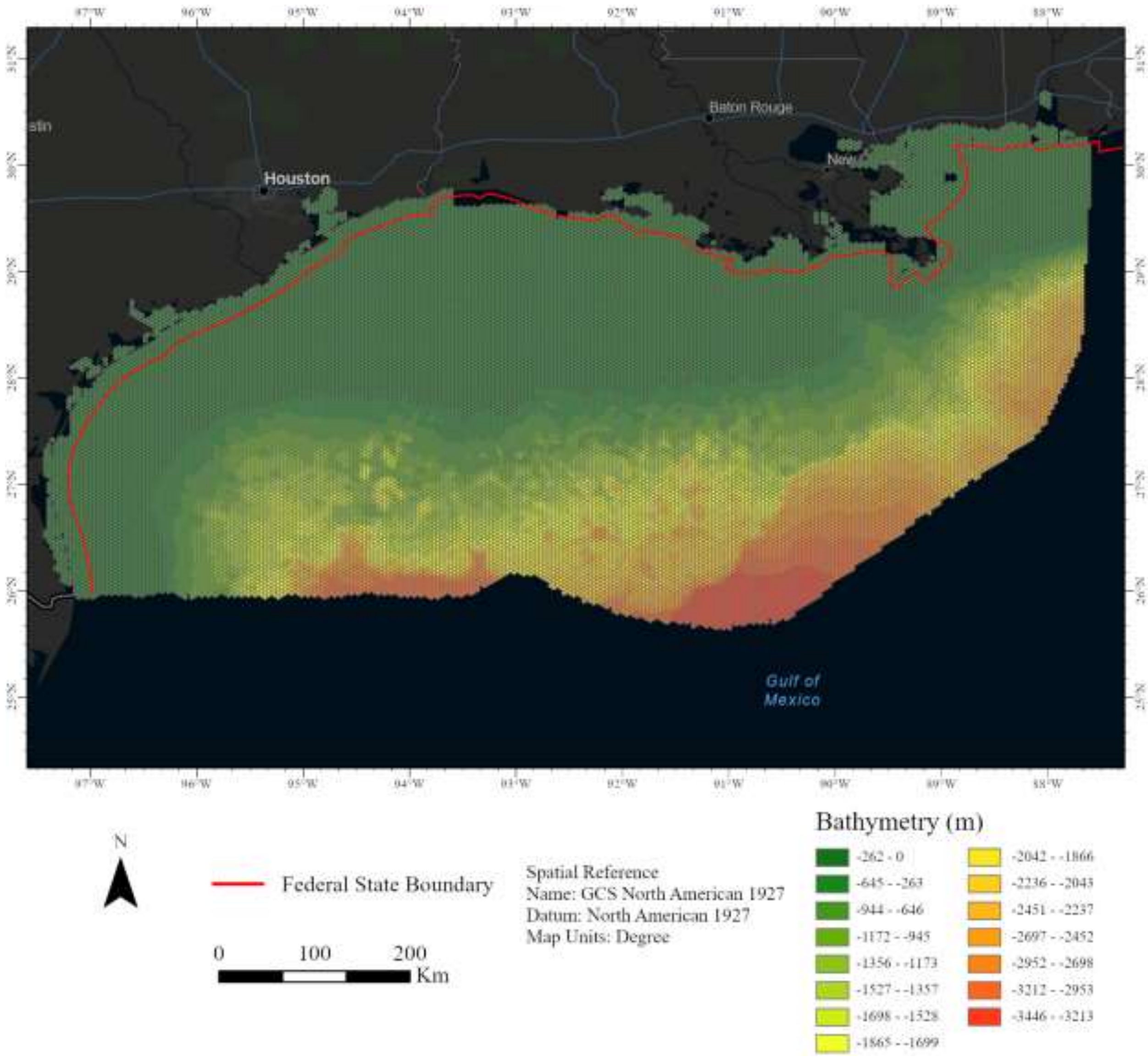

Figure 3: Bathymetry variations along the Gulf of Mexico

2.1.2. Installation, Operation and Maintenance (O&M) Ports

Installation and O&M costs are expected to account for nearly one-third of offshore LCOE in the United States (double check this). Therefore, there is a large potential for reducing LCOE through advanced installation, and O&M approaches (Dinh and McKeogh, 2019). Figure 4 illustrates the proximity of each location to the nearest installation and O&M ports. It's important to note that not all ports possess the necessary infrastructure to accommodate wind turbine installations or provide the facilities required to house crews and equipment for O&M activities. The map therefore only includes those ports that can support these activities. These Geographic Information System (GIS) inputs play a pivotal role in determining essential cost elements. For instance, these inputs contribute to the calculation of the O&M service factor, installation time, and vessel travel times.

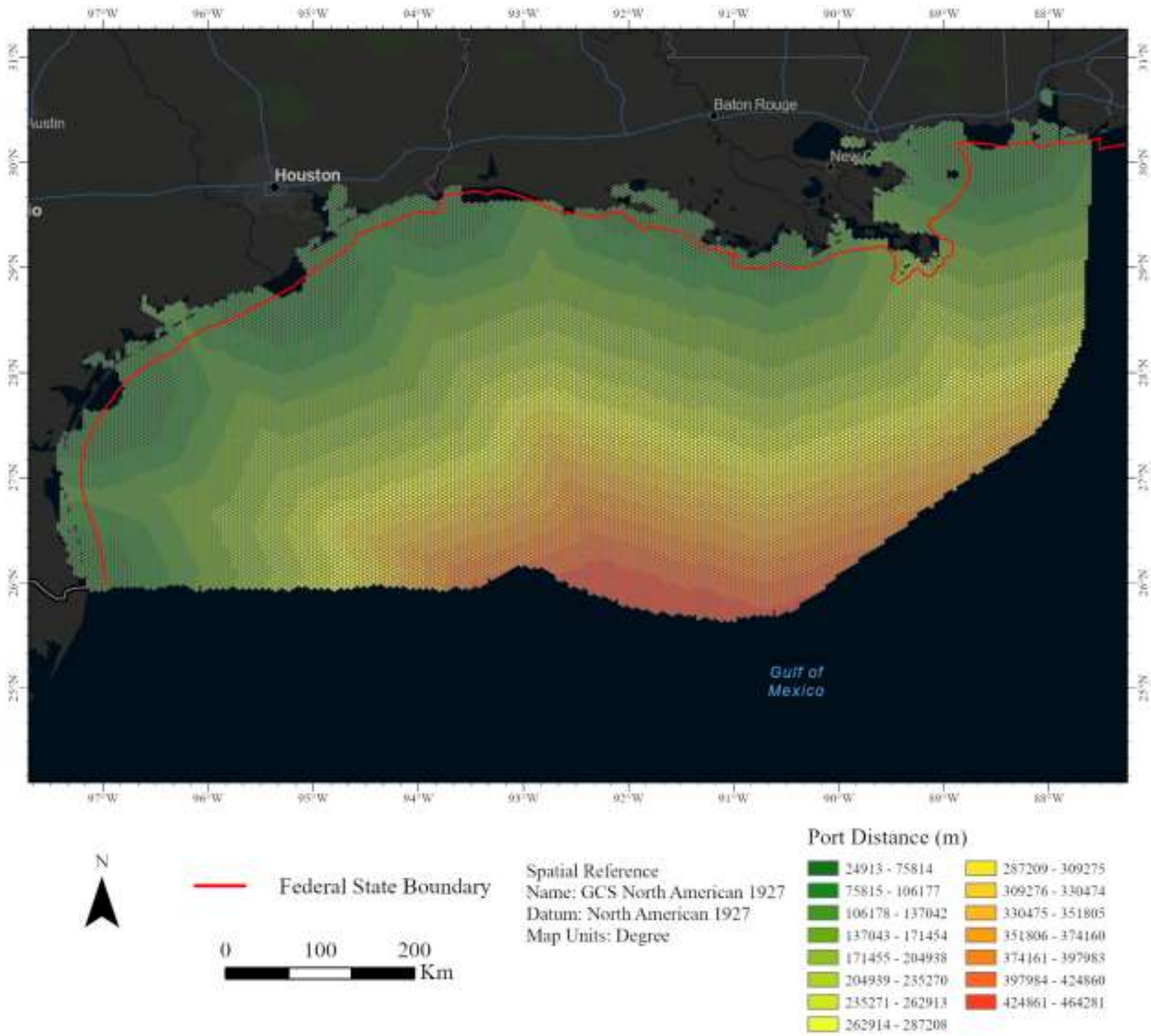

Figure 4: Both the Installation and O&M ports proximity

2.2. Methodology

2.2.1. ROICE LC Model

The ROIC LC Model has been developed and used to estimate the LC for wind power and hydrogen H_2 generation for both repurposed and new build case studies (add reference here). The workflow of this model is shown in Figure 5. The model was able to generate the LCOE and LCOH for any particular location, provided its GIS details including distance to the nearest export connection, distance to the nearest O&M port, average wind speed, and bathymetry, etc. Initially, three representative locations were used to illustrate the diverse range of results generated by this model, which enhances the clarity and understanding of how different factors such as water depth, proximity to shore ports, and wind speed interact and influence the LC.

The LCOE is computed by using the following Eq 1 & 2 respectively (EIA, 2022):

$$\mathrm{LCOE} = \frac{\mathrm{TLCC}}{\sum_{n=1}^{N} \frac{Q_n}{(1+d)^n}} \quad (1)$$

Where:

LCOE = levelized cost of energy

TLCC = total life-cycle cost

Q_n = energy output or saved in year n

d = discount rate

N = analysis period

TLCC is computed as follows:

$$\mathrm{TLCC} = \sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \quad (2)$$

Where:

LCOE = levelized cost of energy

TLCC = total life-cycle cost

C_n = cost in period n: investment costs include finance charges as appropriate, expected salvage value, nonfuel O&M and repair costs, replacement costs, and energy costs

d = discount rate

N = analysis period

We used this process to generate the values of LCOE and LCOH for the whole region.

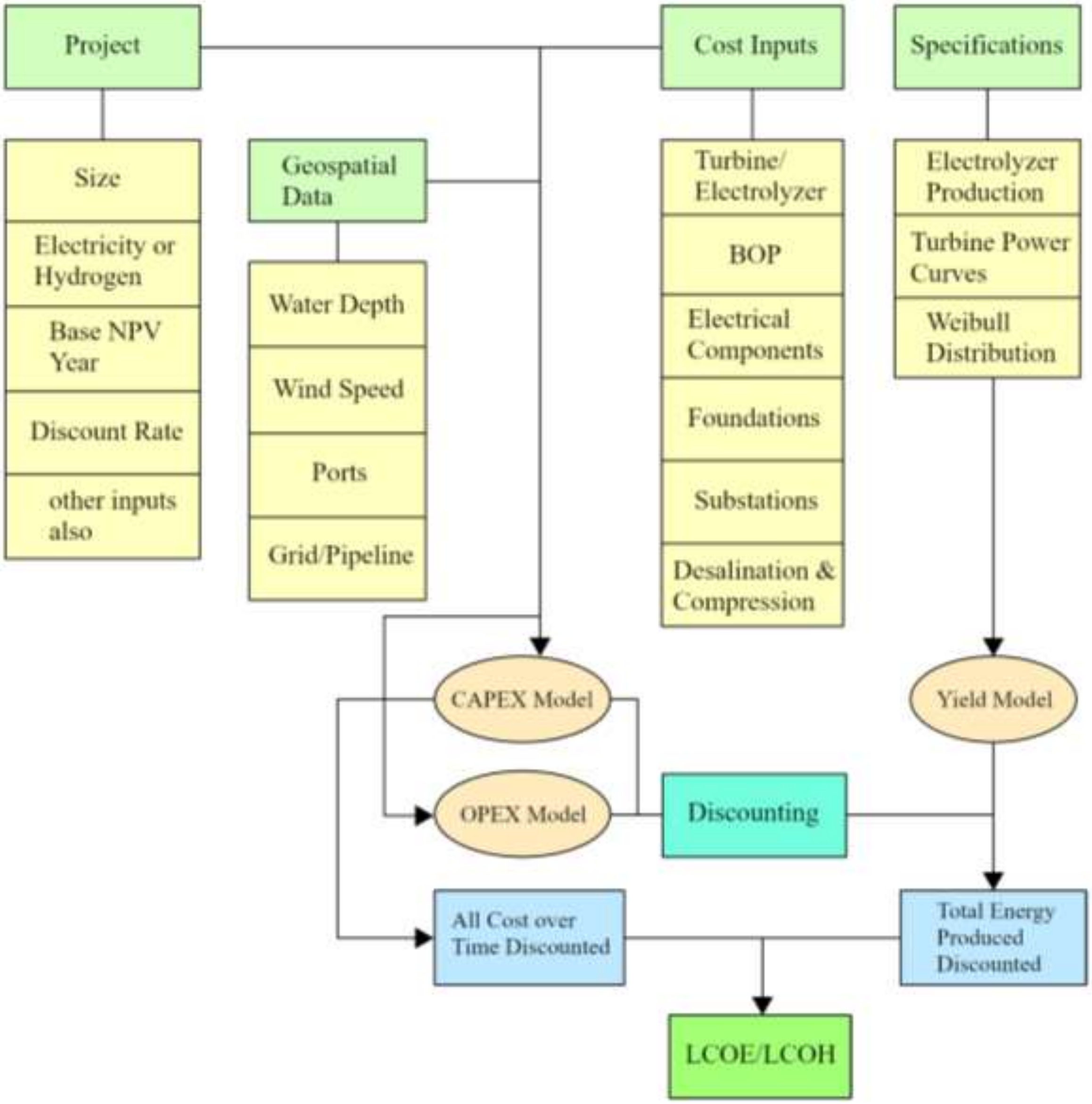

Figure 5: The workflow of the ROICE LC Model

2.3. Iterative Geospatial Algorithm

With all of the above-mentioned inputs, the ROICE LC Model can generate LC values for a power export or hydrogen export project for any given point in the Gulf of Mexico. An iterative geospatial algorithm was then developed to efficiently calculate LC values across the entire GOM and generate GSLC maps. A hexagonal grid across the GOM developed by The Xodus Group for a previous project was used. This included a shapefile containing data for these polygons more than 64,500 polygons covering the US GOM, including the mean wind speed, mean bathymetry, and mean wave height as well as the export distance, installation port distance, and O&M port distance. Python-coded scripts were developed to extract daa from the shapefile, execute the ROICE LC Model and gather the results for each polygon.. The scripts extract data from the The scripts aggreage the results such as LCOE and LCOH, for mapping in ArcGIS tools. Additional geospatial data provided include annual energy output, annual hydrogen production, energy dedicated to hydrogen production, total capital expenditures (CAPEX), and total operating expenditures (OPEX).

2.3. Hexagon Gridding

GIS is a computer-based system that examines and reveals geographically referenced data (Acevedo-Garcia et al., 2008). This system assists in the analysis of conventional quantitative and qualitative information, laying those facts in a geographic context, and enabling deeper inferences regarding that information (Archbald et al., 2018). A GIS tool (ArcGIS Pro) was used to integrate multiple datasets and the tessellation method was employed to evaluate the whole US GOM study region. The tessellation method was utilized to create an H3 hexagon grid of recurring shapes over the area of interest. H3 is a hierarchical indexing system, which was created by Uber (Sahr, 2011; Zeidan & Rempel, 2023). A hierarchical indexing grid suggests that every hexagon can be subdivided into sub-unit hexagons. There are numerous advantages to using hexagonal grids for aggregation and summarization rather than to use administrative boundaries such as states, counties, or block groups. H3 hexagons are excellent because they are made over a model of the Earth, suggesting their position remains constant at every resolution. Therefore, H3 hexagons are used as standardized grid techniques across the study region because of their balanced compromise and uniformity in size. H3 hexagon contains a total of sixteen resolution levels, ranging from 0 (coarsest) to a higher number (finer) and each resolution level subdivides the study area into smaller hexagons. In this study, the resolution level of 4 and the diameter of 2.8 miles for each hexagon was used to get the significant and promising patterns. Furthermore, the statistical mean of all available input data points within each hexagon was calculated by using the geoprocessing tool to display all the outcomes across the region.

2.4. Case Nomenclature

The ROICE LC Model and the iterative geospatial algorithm were used to generate LC values and GSCL maps across the US GOM for a set of eight ROICE cases. These are listed below in Table 3.

Table 3: Case Nomenclature

Product	Capacity	Repurposing	New Build
Power	435 MW	E500R	E500N
	105 MW	E100R	E100N
Hydrogen	435 MW (180 MW Electrolyzer Capacity)	H500R	H500N
	105 MW (40 MW Electrolyzer Capacity)	H100R	H100N

The case nomenclature follows a simple set of rules: E for "Electricity" or power export projects, H for Hydrogen export projects; R for repurposing projects, N for New Build Projects; 500 to represent a commercial scale project (actual project capacity modeled is 435 MW) and 100 to represent a demonstration-scale project (actual project capacity modeled is 105 MW). Thus, E500N is a newly built commercial scale power export project; H100R is a repurposed demonstration scale hydrogen export project. As discussed before, the hydrogen export projects assume that all of the power generated from the turbines is used to generate hydrogen. The equivalent electrolyzer size is shown above. The total project CAPEX used in calculating levelized costs for hydrogen projects also includes the cost of power generation as CAPEX.

2.5. LC Estimation for Assets

The GSCL maps were used to assign LC values to each of the almost 1700 assets across the GOM. Spatial joining is a prevailing practice used in the GIS that allows combining information from two or more spatial datasets to get new insights and determine how properties from the datasets should be matched. In the study, this technique was used to assign attributes obtained from the ROICE LC model to the hexagonal grid system (join layer) and subsequently to the location of the oil and gas platforms (target) using a nearest location technique. Once LC values and other data were assigned in this manner to each asset location in the GOM, these assets were able to be ranked to identify the most favorable locations for ROICE projects. This was used to shortlist assets for which detailed site-specific ROICE design will be developed in Phase 2. For a select group of less-favorable assets, it will also enable investigation during Phase 2 of what would make a ROICE project profitable on these assets.

3. Results and Discussion

Levelized Cost of Energy (LCOE, $/MWh) and Levelized Cost of Hydrogen (LCOH, $/kg of H_2) GSLC maps provide a convenient visual representation of the relative cost of implementing a power or hydrogen export project across a wide geospatial area. These maps are very significant for policymakers, energy planners, and investors to assess the economic viability of different energy technologies and make informed decisions about energy infrastructure development. These GSLC maps for Power Export and Hydrogen Export cases will now be presented and analyzed.

3.1. Power Export Cases (LCOE, $/MWh)

The GSLC map for E500R (Power Export, 435 MW Size, Repurposed) is shown in Figure 6. The levelized cost ranges from 81.97 to $168.23/ Megawatt-hour (MWh). The GSLC map for E100R (Power Export, 105 MW, Repurposed) is shown in Figure 7 and the LCs range from 86 to $ 231/MWh for this case. As expected, economies of scale help keep the costs down for the larger project, especially at the higher end. In both these cases, as can be seen from the color shading in these GSLC maps, locations closer to shore in shallow waters have lower costs. The lower end of the LCOE ranges above thus correspond to near-shore shallow water locations while the higher end locations are farther from shore in deeper water. This is primarily driven by the higher costs for floating turbines and longer cable lengths to bring the power to shore. A secondary contributor is higher installation and maintenance costs for locations further from shore and in deeper water, requiring more complex service vessels.

The GSLC maps for new build cases can be seen in Figure 8 and Figure 9 for both the E500N case (Power Export, 435 MW Size, New Build) and the E100N case (Power Export, 105 MW Size, New Build) respectively. LC for the E500N case ranges from 82.06 to $220.26/MWh, while those for the E100N case range from 86.14 to $436.78/MWh. As can be seen from a comparison of these LC ranges to their equivalent repurposed cases, repurposing provides a greater LC reduction at the higher end of the range (deeper waters and/or further from shore). This is primarily driven by the cost of the foundation jacket for the Offshore Substation (OSS) which becomes more expensive as the water depth increases and repurposed projects do not incur these high costs. Repurposing also has a greater impact on the levelized costs for smaller projects, since the savings from reusing the jacket is a larger fraction of the total cost.

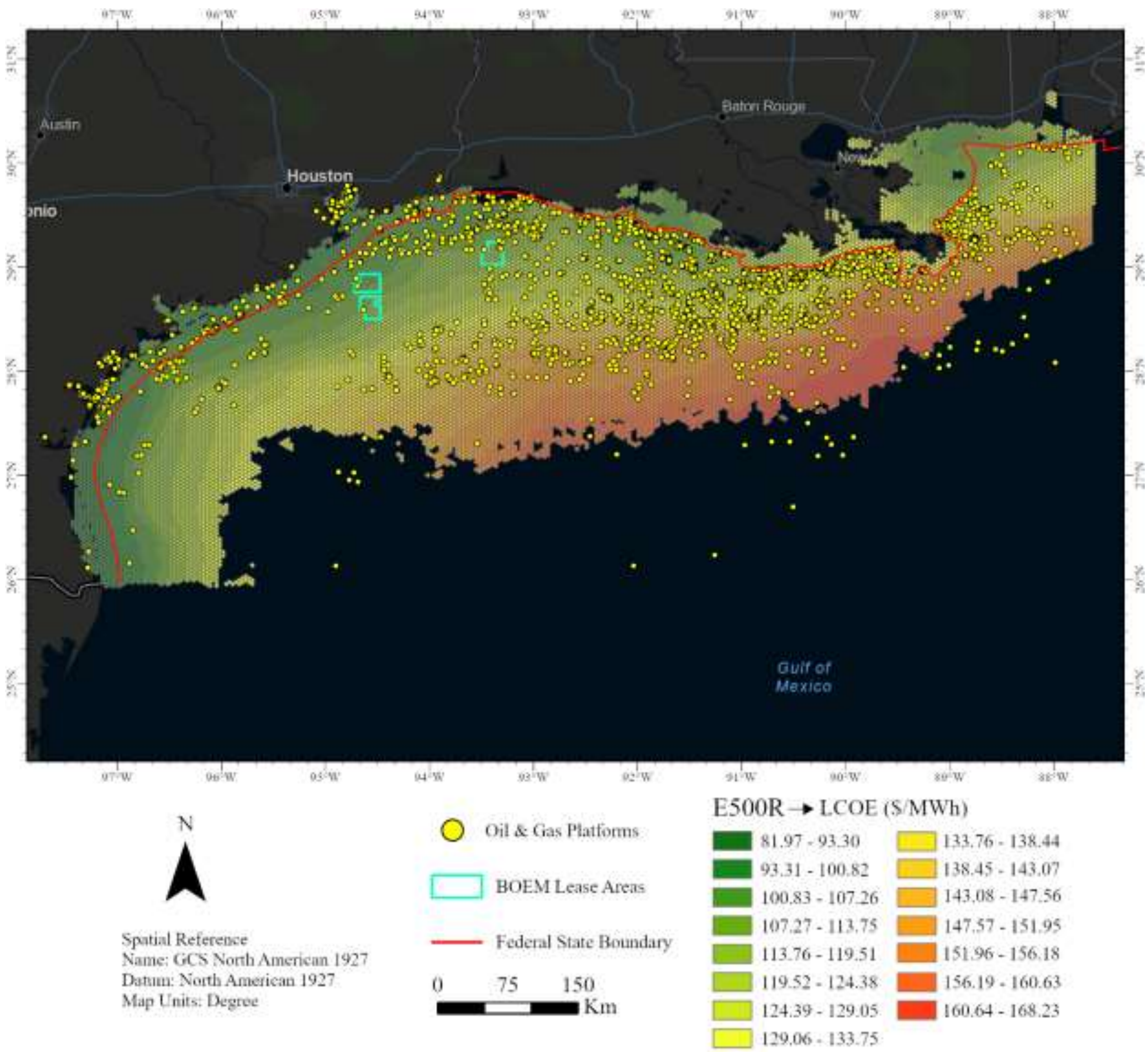

Figure 6: LCOE distribution for power export E500R

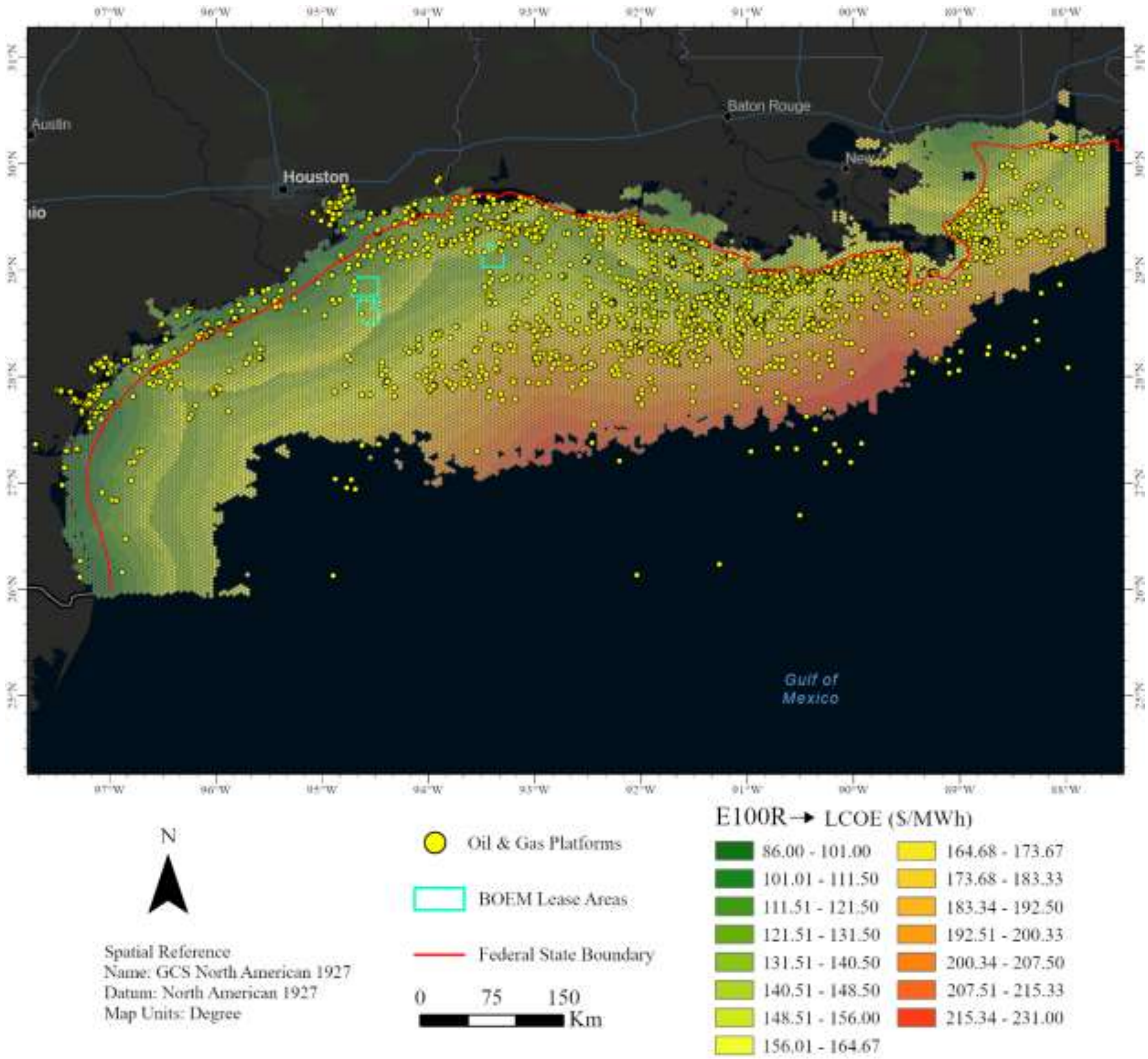

Figure 7: LCOE distribution for power export E100R

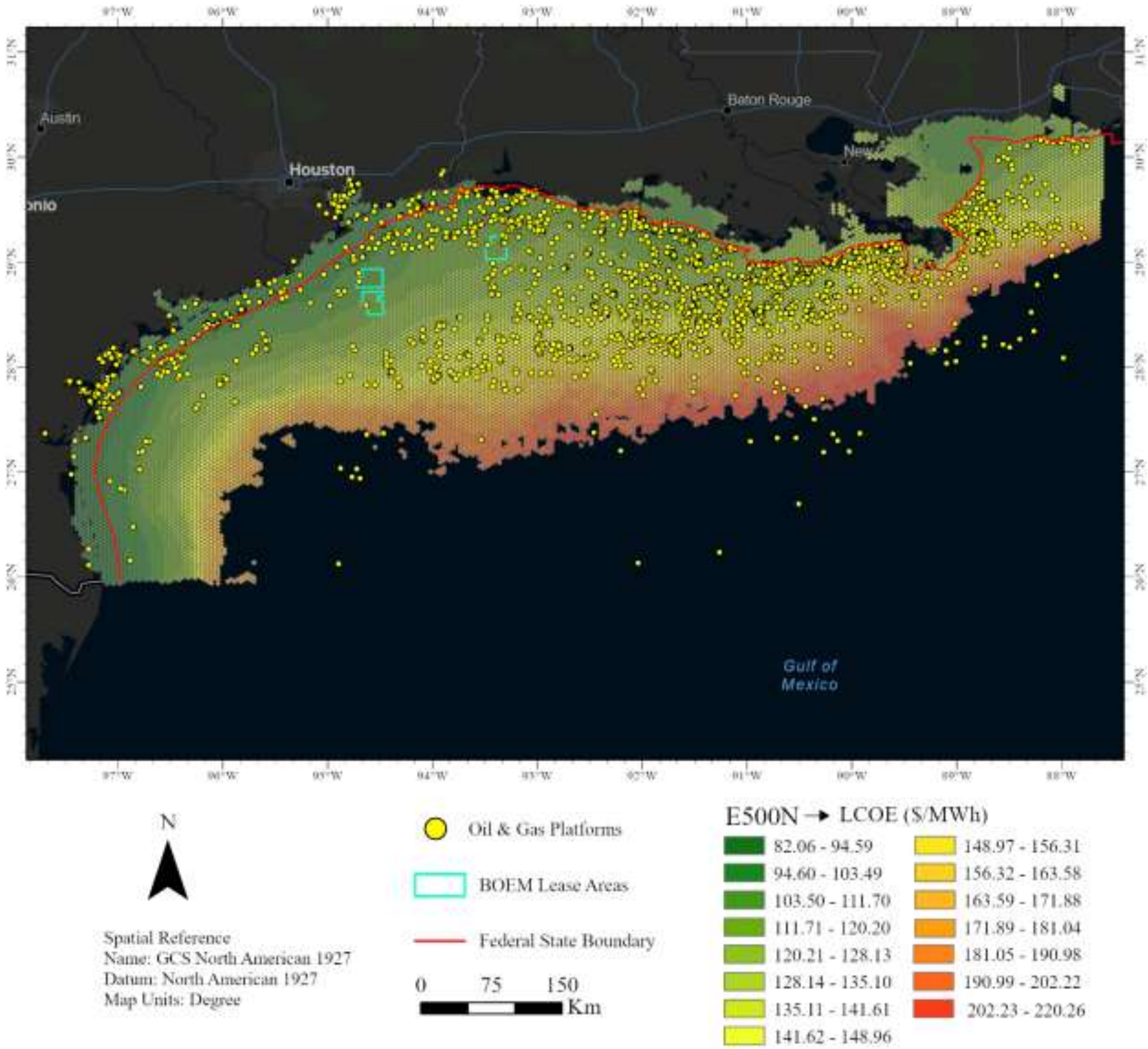

Figure 8: LCOE distribution for power export E500N

In all these GSLC maps, the recently announced wind lease areas by BOEM (Bureau of Ocean Energy Management) are also shown. As can be seen, while not in the lowest-cost areas, the LC values in these areas are still quite favorable. Closeness to population centers will also have a positive impact on project economics in this area. A closer look at assets near these areas will be taken in the next phase (Phase 2) of this project and pathways to make these projects economically attractive will be developed.

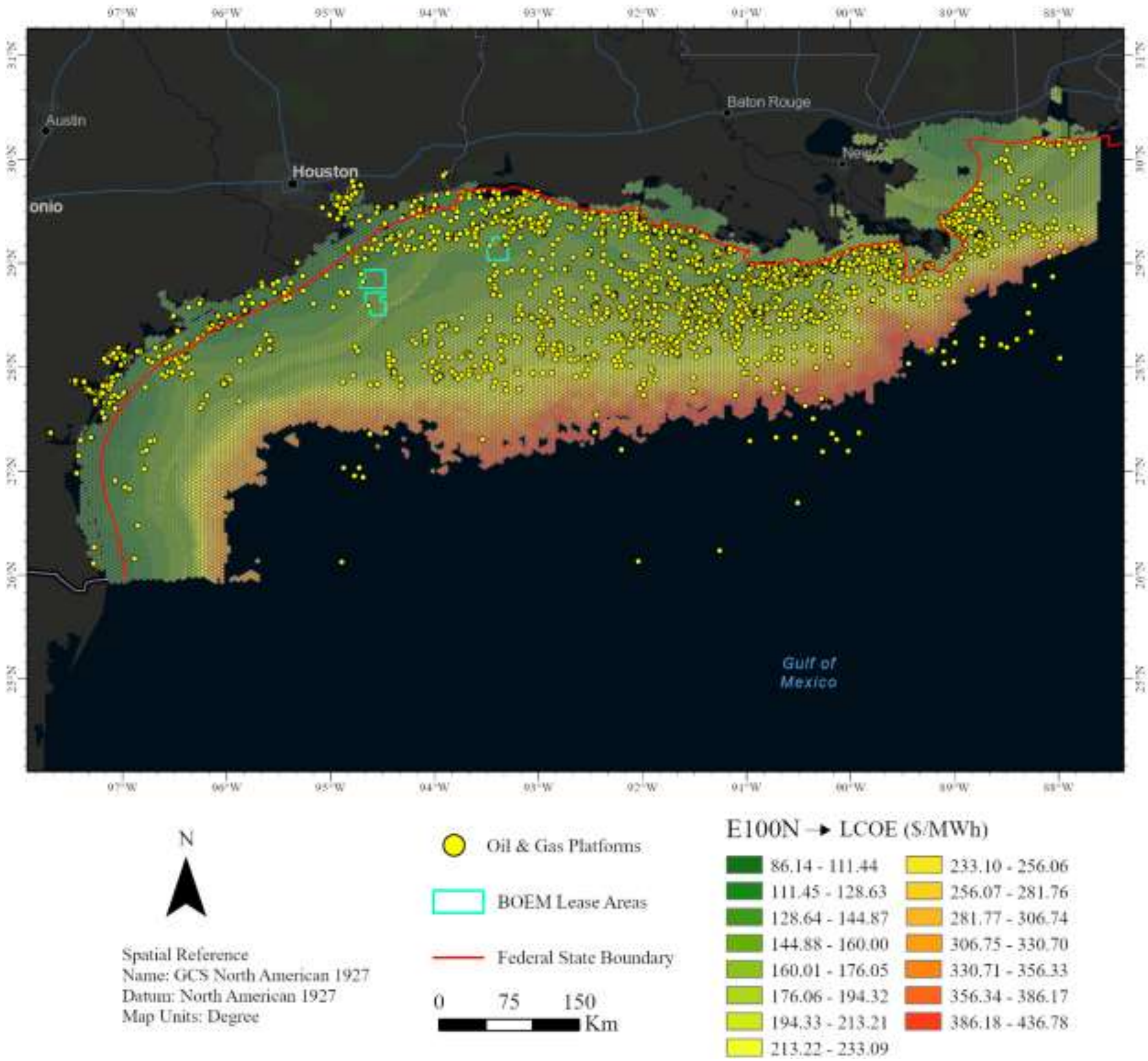

Figure 9: LCOE distribution for power export E100N

Figure 10 compares the LCOE range for the four power export cases in this study to onshore wind and solar photovoltaic (PV) with and without production and investment tax credits (PTC and ITC), with or without storage, and at utility scale or not. The lighter-colored bars on the right for each of the project LCOE cases represent cases in water depths greater than 400 m.

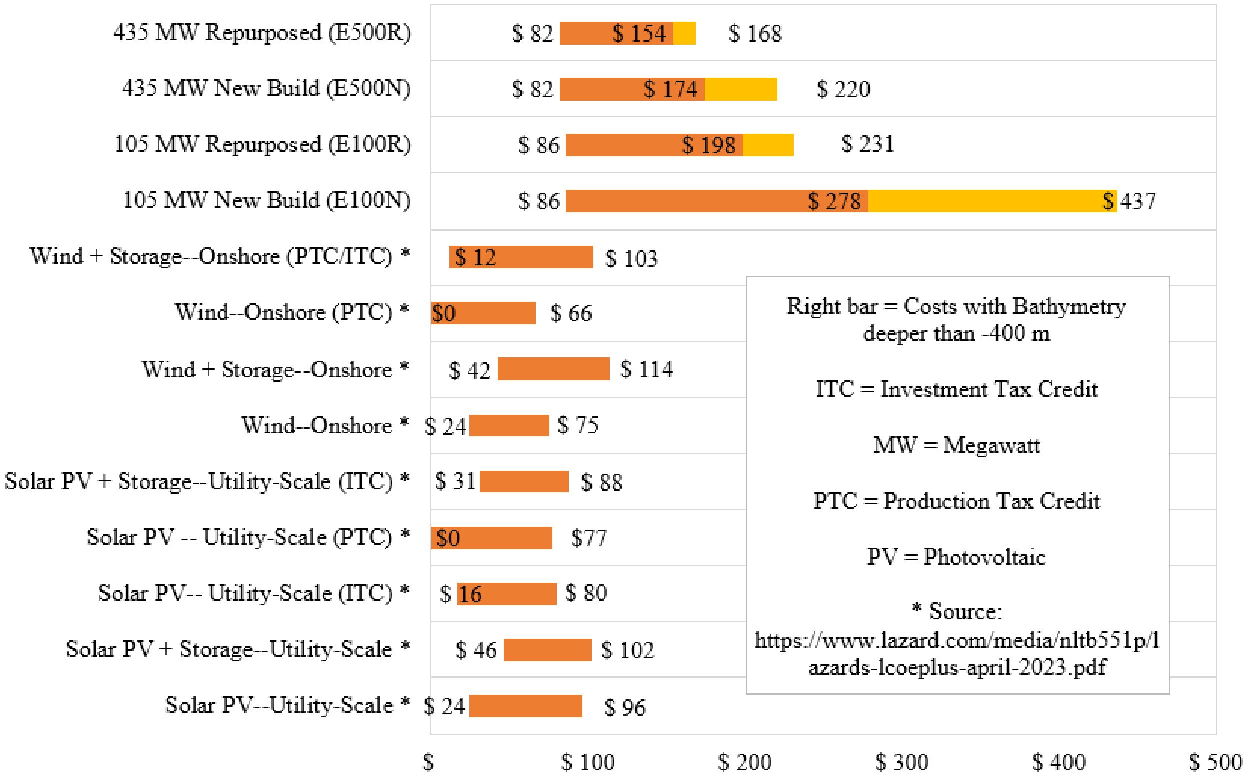

Figure 10: Levelized cost of electricity ($/MWh) (Lazard, 2023)

Figure 11 (a-d) compares all four power export cases from this study on a common scale, enabling comparison and seeing the impact of project scale and comparing new build and repurposing cases.

Key conclusions to draw from the comparisons in Figures 10 and 11 are as follows:

- As expected, the range of LC for offshore renewable projects is higher than onshore renewables.
- With suitably designed incentives and design optimizations, the lower end of offshore projects have the potential to be competitive with onshore projects.
- Smaller scale projects need to be in shallow water/near-shore locations to be economic
- Repurposing helps reduce the LC for deeper water and/or far-shore locations
- Repurposing has a greater impact on small-scale projects
- In several regions where repurposing does have a tangible impact, the overall LC is high even with repurposing, indicating challenging project economics

However, it should be pointed out that these LCs do not account for any federal credits such as ITC or PTC for renewables. It should also be pointed out that these are screening-level estimates with generalized assumptions. More definitive conclusions will be expected to be drawn in Phase 2 where ROICE designs will be developed for specific assets with more accurate cost estimates and include all applicable credits to estimate more accurate project economics.

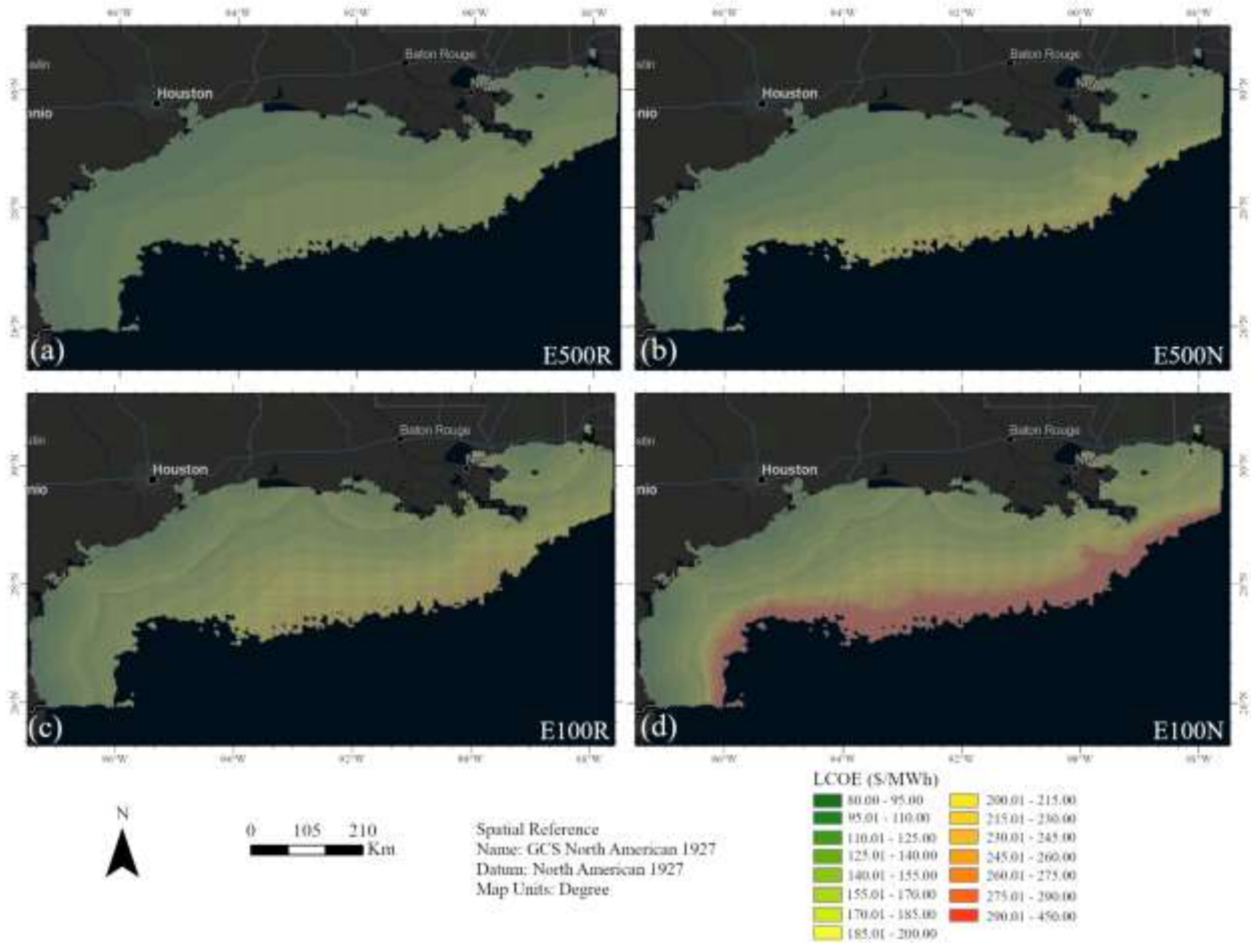

Figure 11: Four Power Export Cases on a common scale (a) E500R (b) E500N (c) E100R (d) E100N

3.2 Hydrogen Export Cases (LCOH, $/kg)

The Levelized Cost of Hydrogen (LCOH) GSLC maps allow for a comparison of the screening level cost of producing hydrogen at various locations in the Gulf of Mexico. As discussed above, the levelized costs for these hydrogen generation cases include the CAPEX cost of the appropriate size of wind power generation systems. The "H100" cases thus are supported by a 105 MW wind power generation system identical to the equivalent "E100" case, without, of course, the need for export cables. The "H500" cases are supported by 435 MW wind power generation systems identical to those in the equivalent "E500" cases.

The GSLC map for the H500R case (Hydrogen export, 435 MW size, Repurposed) is shown in Figure 12. The LC for this case ranges from 4.76 to $8.21/kg. The equivalent chart for a demonstration-scale project H100R (Hydrogen export, 105 MW Size, Repurposed) is shown in Figure 13. LC for this case ranges from 4.91 to $8.44/kg. In both these cases, the lower end of the LCOH ranges above correspond to near-shore and shallow water locations while the higher end locations are further from shore in deeper water. This is primarily driven by the higher cost for floating wind turbines, and higher pipeline repurposing costs due to a greater distance from shore. A secondary contributor is higher installation and maintenance costs for locations further from shore and in deeper water, requiring more complex service vessels. However, unlike in the power export cases, hydrogen projects do not have significant economies of scale. The LC for H100R is only 3% higher than that of H500R, across the entire range of LC. This implies that a large fraction of costs for a hydrogen project scale well with project size. Said another way, in power projects, the cost of export cables does not scale according to the power being exported via these cables. Therefore, higher capacity projects result in lower LC values by sending more power through the same cost of cables. The scale effect is further diluted because hydrogen projects have the option to repurpose pipelines at a cheaper cost than laying new export cables in a repurposed electricity project.

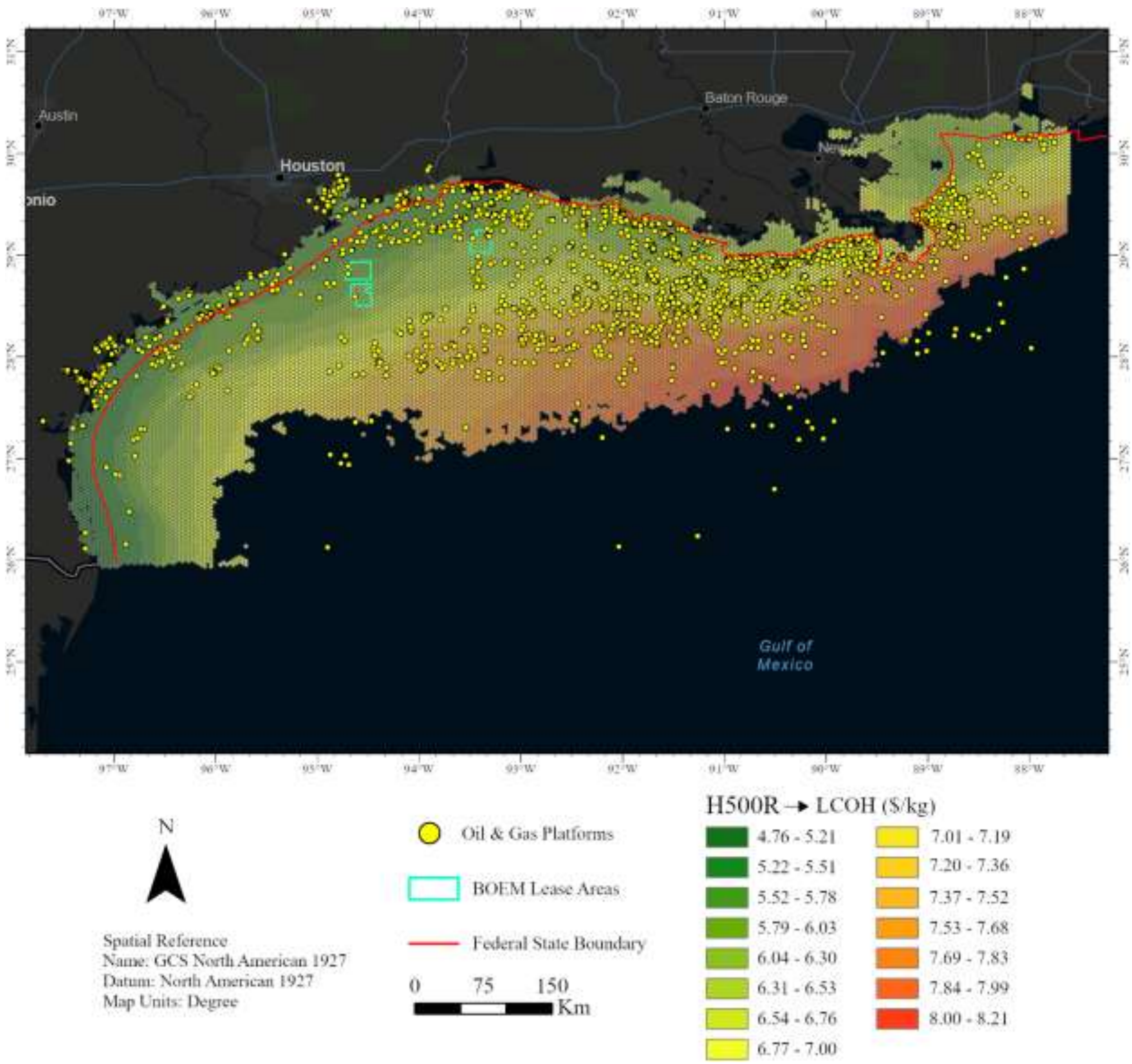

Figure 12: LCOH distribution for power export H500R

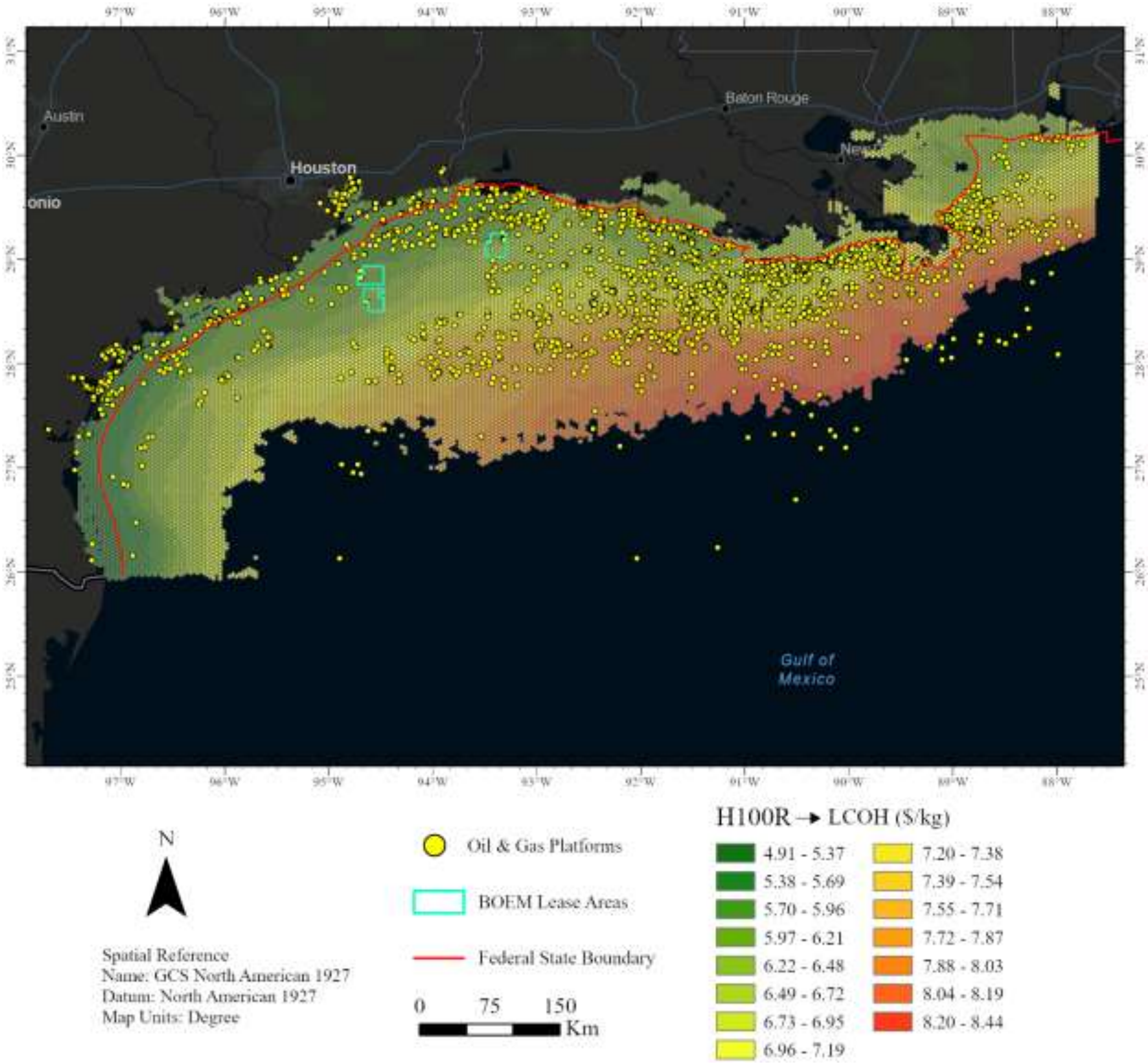

Figure 13: LCOH distribution for power export H100R

The GSLC maps for the equivalent new build cases - H500N (Hydrogen Export, 435 MW size, new build) and H100N (Hydrogen Export, 105 MW size, new build) are shown in Figure 14 and Figure 15 respectively. LC for H500N range from 4.77 to $10.81/kg, while those for H100N range from 4.91 to $19. 64/kg. As in the Power Export cases, repurposing reduces the LC at the higher end of these ranges (deeper water and/or further from shore). Again, this is because new build projects need to install a new foundation and structure to support the hydrogen generation components, the cost of which can be quite significant in deeper waters. Repurposing cases avoids this cost by reusing the existing oil and gas structure.

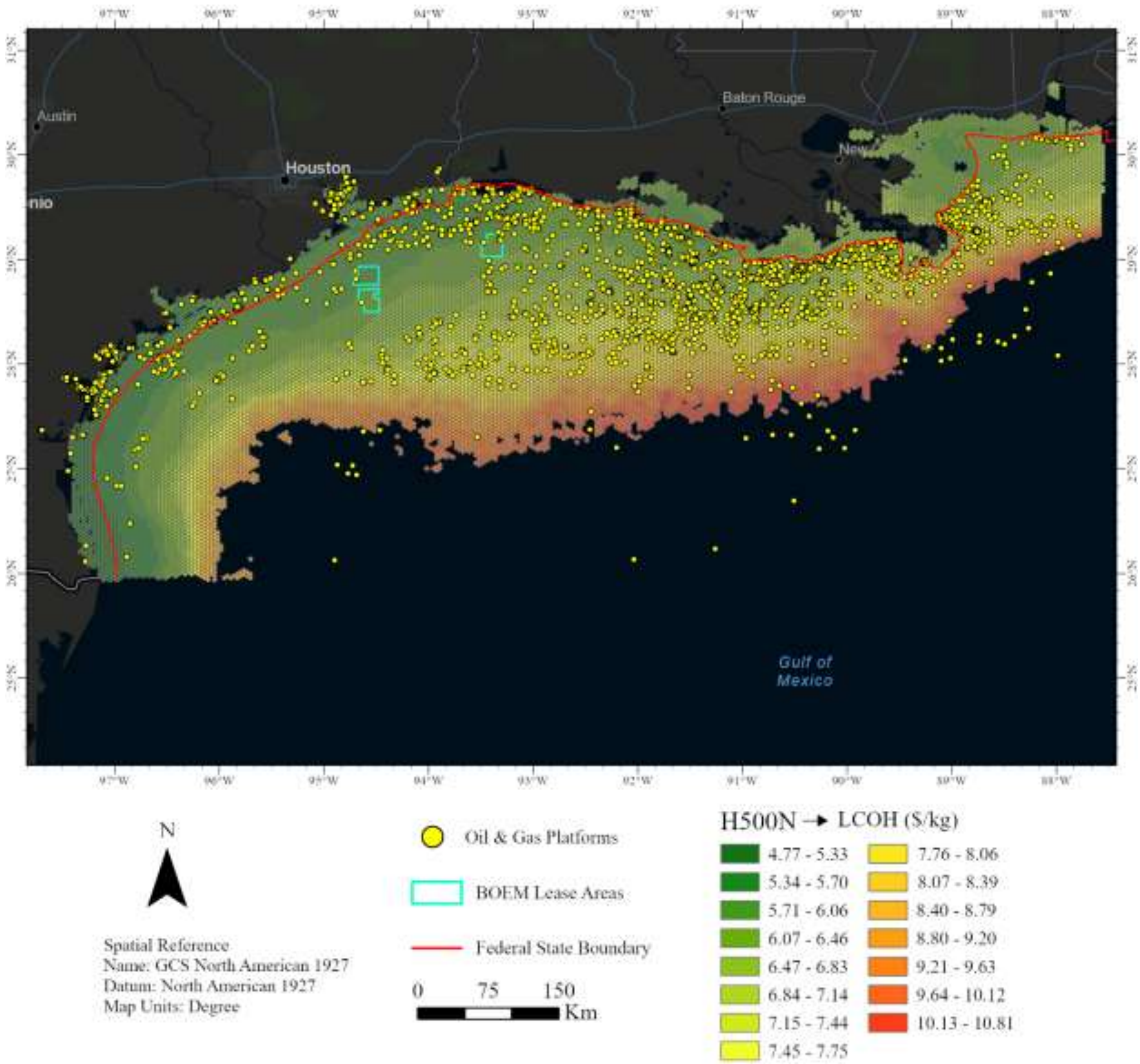

Figure 14: LCOH distribution for power export H500N

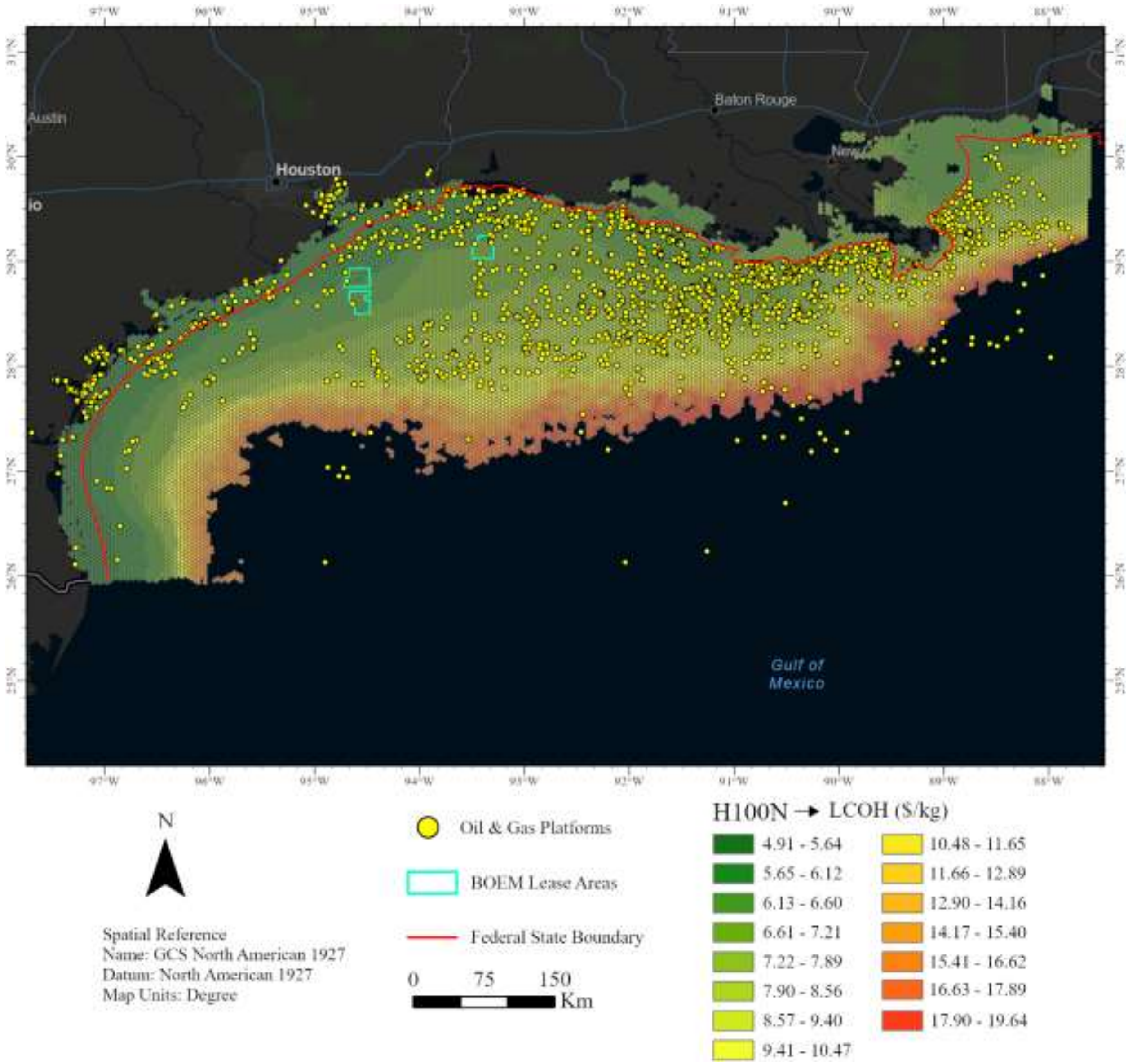

Figure 15: LCOH distribution for power export H100N

Figure 16 compares the LCOH ranges for the above four hydrogen export cases to onshore hydrogen generation pathways such as steam methane reforming (SMR), steam methane with carbon capture, and electrolysis by wind or solar. The lighter green colored bars on the right for each of the project LCOH cases represent cases in water depths greater than 400 m. As can be seen from the figure, the project cases are all to the right of the onshore, with a significant cost differential to conventional hydrogen production through SMR and fossil fuel use. However, the gap is not as high when compared to hydrogen generated from low-carbon energy. With a production or investment tax credit applied, the LCOH for offshore ROICE cases could potentially become competitive with onshore low-carbon hydrogen. Having said that, it is not entirely clear if the other reference cases include applicable tax credits.

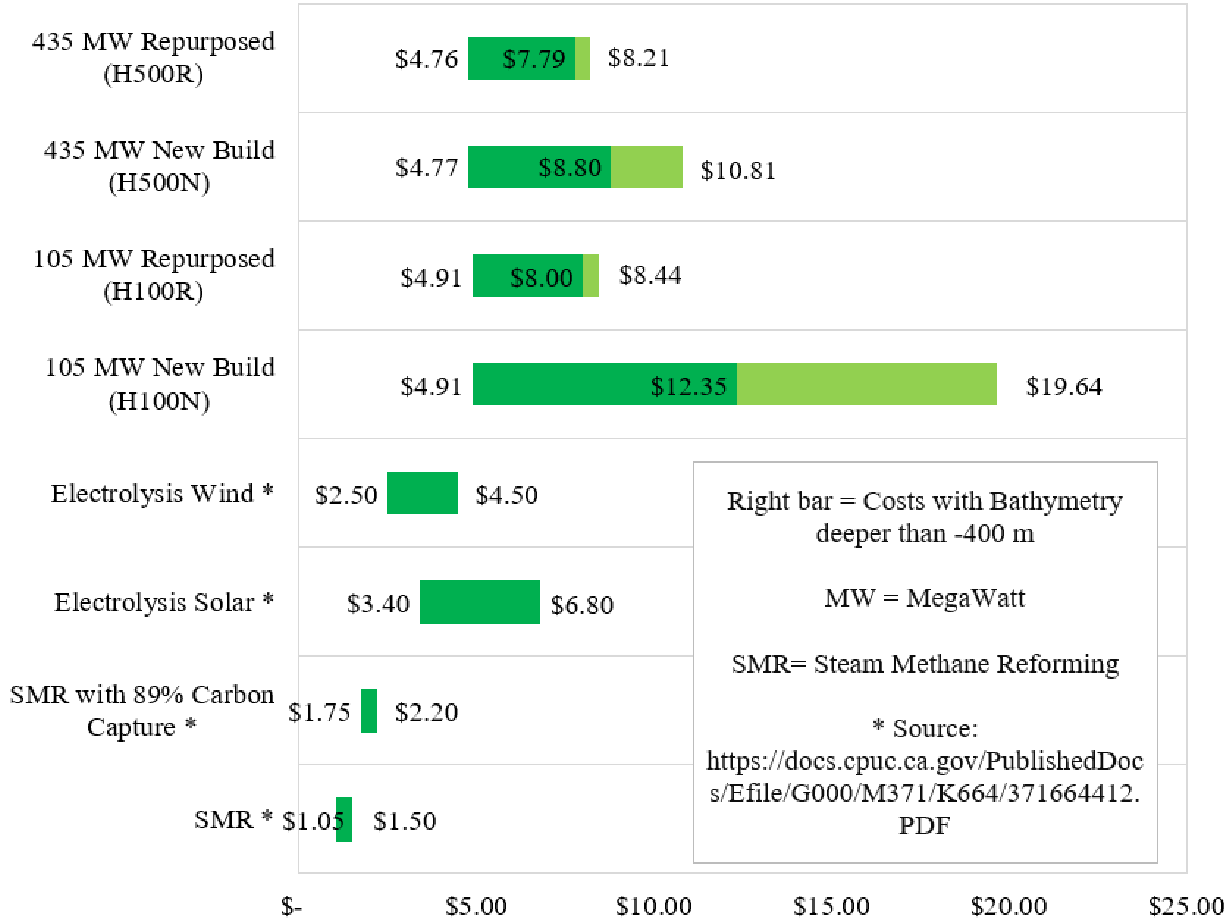

Figure 16 Levelized Cost of Hydrogen (LCOH) Comparison ($/kg H_2) (Bartlett & Krupnick, 2020).

Figure 17 (a-d) displays all four Hydrogen Export Cases on a common scale, enabling visualizing the impact of project scale and comparing new build and repurposing cases.

On examining all these comparative GSLC maps and charts, similar conclusions can be drawn from comparing the LCOH cases as was done in comparing the LCOE cases:

- As expected, the range of LC for offshore renewable projects is higher than onshore renewables
- Hydrogen projects appear to be more competitive in the lower end of the LC range with onshore projects relative to equivalent power generation projects
- Repurposing helps reduce the LC for deeper water and/or far-shore locations
- Repurposing has a greater impact on small-scale projects
- In several regions where repurposing does have a tangible impact, the overall LC is high even with repurposing, indicating challenging project economics

However, one unique conclusion for hydrogen generation cases is that levelized costs are similar for a wide range of project sizes. This would imply that small-scale hydrogen projects with lower CAPEX outlays could provide similar returns on invested capital as larger projects. Therefore, a lead case for repurposing projects could be a small-scale nearshore hydrogen project.

As mentioned earlier, these are screening-level estimates with generalized assumptions. More definitive conclusions are expected to be drawn in Phase 2 where ROICE designs will be developed for specific assets with more accurate cost estimates and include all applicable credits to estimate more accurate project economics.

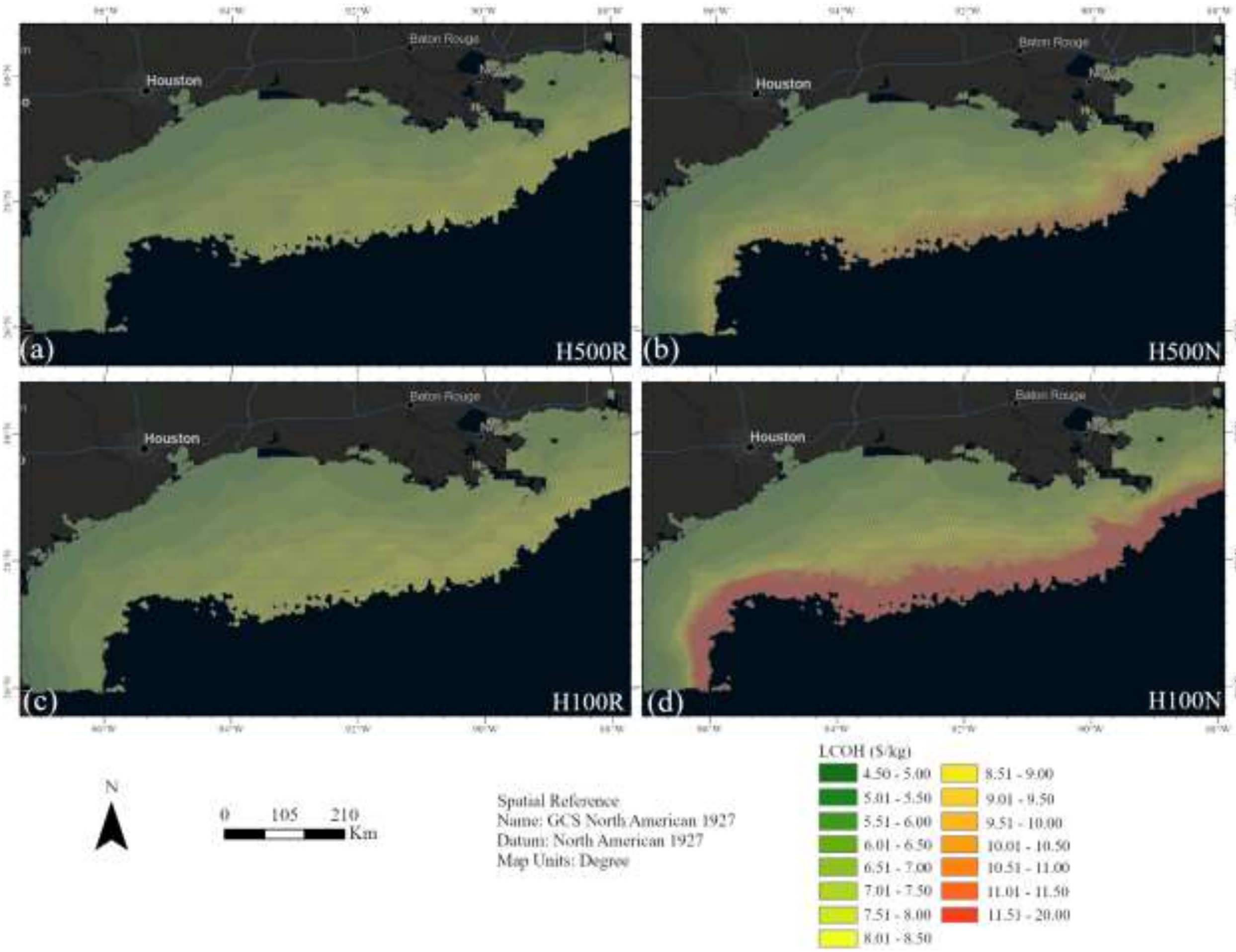

Figure 17: Four Hydrogen Export Cases on a common scale (a) H500R (b) H500N (c) H100R (d) H100N

3.2 Levelized Costs in BOEM Wind Lease Areas

As mentioned earlier, BOEM has announced three offshore Wind Energy Lease Areas in the Gulf of Mexico. The outlines of these lease areas can be seen below in Figure 18. An auction for these areas was recently concluded and the Lake Charles lease area was awarded to a bidder.

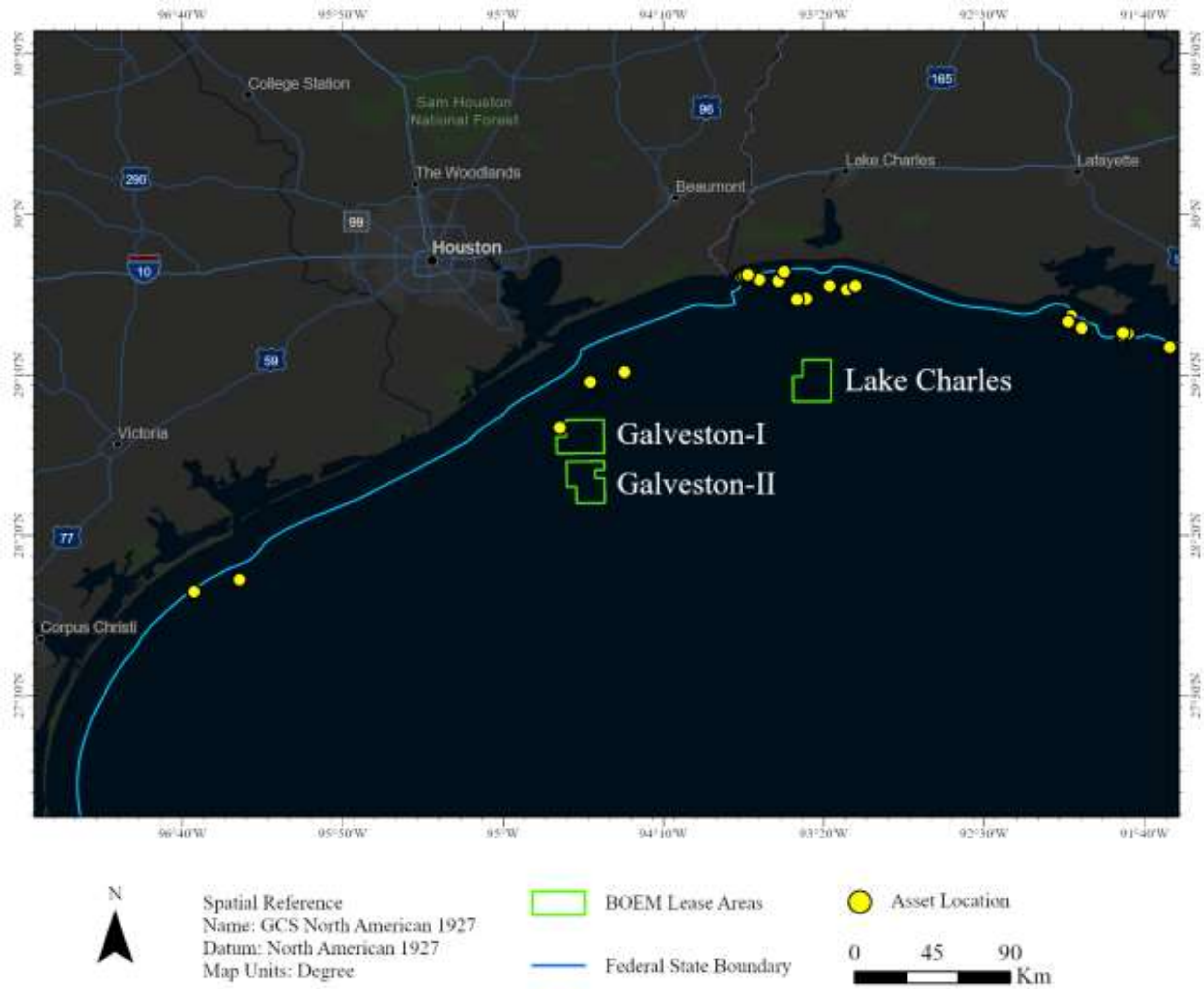

Figure 18: BOEM Lease area with nearby locations

Table 4 shows the average levelized costs for projects situated within these lease blocks for the eight different project configurations examined in this study. As can be seen, repurposing brings down the LC for all projects, but not significantly. No assets exist within these lease blocks, but several assets are in close proximity. These assets can be repurposed and connected to wind farms in the wind lease areas. Some of these assets will be studied in greater detail in Phase 2 to estimate the economics for new and repurposed projects.

Table 4: LC Distribution over BOEM Lease Areas

Lease Blocks	**E100N ($/MWh)**	**E100R ($/MWh)**	**E500N ($/MWh)**	**E500R ($/MWh)**	**H100N ($/kg)**	**H100R ($/kg)**	**H500N ($/kg)**	**H500R ($/kg)**
Lake Charles	142.7	138.9	118.2	117.3	6.65	6.44	6.33	6.28
Galveston-I	136.3	134.5	108.0	107.6	6.15	6.04	5.89	5.87
Galveston-II	153.2	150.4	115.6	114.9	6.45	6.30	6.18	6.14

3.3. Analysis of Major Influences on Levelized Cost

LC values are a complex function of four primary variables:

- Wind speeds at the location determine power generation and hydrogen generation levels
- Project size dictates the size and cost of power and hydrogen generation equipment installed and supported
- Water depths determine foundation type – fixed or floating wind turbines for example
- Distance to shore determines the length and cost of power export cables, length of pipeline to be repurposed or newly installed for hydrogen

In addition, some factors have secondary influences:

- Water depth dictates the type of installation and maintenance vessels to be used
- Distance to shore, specifically distance to installation ports O&M ports, and power grid tie points, determines vessel days required for installation and maintenance

The distribution across the GOM of the above three geospatial variables follows different trends, with wind speeds forming east-west bands (Figure 2), water depths forming north-south bands (Figure 3), and distance to shore dependent on the variations of the coastline and the location of various ports (Figure 4). This results in a complex interrelation between costs and product generation making it hard to map trends to any one specific variable. GSLC maps shown in the previous sections are therefore the best way to view the distribution across GOM. However, there are still a few learnings to be gleaned from looking at dependence on specific variables. That is done by looking at the CAPEX components for the three representative locations.

The impact of wind speeds does not warrant much analysis since the average and variation are given once the location is fixed. The higher the wind speed at the location, the more power or hydrogen is generated for a given CAPEX, thus reducing the LC. The impact of the other variables on CAPEX is disucssed below, including the CAPEX savings from repurposing.

3.4. Levelized Cost Trends for Asset Locations

As discussed above, the GSLC maps were used to assign LC values and other parameters to each of the ~1700 assets in the GOM. To improve the understanding of the impact of various factors on levelized cost, a switch is now made from GSLC maps to this asset database. Each data point shown in the graphs in this section represents an asset location in the GOM.

3.4.1. Power Generation

Figure 19 shows the relationship between water depth and levelized cost for power generation projects. The LC values for the two project sizes (500 and 100) and new and repurposed (N and R) cases are compared. Figure 20 zooms in on assets in water depths up to 200m.

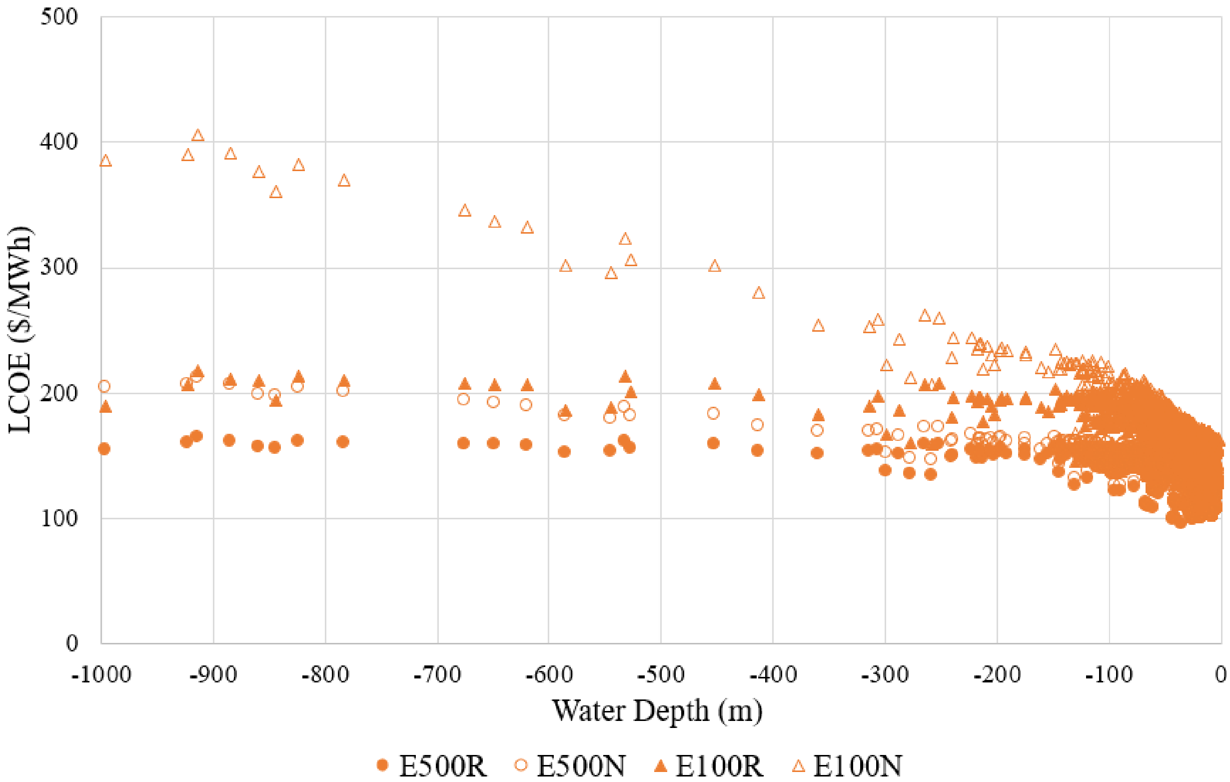

Figure 19: Impact of Water Depth on LC for Power Export Projects

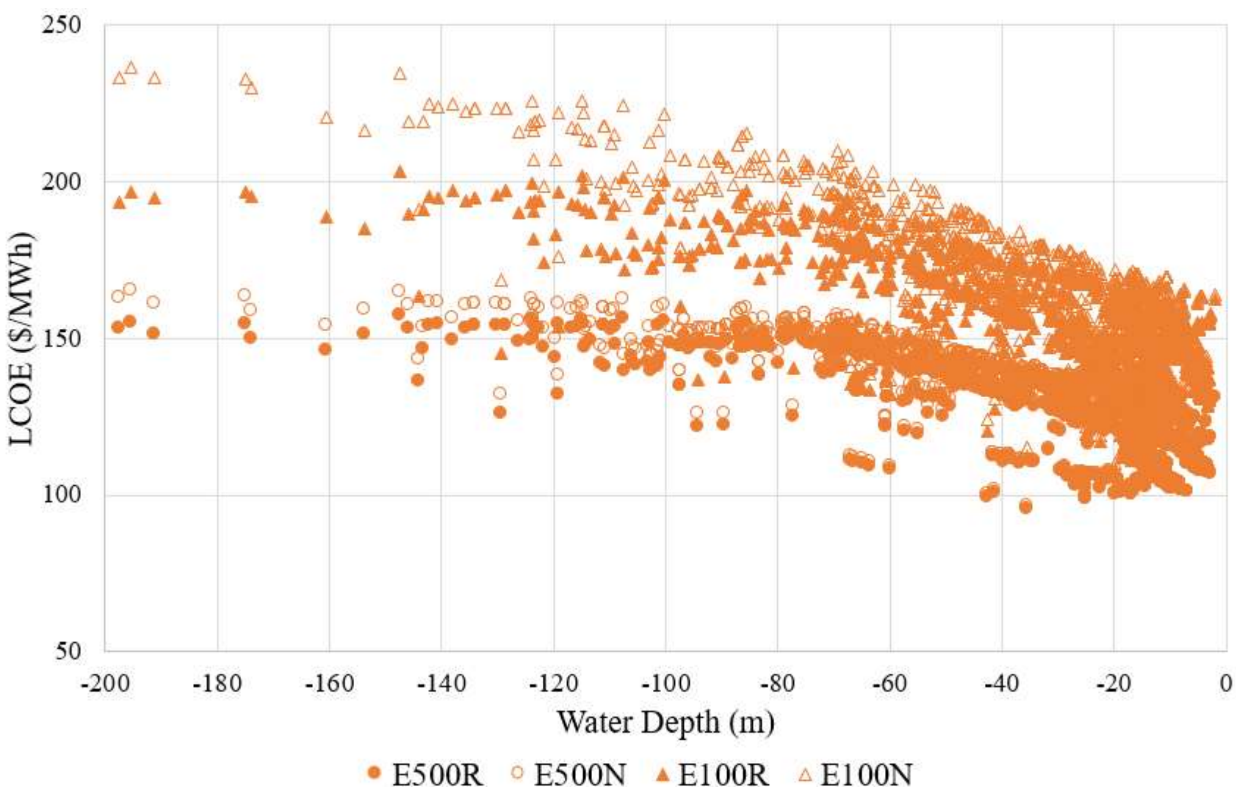

Figure 20: LC Variation for Power Projects in Shallow Water

The lesser degree of correlation of LC values for assets at water depths less than 50 m reflects the higher proportional impact of wind speeds at these locations on the levelized cost. As mentioned earlier, the correlation between water depth and wind speed is weak with wind speed trending from west to east, rather than with water depth. Therefore, for assets in similar water depths, wind speeds can be quite different, resulting in varying levels of power generation and a variance in LC.

Looking past this nearshore cluster, two distinct slope lines can be seen– one up to about ~80 m of water depth and one in deeper waters. These slopes are more evident in Figure 21 which shows the correlation between CAPEX for power export projects and water depth. There are multiple reasons for this slope change.

- Switching from HVAC transmission systems to HVDC. This is a switch driven by distance to shore rather than water depth, however generally speaking, deeper water assets are further from shore.
- When the transmission system changes to HVDC, the cost of cables per meter comes down by more than half, driving a reduction in the slope of CAPEX (and LC) vs water depth. However, for assets further from shore, the project will need greater lengths of cable to bring the power to shore.
- Switching from fixed to floating wind turbine foundations. Floating foundation costs are less impacted by water depth while fixed foundation costs are proportional to water depth.
- Installation and maintenance costs also could be higher for these assets.

The net effect of all these factors is a much slower increase in CAPEX and LC for deeper water assets.

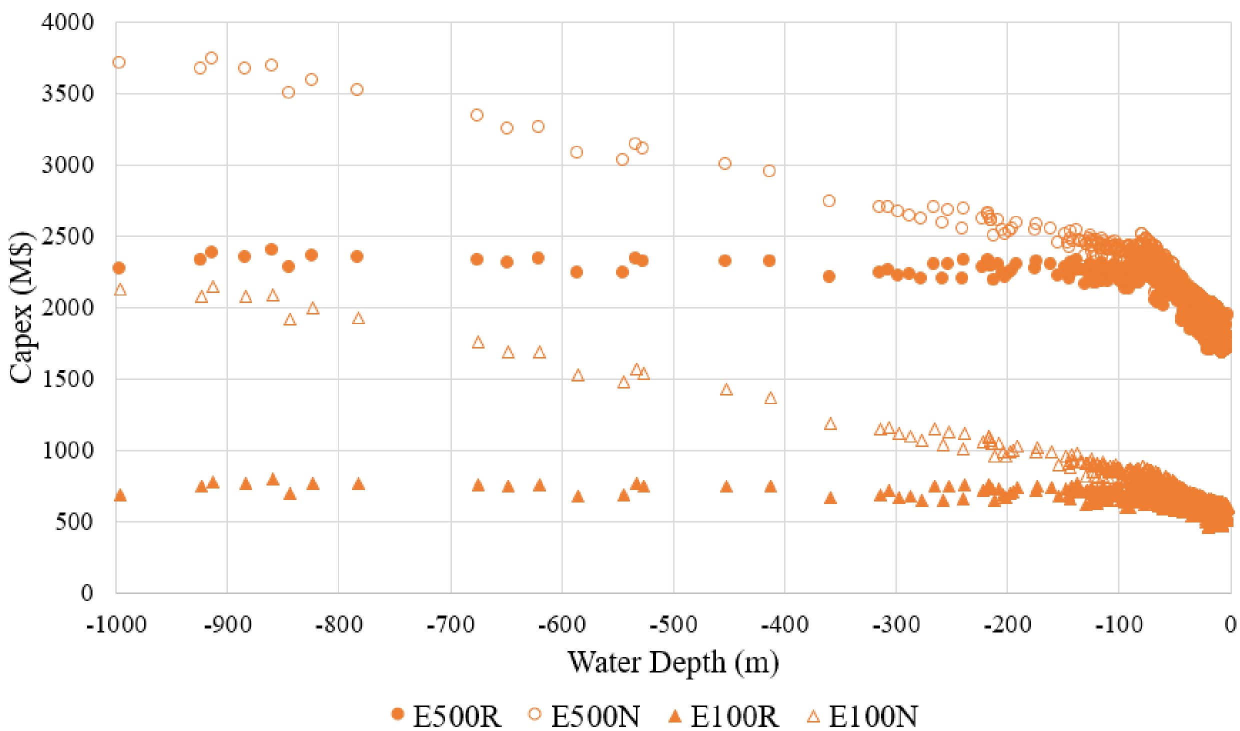

Figure 21: Impact of Water Depth on Project CAPEX for Power Export

Figure 19 and Figure 20 also indicate that larger projects are a more efficient investment of capital, reflected by the lower LC for the E500 projects, especially in deeper waters. For new build projects, comparing the slope of CAPEX vs water depth (Figure 21) and LC vs water depth (Figure 19), it is clear that the larger E500N projects are able to absorb the CAPEX increase due to their higher power outputs, thus reducing the slope of LC vs water depth. Smaller projects on the other hand do not generate enough power to absorb the CAPEX ncrease in deeper waters, resulting in a steep increase in LC with water depth. Thus, smaller new build projects may not be viable in deeper waters / further from shore locations. Project size has an impact on LC for repurposing projects (E500R and E100R) as well, although the improvements in LC are not as pronounced as in new build projects because of the buffering effect of reusing existing structures.

Repurposing reduces the CAPEX and LC by a greater percentage for smaller projects. This is because the foundation/platform costs represent a greater fraction of total project costs compared to larger-scale projects where the WTG and other costs dominate. This also explains the relatively lower slope of LC vs depth for repurposed projects versus new builds. Once you take the jacket out of the picture, the remaining components are less sensitive to water depth. The main reason for the gradual increase in LC in deeper waters for repurposed projects is increased installation and maintenance costs due to a longer distance to ports for these deeper water locations.

It can also be seen from Figure 20 that if a smaller project is planned for deeper waters, repurposing an existing structure can significantly reduce the LC by as much as half for a repurposed project (E100R) vs a new build one (E100N).

3.4.2 Hydrogen Generation

Figure 22 shows the relationship between water depth and levelized cost for hydrogen generation projects. The LC values for the two project sizes (H500 and H100) and new and repurposed (N and R) cases are compared. Figure 23 zooms in on assets in water depths up to 200m.

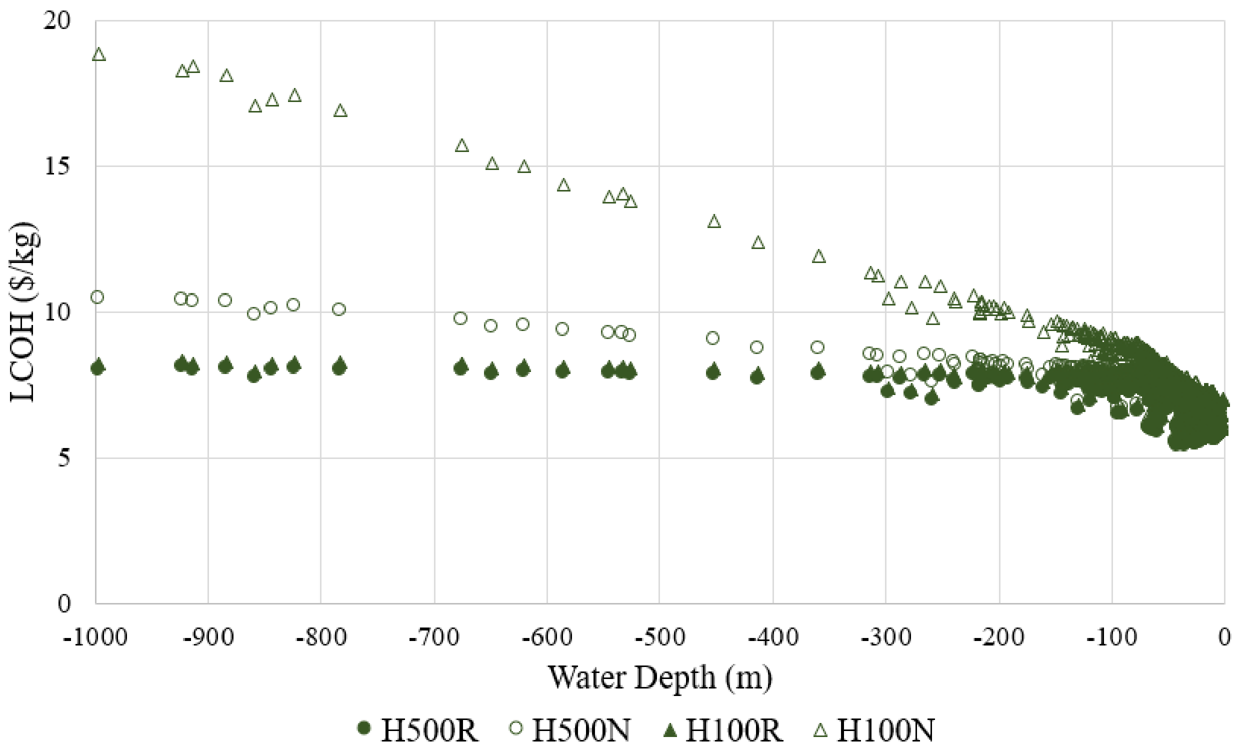

Figure 22: Impact of Water Depth on LC for Hydrogen Export Projects

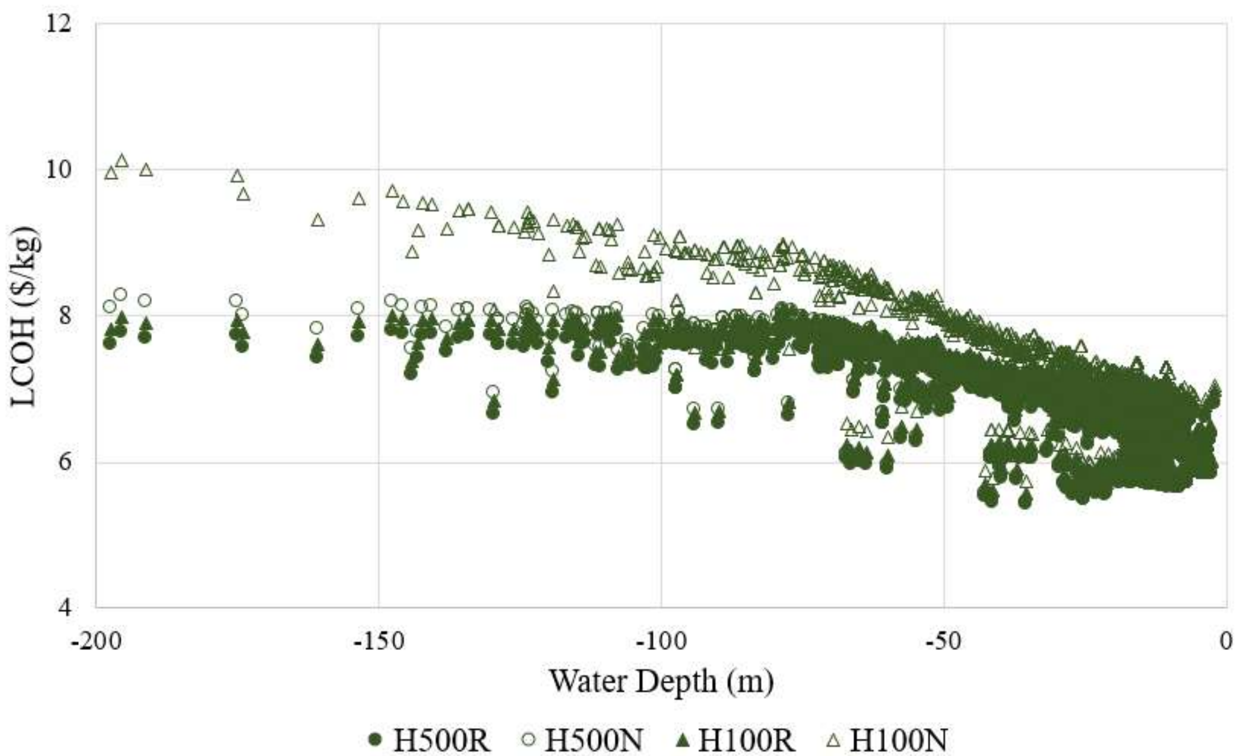

Figure 23: LCOH vs Water Depth for Shallow Water Assets

As noted before, the power supply to these hydrogen projects is from equivalent wind power projects. Other than not needing power export cables and onshore substations, the power generation equipment is the same. Therefore, some of the observations made in comparing power projects in the previous section on power projects apply to hydrogen projects as well.

- The large cluster of LC values for assets at water depths less than 50 m reflects the greater impact of wind speeds at these locations on the levelized cost relative to water depth. Depending on the east-west location of the shallow water asset, wind speeds can be quite different, resulting in varying levels of power generation and resulting hydrogen generation.
- Looking past this nearshore cluster, two distinct slope lines can be seen– one up to about ~80 m of water depth and one in deeper waters. These slopes are more evident in Figure 24 which shows the correlation between CAPEX for power export projects and water depth. The primary driver for the lower slope in deeper waters for hydrogen systems is the switch from fixed foundations for the wind turbines (whose costs go up with water depth) to floating foundations (whose costs are less dependent on water depths).
- Other factors impacting the slope that were relevant for power generation projects, such as cable costs and transmission system impacts, are not applicable to hydrogen systems.
- Just as in the power projects, distance to shore impacts LC. Generally speaking, deeper water assets are further from shore, so these impacts are also seen in correlations to water depth. For these locations, a hydrogen export project will need to repurpose greater lengths of pipeline to bring the hydrogen to shore or lay greater lengths of new pipelines. Installation and maintenance costs also depend on the distance to shore.
- For new build hydrogen projects, as for power projects, project size has an impact. Larger projects are more capital-efficient and result in reduced LC at a given water depth. This is not true for repurposed projects as discussed below.

There are a few trends that are unique to hydrogen projects:

- As can be seen in Figure 24 below, the costs for repurposed hydrogen projects (H500R and H100R) increase only slightly with water depth beyond water depths greater than ~100m. This is because once the depth-dependent cost of a support equipment platform structure is eliminated through repurposing, the costs of the rest of the hydrogen project components are not dependent on water depth. There is a secondary dependence on the distance to shore for installation and maintenance costs, but this does not impact the LCs significantly.
- A corollary of the above trend is that for new build projects, there is a strong depth dependence on CAPEX and LC. Therefore, it is advantageous to consider repurposing options for deeper water / further from shore hydrogen projects. Of course, these projects are challenged with high LCs even after repurposing, so further optimization and greater production incentives are needed to make these projects attractive.

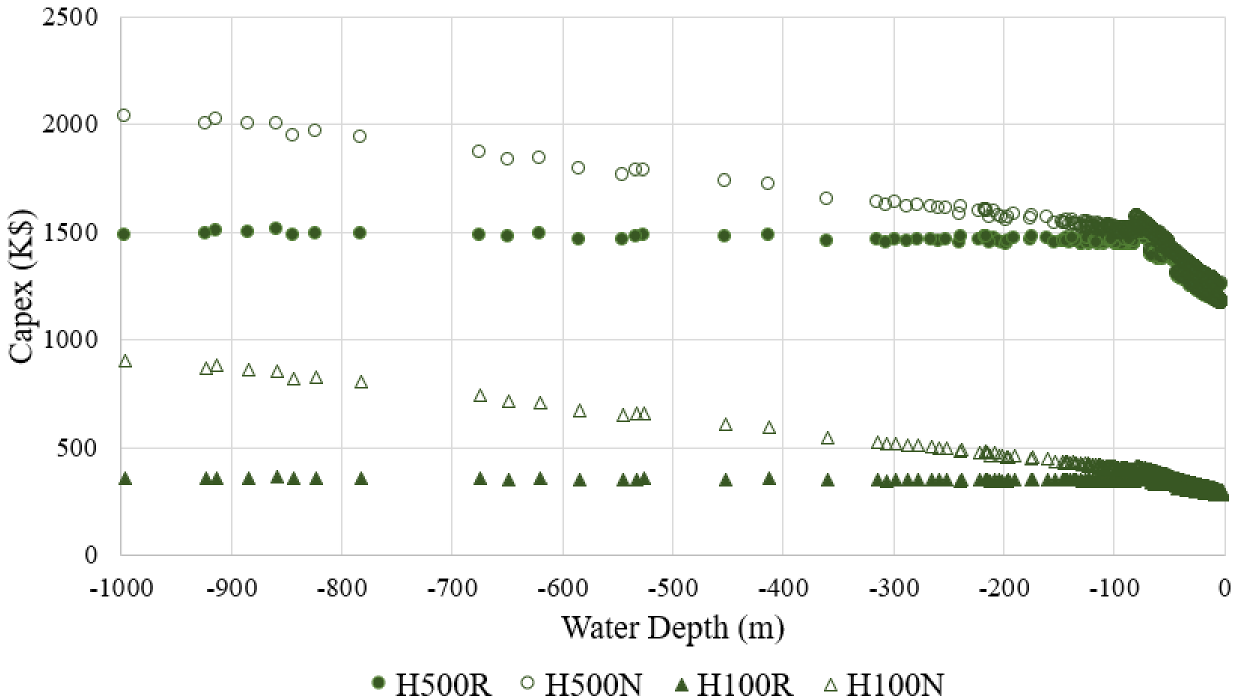

Figure 24 Impact of Water Depth on Project CAPEX for Hydrogen Export

- Eliminating the cost of the support structure platform through repurposing also removes the dependence of hydrogen project LCs on project size. This can be seen in Figure 22 where H500R and H100R points lie almost on top of each other. This is because the other hydrogen project cost components scale in direct proportion to project size and resulting hydrogen generation. Power export projects do not have this advantage, since cable costs increase with distance to shore, and do not scale with the amount of power being exported.
- Repurposing thus has dual advantages for hydrogen projects in deeper water/further from shore locations – it limits the increase in CAPEX and LC for these locations relative to shallow water/near shore locations, and it also eliminates the need for increasing project size to capture economies of scale. These advantages may make it more attractive to implement hydrogen export projects in these locations versus power export projects.

3.4.3. Impact of Repurposing

This section takes a deeper look at the impact of repurposing on levelized cost (and therefore ROICE project economics). A % reduction in LC for each asset resulting from repurposing was calculated. This is done for each of the four cases – E500, E100, H500, and H100 – by taking the ratio of the levelized cost for the repurposed project (R) to the corresponding new build project (N). Figure 25 plots the % Reduction in LC as a function of water depth for each of the ~1700 assets in the GOM.

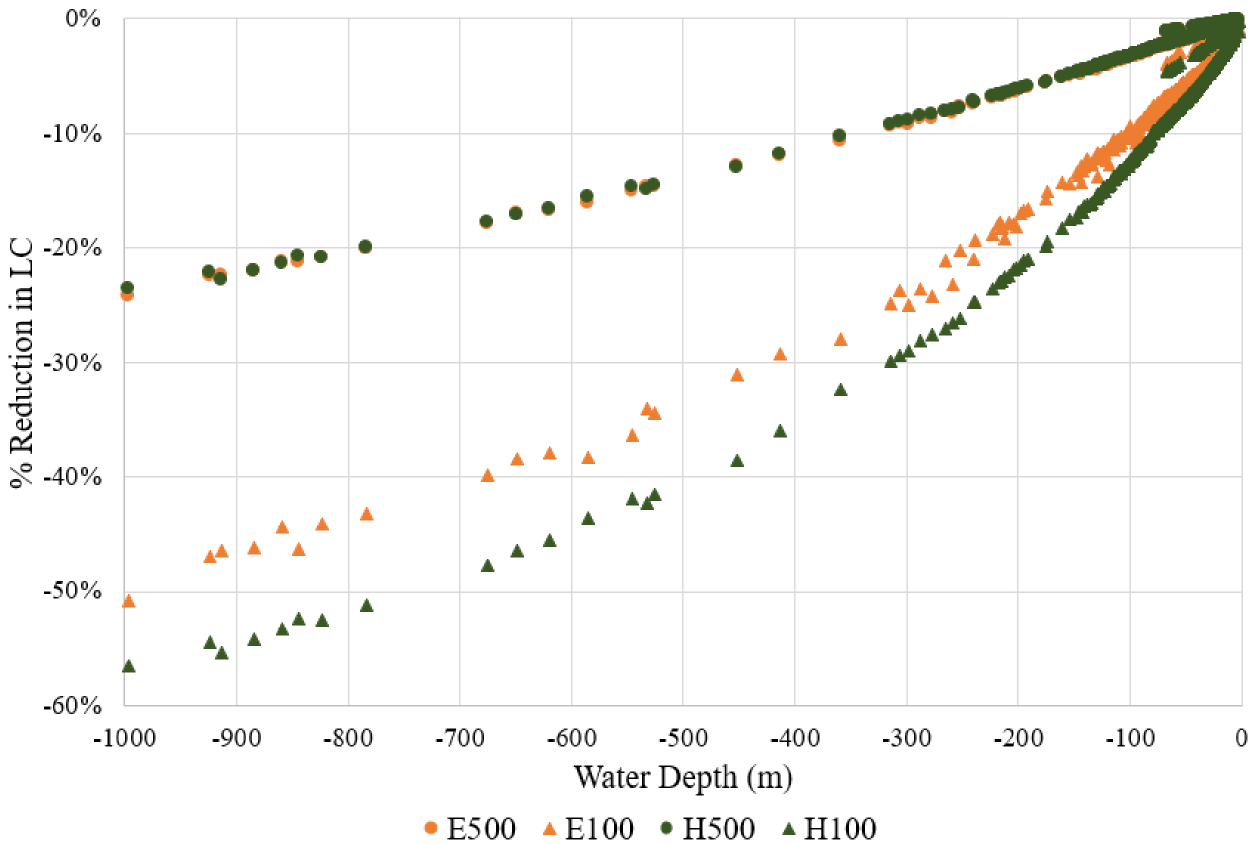

Figure 25 Levelized Cost Reduction from Repurposing

As can be seen, repurposing appears to have a greater impact on deeper water projects. This can be ascribed to cost-avoidance, through repurposing, of an increasingly expensive new build platform to support the power and hydrogen infrastructure as the water depth increases. Repurposing also appears to have a greater impact on smaller projects. This is because the cost of the support platform forms a greater fraction of the total CAPEX for smaller projects. Therefore, saving on those costs by reusing existing structures results in a larger LC reduction. Further reusing pipelines to bring hydrogen back to shore allows for a greater % LC reduction for smaller hydrogen projects.

4 Conclusions and Future Study

In this research study, the ROICE LC model has been used to generate the GSLC maps that show LC distributions for different project scenarios across the GOM. These scenarios include new builds and repurposed versions of wind and hydrogen projects at both demonstration and commercial scales. The maps were used to estimate screening level LC values for each of the ~1500 assets in the GOM to identify favorable locations for different versions of ROICE projects. A shortlist of 50 assets has been developed for a more detailed study in Phase 2 of this project. Key Phase 1 conclusions are listed below.

General Conclusions:

- LC for repurposed wind projects in the GOM range from \$82 to \$231 per MWh. Equivalent new build projects have LC ranging from \$82 to \$437.

- LC for repurposed hydrogen projects in the GOM range from $4.76 to $8.44 per kg of hydrogen. Equivalent new build projects have LC ranging from $4.77 to $19.64.
- While noting that the above LC do not include any federal or state incentives, these are higher than equivalent low-carbon renewables-based onshore projects, and even more challenged versus high-carbon alternatives.
- However, projects at the lower end of the range of LC across the GOM have the potential to be competitive with onshore projects through efficient design, cost reductions, and use of all available federal and state incentives.
- Of the different components of the oil & gas structure to be repurposed, it is probably most cost-effective to reuse the jacket (main support structure) and the deck (flooring above the structure) for ROICE projects. The remaining equipment will need to be decommissioned as per normal practice - removal of oil & gas topsides, abandonment of all wells, and any pipelines that will not be used to transport hydrogen.
- Such repurposing has the dual impact of reducing CAPEX and shortening the schedule of implementation of ROICE projects. Repurposing will have a positive impact on LC for most projects. This improvement is more pronounced for deeper water projects and for smaller-scale projects where the savings from reused infrastructure form a significant portion of the total project CAPEX.
- Shallow water / near-shore locations appear to have the lowest LC for all cases - new build or repurposed, power or hydrogen projects. This is due to several reasons – higher wind speeds, lower structural costs, lower cable costs, etc. Repurposing improves the LC by 5 to 10% for these locations.
- Further away from shore, in deeper waters, hydrogen projects and repurposing prove to be more attractive. Repurposing can reduce the LC by up to 25% for larger-scale projects and up to 60% for smaller-scale projects.
- In regions where repurposing has a significant impact, the overall LC is high even with repurposing, indicating challenging project economics. Stronger government incentives and major cost reductions will be needed to make these competitive.

Impact of Water Depth and Distance to Shore

- An increase in CAPEX for components dependent on depth and distance-to-shore makes deeper water / far-from-shore projects more challenging. At these locations, reducing CAPEX outlay via a small-scale hydrogen project or leveraging economies of scale with a large-scale power project may be the best option for new build projects.
- Repurposing has a greater impact on power generation projects in deeper water. This can be ascribed to cost-avoidance, through repurposing, of an increasingly expensive new build platform to support the power and hydrogen infrastructure as the water depth increases.
- The costs for repurposed hydrogen projects increase only slightly with water depth beyond water depths greater than ~100m. This is because once the depth-dependent cost of a support equipment platform structure is eliminated through repurposing, the costs of the rest of the hydrogen project components are not dependent on water depth.

Impact of Project Size

- Larger projects are a more efficient investment of capital for new build power or hydrogen projects, especially in deeper waters. Shallow water projects are less sensitive to economies of scale.
- Project size has an impact on LC for repurposing projects as well, although not as pronounced as in new build projects because of the buffering effect of reusing existing structures.
- Repurposing has a greater impact on smaller projects since the cost of the reused support platform forms a greater fraction of the total CAPEX.
- Reusing pipelines to bring hydrogen back to shore allows for an additional LC impact for smaller hydrogen projects.
- Repurposed hydrogen projects are less sensitive to economies of scale, allowing for smaller CAPEX outlays. Once the cost of the support structure platform is eliminated through repurposing, the other hydrogen project cost components scale in proportion to the project size.
- Repurposed power export projects do not have this advantage, since cable costs are more a function of distance to shore, and do not scale with the amount of power being exported.

Hydrogen vs. Power Export

- A hydrogen generation project trades off power export cables and an onshore substation for electrolyzers, desalination units, and hydrogen pipelines. For new build cases and larger scale repurposed cases, this tradeoff only results in a ~10% increase in CAPEX for hydrogen export projects over equivalent power export projects.
- For small-scale repurposed cases, switching to hydrogen can even result in a 15 to 10% reduction in CAPEX. Note that repurposed hydrogen projects in this study assume that pipelines can be reused to bring hydrogen to shore.
- The incremental economics on the additional CAPEX for hydrogen generation is therefore likely to look quite promising in all cases, especially considering the healthier federal incentives for hydrogen production vs wind power generation.
- Repurposed hydrogen projects in deeper water / further from shore locations have a few advantages over equivalent power projects at these locations. CAPEX and LC for these locations are not significantly higher than shallow water / nearshore locations; reducing the project size to manage CAPEX outlay does not result in a large increase in LC.

Optimal Project Options

- Nearshore, locations are attractive for both wind power export or hydrogen export, over a range of project sizes. Repurposing improves the LC by 5 to 10% for these locations.
- Further away from shore, in deeper waters, hydrogen projects and repurposing prove to be more attractive. Hydrogen projects remain relatively attractive as water depth increases, and repurposing can reduce the LC by up to 25% for larger-scale projects and up to 60% for smaller-scale projects.
- If a smaller power generation project is planned for deeper waters, repurposing is highly recommended. It can reduce the LC by as much as half for a repurposed project vs a new build one.

Future Studies:

In Phase 1 of this study, any federal credits such as ITC or PTC are not applied for renewable energy or 45V for low-carbon hydrogen generation since these are likely to be project-specific. Further, several broad assumptions have been made to generate LC over a large geospatial area. More definitive conclusions are expected to be drawn in Phase 2 where ROICE designs will be developed for specific assets with more accurate cost estimates and include all applicable credits to estimate more accurate project economics. The work scope for Phase 2 includes:

- Enhance the ROICE LC Model using advanced digital models to include location specific annual wind speed variations and advanced turbine performance curves
- Switch from the Levelized Cost concept to project economic metrics such as NPV and Rate of Return
- Conduct sensitivity studies to see which parameters and scenarios have the greatest potential for optimizing and improving project economics
- Develop conceptual ROICE project designs for shortlisted assets using public domain information
- Refine the asset shortlist to identify potential demonstration and commercial project locations

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