THE ECONOMICS OF GULF STREAM ENERGY OFF THE NORTH CAROLINA COAST

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INTRODUCTION

Marine energy, including wave, tidal, ocean current and ocean thermal [1], is an important source of low-carbon, renewable energy. Previous research has shown great potential for marine electricity generation worldwide. For example, the estimated wave energy resource for the United States is approximately 2100 TWh/yr and the total amount of ocean current energy resource worldwide is estimated to be 5000 GW [1–3].

Marine current refers to a continuous, directed seawater circulation driven by temperature or pressure differences in the ocean [1]. It moves in one direction with relatively constant flow. As the most intensely studied ocean current, the Gulf Stream begins in the Caribbean and ends in the Northern Atlantic. This fast moving ocean current brings a significant amount of heat and salt to the European continent, and also provides an opportunity for energy capture.

The study on the potential of Gulf Stream energy dates back to late 1970s [4] and numerous analyses can be found in literature since then. In a recent study, Duerr et al. [5] estimates that the total hydrokinetic resource in the Florida Current, which is the upstream stretch of the Gulf Stream, is between 20 and 25 GW. By representing the effect of ocean current turbines as an additional drag force in a simplified analytical model, Yang et al. [6] found that the maximum energy dissipation by turbines is estimated to be approximately 44 GW. Using model data from the Hybrid Coordinate Ocean Model (HYCOM), Kabir and Lemongo et al. [7] assess the hydrokinetic energy resource for several locations near Cape Hatteras, NC and found that the theoretical power density of this region is estimated to be more than 275 W/m^2 around 70% of the time.

To our knowledge, no research has been done to estimate the cost of extracting electric energy from the Gulf Stream off the North Carolina coast. Although a reference model has been developed for a similar project in the Florida Strait [8,9], the marine environment and resource quality differs significantly off the North Carolina coast. Therefore, this study develops a levelized cost of electricity (LCOE) model to provide a techno-economic assessment of NC Gulf Stream energy, which can be used as a guide for future researchers and developers.

METHOD

A key indicator of the economic performance of an electric generator is the LCOE, which is defined as the ratio of total annual cost to total annual electricity generation. This section focuses on both the energy resource characterization and the cost calculation.

Resource Characterization

The resource data is obtained from a regional ocean circulation model, which is used to hindcast the circulation of the Middle Atlantic Bight (MAB), South Atlantic Bight (SAB) and parts of the Gulf Stream, Slope Sea and Sargasso Sea. The MABSAB model is based on the Regional Ocean Modeling System (ROMS), a free-surface, terrain-following, primitive equations ocean model in widespread use for estuarine, coastal, and regional ocean-wide applications [10]. The MABSAB model domain covers the domain from 81.89° W to 69.80° W, 28.41° N to 41.84° N. The horizontal resolution is

1.94 km to 2.37 km. Depth is represented by 36 terrain-following layers [10]. The sub-domain selected for analysis was 77° W to 74° W, 33° N to 36° N, which includes the strongest, near-shore Gulf Stream resources off the North Carolina coast.

MABSAB output for the years 2009-2014 was provided by Ruoying He of NCSU [11,12]. The 2009-2014 dataset includes the entire sub-domain referenced above, and includes daily average current speeds. The studied domain in each year is shown in Figure 1.

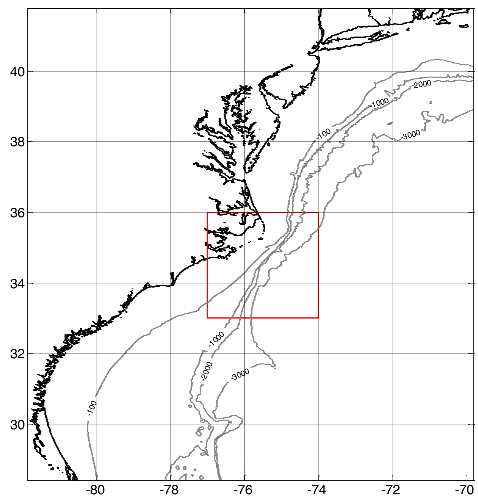

FIGURE 1. THE SELECTED STUDY DOMAIN (SHOWN AS A RED BOX).

To convert Gulf Stream currents into electricity, arrays of marine hydrokinetic turbines are assumed to be installed in the domain shown in Figure 1. The electrical power output of the turbine at a given current velocity is expressed by the following equation:

$$P(v) = \frac{1}{2}\eta C_p(v)\rho A v^3 \qquad (1)$$

where A is the swept rotor area, ρ is the density of sea water, v is the current velocity, $C_p(v)$ is the power coefficient that accounts for the conversion of current power to mechanical power and η is the combined power chain conversion efficiency, which includes the gearbox, generator, transformer and power inverter efficiencies. Equation 1 implies that with higher current velocity and a larger rotor diameter, the turbine will generate more power. However, the maximum electrical output can never exceed the installed capacity of each turbine and therefore the electrical output is truncated at the turbine's installed capacity. In this study, the installed capacity for each turbine is assumed to be 1 MW and the rotor diameter is 30 m, following Sandia's assumption [9] for the Reference Model of the Florida Current.

The annual electric energy output is obtained by integrating the product of the turbine's output at a specific current velocity with the velocity probability distribution over the entire velocity interval:

$$E = AF \cdot \eta_{TL} \cdot 8760 \int_0^{v_{max}} P(v) \cdot Pr(v) \mathrm{d}v \qquad (2)$$

where AF is annual availability factor, η_{TL} is transmission line efficiency and $Pr(v)$ is the probability density at given current velocity v.

Ideally, the integration in Equation 2 would be over a continuous velocity interval; however, for computational purposes a summation over discretized velocities obtained from the MABSAB model is performed.

To estimate the LCOE for each grid in the studied domain, it is assumed that an array of 16 turbines, with each turbine rated at 1 MW, is installed within each 2 km × 2 km grid cell, following similar turbine array layout in the Reference Model by Sandia [13]. In addition, a dedicated transmission cable is assumed to connect to existing grid infrastructure in Kitty Hawk. The array of turbines is assumed to be installed 50 m under the sea surface to allow for access to current with maximum velocity and to prevent navigational hazards [5].

Cost Assessment

Costs associated with Gulf Stream project development can be grouped into two categories: a one-time capital cost and annual recurring costs. The capital cost consists of pre-installation development, generating equipment, transmission, and project deployment costs, as shown in Table 1, while annual recurring costs include annual project operation and maintenance costs and recurring environment monitoring costs (Table 2).

All capital costs incurred at the beginning of the project are multiplied by the capital charge rate (CCR) to calculate the annual payments required to pay off that investment over the chosen life of the project. The CCR calculation is affected by the discount rate and the lifetime of the project. The lifetime of the project is assumed to be 30 years, based on the lifetimes of most renewable energy projects. A discount rate of 5% is selected as a reasonable estimate when taking a societal perspective.

There is no commercial experience with ocean current energy, and even basic technology assessment focused on site location, resource assessment, turbine design, mooring, operations and maintenance, and cost-effectiveness are in the earliest stages. Substantial uncertainty exists regarding capital cost as well as maintenance requirements and longevity in a harsh and unpredictable marine environment.

Capital Costs

Due to limited available data for the marine hydrokinetic turbine, the capital cost for the generating equipment is based on Verdant Power's estimate for the turbine of the Roosevelt Island Tidal Energy (RITE) project in 2010 [14]. The transmission cost is based on a previously developed offshore wind energy model, a similar project [15] with undersea cable tied to the grid of North Carolina. To calculate cabling distances, the model assumes that the undersea cabling connects to Kitty Hawk, NC where existing transmission and distribution infrastructure exists.

TABLE 1. CAPITAL COST COMPONENTS

Category	Subcategory and Values	
Development	Siting and scoping, Project Design, Engineering & Management	
	120,000	$
Generating Equipment	Hydrokinetic turbine	
	4,000,000	$/MW
Transmission	Cable, Transformers, Converter	
	30,000	$/mile
	24,200	$/MW
	14,300	$/MW
Deployment (Fixed + Variable)	Cable Shore Landing, Mooring/Foundation System, Cable Installation, Device Installation	
	4,661,200	$
	20,000	$/MW
Initial Permitting Cost	Surveying and Environmental Monitoring (fixed), Surveying and Environmental Monitoring (variable with project size - per MW), Developer Resources, Delay, Uncertainties, Contingency	
	4,861,000	$
Environmental Monitoring Set-up Cost	Up-front cost	
	330,000	$

Notes: For detailed cost decomposition, please email the authors for the spreadsheet model.

The components considered in the deployment cost include the cable shore landing, mooring/foundation system, cable installation, and device installation. Cost estimates for a marine system were unavailable when the project began, so estimates were drawn from the Sandia river turbine model [13]. A linear scaling of the capital cost is applied to Sandia's 90kW river turbine to obtain the development cost for the Gulf Stream project. Since the estimates are for a river turbine, costs are likely to be higher in a marine environment with longer distances to shore. In the Discussion section we compare our cost model with the Sandia Reference Model for marine currents, which was released in 2014.

The expense of ongoing monitoring of current energy installations is highly dependent on location, regulatory requirements, and the degree to which travel to and from the installation location is necessary to gather and verify data. Our baseline values are taken from Verdant Power's RITE installation [14]: an upfront cost for equipment and installation, and an annual cost for maintenance, analysis, and reporting (categorized as an annual recurring cost).

Annual Recurring Costs

O & M costs are those associated with energy production and transmission on an ongoing basis. Annual fixed O&M costs are drawn from the Sandia river turbine model [16]. It includes O&M for marine operations, shore-based operations, replacement parts, and consumables. As with deployment, a linear scaling is applied to these estimates based on the installed capacity. The O&M cost is likely to be underestimated given the application of a river turbine cost estimate to represent costs in a harsher marine environment.

TABLE 2. ANNUAL RECURRING COST COMPONENTS

Category	Value	
Fixed O&M	570,000	$/MW-yr
Environmental Monitoring Set-up Cost	290,000	$/yr

RESULTS

Levelized Cost Estimation

The average capacity factor over a six-year span (2009-2014) is depicted in Figure 2a. The capacity factor at each site is defined as the ratio of its estimated electrical output over the full six years to its maximum electrical output, if it operated at its full capacity over the same period of time. Therefore, a higher site-specific capacity factor implies a lower LCOE. Figure 2b indicates that at the center of the Gulf Stream, the lowest LCOE is slightly above 300 $/MWh, or 30 ¢/kWh. Lower LCOEs are estimated at the center of the Gulf Stream, which is consistent with the result from the capacity factor study in Figure 2a. Together, this shows that the higher resource quality at the center of the Gulf Stream offsets the additional investment needed for higher transmission, installation, and mooring costs due to longer transmission distances and greater sea floor depths.

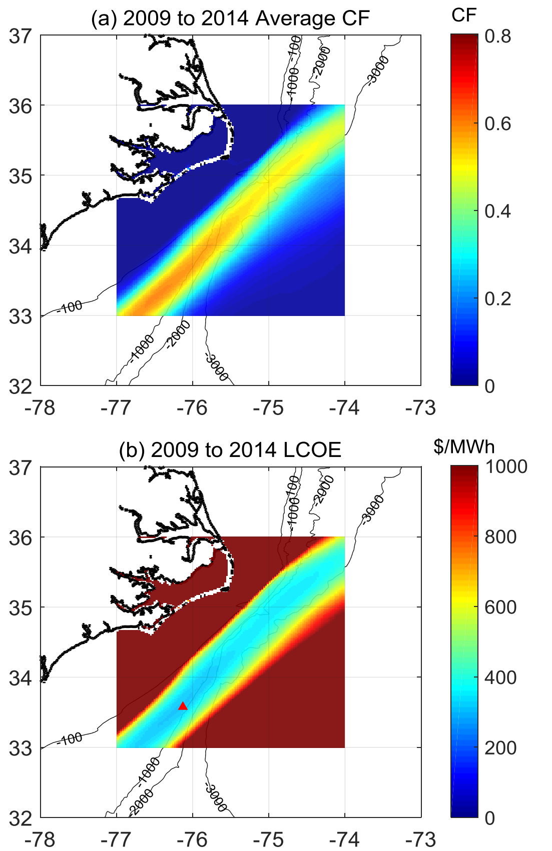

FIGURE 2. (A) SIX YEAR AVERAGE CAPACITY FACTOR FROM 2009 TO 2014. (B) SIX YEAR LEVELIZED COST FROM 2009 TO 2014, RED TRIANGLE INDICATES LOCATION WITH MINIMUM LCOE.

The LCOE results depicted in Figure 2 provide a useful visualization of the resource quality and LCOEs for a continuous domain. More importantly, they also provide a first step towards understanding the spatial variation in Gulf Stream energy.

Supply Curve Study

To study the LCOE as a function of total cumulative amount of electricity generation from the Gulf Stream, supply curves for the years 2009 to 2014 are shown in Figure 3. It represents the marginal cost to get the next increment of electricity versus the total amount of Gulf Stream electricity generated. In this case, as more electricity is generated, the cost to extract it becomes more expensive since locations with declining resource quality must be utilized. The curve indicates that it is possible to recover on the order of 200 TWh of electricity at a cost less than 300 $/MWh in the years with the best resource quality, such as from 2012 to 2014.

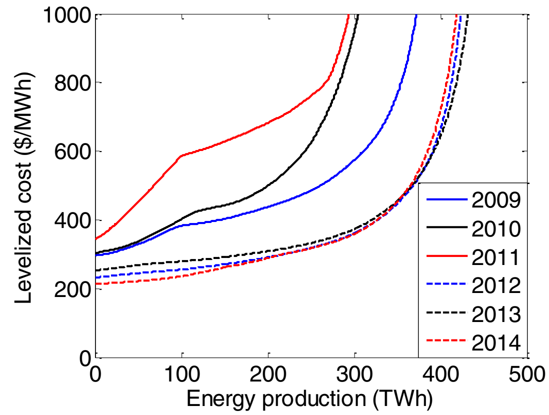

FIGURE 3. SUPPLY CURVES FOR THE YEARS FROM 2009 TO 2014.

Significant inter-annual variability is shown in Figure 3: 100 TWh of electricity energy costs only slightly above 200 $/MWh in the years 2012 to 2014, but in 2011, it is over 500 $/MWh. These results suggest that inter-annual variability in Gulf Stream intensity can have a significant impact on project economics.

DISCUSSION

Our study examines the resource quality and economics of Gulf Stream energy off the North Carolina coast. The results suggest that Gulf Stream energy may be an option in the future, if our assumptions in terms of costs and performance reasonably reflect the real world. Although sites with the best average resource quality (the red triangle in Figure 2b) over the six year timeframe have a LCOE of slightly over 300 $/MWh, it is still prohibitively expensive compared to baseload power such as coal steam and natural gas combined cycle, of which the levelized costs usually range from 70 to 100 $/MWh [17]. Neither is it competitive compared with commercially mature renewables such as solar PV and wind, which can be as low as 70 $/MWh [17]. Due to the fact that the costs used here are from a river current project, our estimate is most likely on the low end. In the future, however, the costs are expected to be brought down by future investment in marine energy development through technology advancement and economies of scale after development of the first few units.

The supply curves generated using multiple years of resource data imply that the inter-annual variability of the resource quality should be carefully assessed by future developers when considering the location. One potential cause of the inter-annual variability is the meandering of the Gulf Stream currents. Previous studies show that the meandering of the Gulf Stream intensifies downstream of Cape Hatteras [18], which is the assumed installation location in this study.

In 2014, Sandia National Laboratory released a report describing the development of four MHK energy converter reference models, among which Reference Model 4 (RM4) [9,19] provides detailed estimates for the LCOE associated with the Florida Current. While future work includes harmonization of cost and performance assumptions with RM4, it was released after our own cost estimates were already developed. RM4 has a more detailed decomposition of cost components for infrastructure, power take-off and maintenance costs. In addition, RM4 assumes that component costs increase nonlinearly as a function of array size to capture the benefits of economies of scale. To compare our model with the Sandia model, LCOEs are calculated for array size equal to 4, 40, 200 and 400 MW, which correspond to 1, 10, 50 and 100 installed units in RM4. Under the same assumptions of installed capacity, bathymetry and transmission cabling distance, the LCOEs from this model and RM4 are depicted in Figure 4. Our estimates hover around 230 $/MWh while LCOEs estimated by RM4 decrease from 650 $/MWh at 4 MW to 152 $/MWh at 400 MW. This is because our component costs increase linearly with the expansion of the array size, in contrast to the nonlinear cost functions in RM4. The comparison suggests that at higher installed capacities at or above 40MW, our estimates are a reasonable proxy for RM4. However, we underestimate the LCOE of small installations (i.e., 4 MW) by more than 50%.

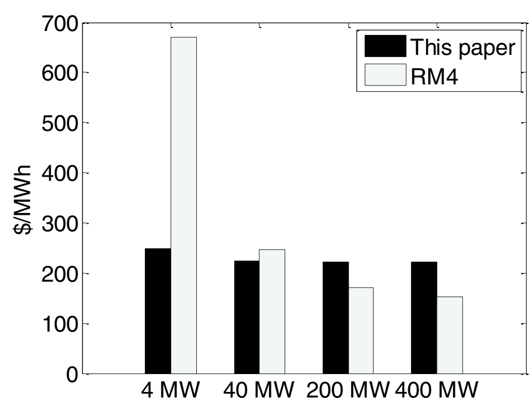

FIGURE 4. LCOE COMPARISON WITH SANDIA RM4.

Several caveats should be noted. First, great uncertainty exists regarding the costs and performance estimates and this study is largely based on river or tidal hydrokinetic turbines. Second, the turbine array layout should be studied in depth to ensure that the interference due to wake effects between neighboring turbines is minimized, i.e., the turbine spacing should be selected such that wakes from upstream devices do not affect the performance of downstream devices. Last, according to LaBonte et al. [20], the US Department of Energy (DOE) asks that all device and project costs be reported within the framework of the DOE MHK Cost Breakdown Structure (CBS) to enable "apples to apples" comparisons of costs. Since our model was developed prior to the issuance of the DOE framework, the LCOE estimates in this study do not follow the DOE standard CBS.

FUTURE AND ON-GOING WORK

The cost decomposition will be reorganized following DOE's standard and the LCOE calculation will be harmonized by referencing Sandia's RM4 model, which provides a more detailed cost accounting of ocean current turbines.

In addition, a portfolio optimization model is being developed to address the temporal and spatial variation in Gulf Stream resource quality by selecting multiple fixed locations to minimize the variance in total energy generation while the system capacity factor is constrained such that it is greater than or equal to a target value.

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