

A FRAMEWORK FOR OPTIMIZING THE PLACEMENT OF CURRENT ENERGY CONVERTERS

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ABSTRACT

This study investigates the potential environmental impacts and performance of a small array of tidal energy converters (TECs) in Cobscook Bay, ME; TECs are a subset of current energy converters (CECs) that are specifically deployed in tidal channels. A previously constructed coarse-grid, regional-scale hydrodynamic model of Cobscook Bay was coupled to a refined domain centered on a proposed TEC deployment location. All models were developed with Sandia National Laboratories-Environmental Fluid Dynamics Code (SNL-EFDC). An optimization framework was then constructed that used results from the refined model to determine optimal device placement locations that maximize array performance and minimize potential environmental effects. Within the framework, environmental constraints can be included to limit CEC-induced changes in flow, sediment transport, or other physical phenomena that might affect the health of aquatic species (i.e., altering fish-swimming behavior and sediment-transport trends that could affect benthic habitat or the stability of the CEC infrastructure). Simulation results were compared between model runs with optimized array configurations, and the originally proposed deployment locations. The optimized array had roughly a 17% increase in power generation. The framework developed also provides regulators and developers with a tool to assess environmental impacts and device-performance parameters for the deployment of CEC devices.

INTRODUCTION

In efforts to speed MHK current energy converter (CEC) technologies to market, Sandia National Laboratories (SNL) has developed a simulation tool, called Sandia National Laboratories-Environmental Fluid Dynamics Code (SNL-EFDC), that can be used to predict optimal

CEC array placements to maximize power production while minimizing potential deleterious environmental effects. SNL-EFDC is a modified version of US Environmental Protection Agency's Environmental Fluid Dynamics Code (EFDC). EFDC solves the hydrostatic, free surface, Reynolds Averaged Navier Stokes (RANS) equations with a Mellor-Yamada turbulence closure. The code was developed to simulate river-, estuary-, coastal-, and open-ocean-scale systems. Recently, SNL has added an MHK module that simulates energy removal from fluid flow by CEC devices and commensurate changes to turbulent kinetic energy and dissipation rates. The motivation for adding the MHK module was to provide a design tool capable of predicting power output and commensurate changes to the environment (i.e., flow characteristics) from field-scale MHK array configurations; it is not intended to provide high-fidelity three dimensional flow predictions around the turbine blades or support structure.

An optimization framework that aims to maximize the power generation of tidal energy converters (TECs) while simultaneously minimizing potential environmental effects, is presented. TECs are a subset of CECs that are specifically deployed in tidal channels. The framework was applied to a TEC array in Cobscook Bay, ME. Cobscook Bay is the first deployment location of Ocean Renewable Power Company's (ORPC) TidGen™ units. One unit is currently deployed with four more units to follow. The developed framework uses SNL-EFDC.

MODEL SETUP

SNL previously built a coarse-grid (100×100-m² cells), regional-scale hydrodynamic model (Figure 1) that included Cobscook Bay and all other landward embayments [1]. This regional model was calibrated against three sets of NOAA Tides and Currents water-level data (Garnet Point,

Coffin Point, and Gravelly Point with correlation coefficients of $R^2 = 0.995$, 0.979 , and 0.958 , respectively). Moreover, the model was calibrated against a month of ADCP velocity data with the model generally under-predicting the flow speeds by 5% [1]. Model results with and without a TEC array were compared to assess how the small five-TEC array might alter the Cobscook Bay aquatic environment. No significant changes in regional tidal range, flow rate, or broader flow patterns were found. The coarse-grid size of the regional-scale model however was not sufficiently resolved to assess flow alterations in close proximity to the devices; the model had limited applicability for assessing local flow patterns and optimal device placement locations. A refined-grid model was therefore created to meet the resolution demands of the optimization framework developed here.

A localized model domain was constructed and calibrated that encompassed the entire available MHK placement region (array footprint) and sufficient surrounding areas to account for important bathymetric features (e.g., a depression on seaward side of array). The model domain was 1,120 m long by 430 m wide with 4,816 $10 \times 10\text{-m}^2$ cells and five vertical (sigma) layers. The inset in Figure 1 shows the location of the local model domain within the regional model. The study region is outlined with a solid black rectangle, and the placement footprint is outlined with a dashed black rectangle. The placement footprint is 30.5 m (100 ft) within the border of the study area.

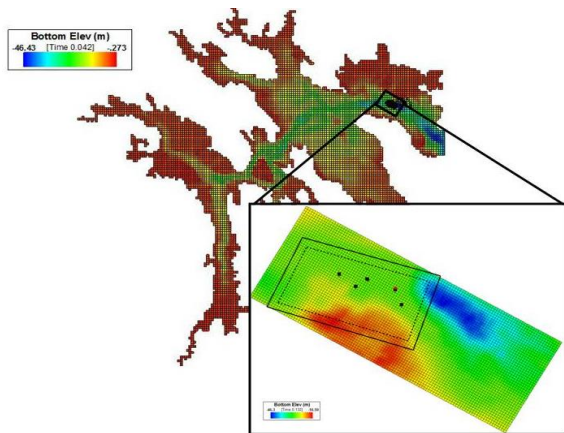


FIGURE 1. REGIONAL-SCALE DOMAIN WITH AN INSET SHOWING THE REFINED-GRID DOMAIN. PROPOSED LOCATIONS OF MHK DEVICES (BLACK SQUARES) AS WELL AS THE LOCATION OF THE ADCP (RED CIRCLE) ARE IDENTIFIED. THE STUDY REGION IS OUTLINED IN THE REFINED-GRID DOMAIN WITH A SOLID BLACK RECTANGLE, AND THE PLACEMENT FOOTPRINT IS OUTLINED WITH A DASHED BLACK RECTANGLE.

The refined-grid model was driven by water levels and flow rates extracted from the regional-scale Cobscook Bay model. A time-variant water level was specified on the northwest face, and flow rates were specified on the southeast face. The two longer domain edges (northeast and southwest faces) were no-flux, slip wall conditions.

Incorporation of CEC Devices

The power generated by MHK turbines comes from energy removed from the flow passing through the turbines. This behavior is represented in SNL-EFDC using momentum sink, turbulence source, and turbulence-dissipation equations at model cells containing turbines. Momentum extraction and wake generation and dissipation depend upon both the properties of the turbines and the incident flow conditions [2, 3].

The TideGen™ Turbine

The specifications for TidGen™ cross-flow turbines used were 30.28 m (100 ft) long and 4.3 m (14.1 ft) high, with blade bottoms 9 m (29.5 ft) from the sediment bed. The support structures were 3 m (9.8 ft) wide and extended from the sediment bed to a height of 11.2 m (36.7 ft). A schematic representation of a TidGen™ unit is presented in Figure 2. Turbines were added to the refined-grid domain once the hydrodynamic model was calibrated to available ADCP data. Each device spanned roughly three cells. Thrust coefficients were specified as $C_T = 0.8$, and the drag coefficients for the support structures were assigned a value of $C_D = 1.2$. A relatively high thrust coefficient was selected to be environmentally conservative; physical environmental changes are expected to increase as more energy is removed from the tidal channel. Different turbine properties can be implemented in future analyses as device parameter data become available.

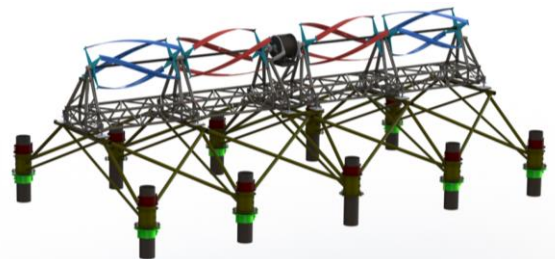


FIGURE 2. SCHEMATIC OF THE ORPC TIDEGEN™ TURBINE.

OPTIMIZATION FRAMEWORK AND APPLICATION

For the purposes of permitting and without the aid of numerical modeling, ORPC proposed a preliminary configuration for the five-TEC array. This was only one possible configuration among

nearly an infinite number of potential layouts. As long as deployment locations fall within the placement footprint (i.e., inside the study region and at least 30.5 m [100 ft] from its border), and are in a water depth greater than 23 m (75 ft), the location is considered acceptable for deployment. The depth restriction ensures sufficient clearance between the top of the devices and the water surface, allowing safe vessel passage.

Optimization Analysis Methodology

To narrow down the near infinite number of possible array configurations within the permitted placement footprint, a methodology was developed to sequentially identify optimal device placement locations using SNL-EFDC. The procedure as applied to Cobscook Bay follows:

(1) Assess the natural hydrodynamic patterns occurring within the placement footprint (no MHK devices).

(2) Identify the region within the footprint with the highest velocities at the depth of a turbine that span the length (30 m) of a turbine (i.e., find the three adjacent cells with the largest average velocity), and that is in at least 23 m (75 ft) of water relative to mean lower low water.

(3) Add an MHK device in the high-velocity region identified in Step 2, and run simulations to reassess hydrodynamics in the placement footprint given the MHK addition. (Note: For this study, SNL had foreknowledge of the first device location since one is already deployed.)

(4) Evaluate the hydrodynamic changes caused by the addition of the MHK turbine. Velocity and bed shear stress changes were examined by calculating percent velocity recovery and bed shear stress differences for simulations with and without turbines. Flow changes manifest directly to velocity changes throughout the water column (potentially affecting fish behavior to hydrodynamic cues) as well as at the sediment bed (potentially altering sediment dynamics and benthic habitat).

(5) If pertinent, establish thresholds for hydrodynamic changes that meet local environmental standard and verify that environmental constraints are acceptable for all cells within the domain. If they are not acceptable go back to Step 2 but choose the second highest velocity location. To illustrate how these criteria operate within the optimization analysis, a minimum threshold was set such that depth-averaged velocities cannot drop below 70% of what they would be without the presence of a turbine, and changes in bed shear stress must be less than 1 Pa. The constraints were arbitrarily chosen to demonstrate how they can be added to the analysis. Physically, a velocity drop constraint

could potentially reflect a threshold in which fish swimming behaviors would change (e.g. if the velocity drops below some value, fish are likely to congregate in the wake), and a bed shear stress constraint could represent a threshold in which bed erosion would initiate. As additional site-specific information becomes available, the constraints used in Cobscook Bay analysis can be redefined or dropped to better address actual site needs.

(6) Repeat Steps 2 through 6 for each additional turbine.

The methodology identifies regions where velocities are largest thereby optimizing the power output of deployed MHK turbines. At the same time, environmental considerations are assessed to avoid array configurations that could potentially negatively impact local sediment dynamics and ecology. In this application of the optimization methodology, changes in flow and seabed shear stress were defined to demonstrate how constraints can be added to the framework. However, the optimization framework is flexible, such that these constraints can be easily modified to meet site requirements and needs. As studies progress at MHK deployment sites, environmental constraints for a given site should be developed collaboratively with local stakeholders, other scientists (i.e. biologists, ecologists, and geologists), device and project developers, and the optimization modeling team to best consider site-specific concerns. For example, if an ecologist determines the benthic activity will change near a proposed deployment location if the near bed velocity increases by 10%, a constraint could be added to the optimization analysis to ensure the velocity increase is prevented.

The three five-TEC arrays analyzed in this study are shown in Figure 3, which comprise the preliminary ORPC-defined configuration, the optimally determined configuration that *accounted for* environmental constraints, and an optimally determined configuration that *did not consider* environmental constraints. Each panel in Figure 3 is color contoured with the percent velocity recovered calculated from sigma-layer three velocities (vertical layer spanning hub height).

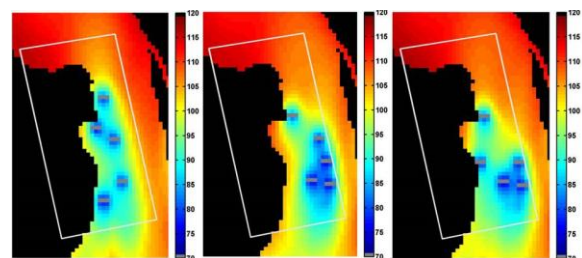


FIGURE 3. THE THREE FIVE-TEC ARRAYS INVESTIGATED: PRELIMINARY ORPC-DEFINED ARRAY (LEFT PANEL), THE ENVIRONMENTALLY CONSTRAINED OPTIMIZED ARRAY (CENTER PANEL), AND THE UNCONSTRAINED OPTIMIZED ARRAY (RIGHT PANEL). ALL THREE PLOTS ARE COLOR CONTOURED WITH PERCENT VELOCITY RECOVERY (UNITLESS).

Array Performance

At the end of the optimization process, power-production results between ORPC's preliminary array layout and the SNL-EFDC-optimized array layouts were compared. All array configurations were run over a 29-day time period to capture a full spring/neap tidal cycle (July 5th through August 2nd, 2011). The preliminary (baseline) ORPC array configuration produced 107 MW-hr, while the environmentally constrained array produced 124 MW-hr, and the unconstrained (power optimized) array produced the largest amount of energy, at 127 MW-hr. For the conditions simulated, both the environmentally constrained and unconstrained optimization scenarios produced more power than the baseline case (16% and 19% increases in power, respectively). These results show the usefulness of the optimization methodology to maximize power while simultaneously considering and minimizing potential deleterious environmental effects.

CONCLUSIONS

The performance and potential environmental impacts of a five-TEC array in Cobscook Bay, ME were investigated using the open-source modeling platform SNL-EFDC. Cobscook Bay is the first deployment location of Ocean Renewable Power Company's (ORPC) TidGen™ units. One unit is currently deployed with four more units to follow.

A coarse-grid, regional-scale model of Cobscook Bay previously demonstrated that the operation of five ORPC tidal turbines would not cause significant changes in regional tidal range, flow rate, or the broader flow patterns. While the model was sufficient for investigating large-scale environmental effects, near field (i.e., fine scale) hydrodynamics were not resolved. Therefore, a refined-grid model with a resolution smaller than the individual turbines was created and incorporated into an array optimization framework designed to determine optimal device placement locations to maximize array performance and minimize potential deleterious environmental effects. The framework was created in a fashion that allows flexible application of environmental constraints. To demonstrate this functionality in the absence of agreed-upon regulations, environmental constraints related to changes in flow and seabed

shear stress were defined and arbitrary threshold values assigned.

The energy output of three array layouts were estimated over a 29-day period. This included the preliminary ORPC-defined configuration (baseline), an optimally determined configuration that *accounted for* arbitrary environmental constraints, and an optimally determined configuration that *did not consider* environmental constraints. Of the three layouts analyzed, the optimally placed array that *did not consider* environmental constraints removed the largest amount of energy from the tide, at 127 MW-hr. This output was roughly 19% higher than the output from the preliminary ORPC-defined array configuration (107 MW-hr). The optimally placed array that *accounted for* environmental constraints removed 124 MW-hr of energy (16% increase from the preliminary array).

When assessing the optimal placement of a TEC array in a real-world application, where bathymetry and flow patterns change both spatially and temporally, generalizing wake recovery and the appropriate spacing between devices is challenging. The difficulties arise due to spatial and temporal variations in turbulence and flow, which both effect wake recovery. The framework presented accounts for these variations, making it a valuable tool for assessing optimal array layouts.

ACKNOWLEDGEMENTS

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