SITING PERFORMANCE METRICS: A SEQUIM BAY CASE STUDY FOR CROSS-FLOW TURBINES

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INTRODUCTION

The prioritized position of turbines within a general deployment site is referred to as "micro-siting" [1]. This involves evaluating trade-offs between different performance metrics. Here, we discuss the implications of such metrics on siting a pair of small cross-flow turbines (1 m^2 projected area) adjacent to PNNL's Marine Sciences Laboratory (MSL) at the inlet of Sequim Bay, WA, USA. The deployment and operation of this scale of turbine will be executed by the University of Washington's Applied Physics Laboratory in FY 2019.

Sequim Bay, shown in Figure 1, is at the eastern end of the Strait of Juan de Fuca. The narrow inlet leading into the bay is roughly 200 m wide, a constriction that produces tidal currents of up to 2 m/s in depths between 6-10 m. Moderate speed, diver-accessible depth, and proximity to MSL make the site favorable for demonstrating feasibility of harnessing marine resources to power maritime applications (e.g. persistent sensing).

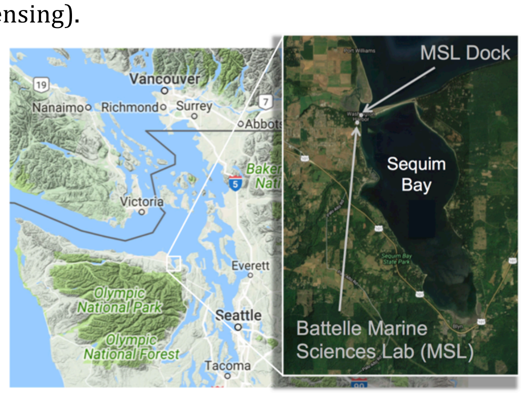

FIGURE 1. SEQUIM BAY (CREDIT: GOOGLE MAPS)

Selection of a specific deployment location within Sequim Bay is complicated by relatively large variability in resource intensity, bathymetry, and depth over small spatial distances. This is analogous to the challenges of micro-siting in larger-scale projects where flow conditions have been shown to vary substantially over distances on the order of 100 m [2].

Here we primarily present three metrics that can be used for micro-siting: power output, foundation weight and overhead clearance limits. The output of a finite volume coastal ocean model (FVCOM) and multibeam sonar bathymetric survey are used to complete our analysis. While the outcomes are specific to this location and turbine, we believe that the metrics and underlying trends are useful to inform deployments at other sites and scenarios of interest.

Turbine Design

The turbine rotor, comprised of straight NACA0018 profile blades, is vertically-aligned, has a frontal area of 1.0 m^2 and an aspect ratio of 1.36. Optimized blade count, cord-to-radius ratio, and blade mounting angle will be determined through full-scale tow-tank and vessel-borne testing. The specifications listed in Table 1 were obtained through laboratory-scale experiments and used to estimate turbine performance. Details of the experimental setup, data collection, and processing can be found in Strom, 2017 [3].

TABLE 1. TURBINE SPECIFICATIONS

Hub Height	2.1 m
Height	1.2 m

Turbine Diameter	0.806 m
Cross-Sectional Area	1 m^2
Cut In Speed	0.4 m/s
Cut Out Speed	0.2 m/s
Rated Speed	3 m/s
Water-to-wire efficiency: η_s	0.25
Coefficient of lift (perpendicular to flow direction): C_L	1.5
Coefficient of thrust (parallel to flow direction): C_T	2

METHODS

Data Sources

The output of a finite volume coastal ocean model (FVCOM) and multibeam sonar bathymetric survey were used to characterize the domain. The FVCOM model of the site, developed by PNNL [4], simulates circulation and tidal elevation patterns in Puget Sound using an unstructured grid, with higher resolution near-shore than in open water. Within the Sequim Bay entrance channel, there are 4461 model grid points with a horizontal resolution varying between 4 and 10 m. The model has ten depth layers, evenly spaced between surface and seabed. Water level and depth-resolved tidal current information over a 2-month period are available at each grid point with a temporal resolution of 15 minutes.

A bathymetric survey, also conducted by PNNL, provides depth information at 1.5 meter resolution. These data were used to evaluate channel depth and slope.

Power Output

The power output of a single cross-flow turbine was estimated over the 2-month period using a simplified model for turbine dynamics in MATLAB. Vertical velocity profiles were linearly interpolated across the turbine rotor. The horizontal velocity across the rotor was cubed and averaged across the rotor height (U^3_{avg}). Water density (ρ) was considered spatially and time invariant at 1020 kg/m^3. Power output was computed at each FVCOM model time step using the turbine specifications for cut in speed and cut out speed. Rated speed was chosen to be greater than the maximum current velocity in the channel. Power at each time step is given by

$$P = \eta_s \frac{1}{2} \rho A U^3_{avg} \qquad (1)$$

where A is the projected area of the turbine and η_s is the "water-to-wire" efficiency. This process yielded spatially-varying representations for power at each possible deployment location. From this time series, mean power, maximum power and the ratio between max and mean power were calculated throughout the inlet.

Foundation Weight

The foundation weight of the turbine system must be sufficient to resist overturning. Weight requirements can be reduced by increasing the horizontal extent of the lander or lowering its center of gravity.

The vessel that will be used for turbine deployment (*R/V Jack Robertson*) limits the size of the turbine lander to 5.5 m on edge. Foundation weight is also limited to 6000 lbf (2700 kg) based on safe working limits for the vessel's A-frame. Operationally, the foundation weight of the turbine system must be sufficient to resist overturning. An analytical expression for the mass needed to resist the thrust on the turbine when deployed on an uneven slope was developed using the static model shown in Figure 2.

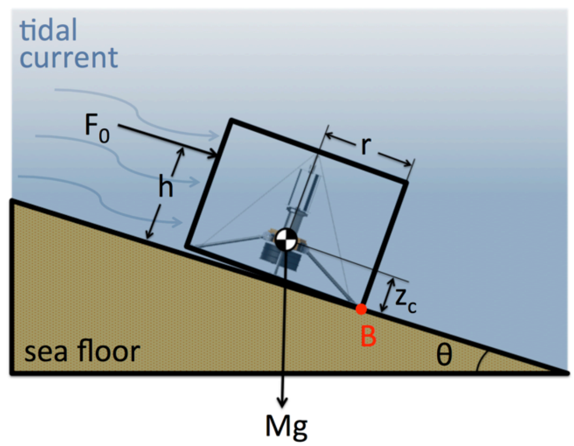

FIGURE 2. FREE BODY DIAGRAM OF OVERTURNING TURBINE

Simplified lander geometries were assumed: a circular base of radius (r) 1.5 m and a vertical center of gravity (z_c) of 1 m. Overturning was modeled by a current-induced overturning force (F_0) acting at a resultant height (h), pushing the turbine over the downstream edge of the lander (B), while being stabilized by its weight (the mass (M) multiplied by the gravitational constant (g)) and pitched at a stream-wise slope angle (θ). Only forces that influence the moment about the overturning point B are shown. Frictional forces between the seabed and lander, and the normal force of the turbine do not have a moment arm about B and therefore are not included in the system model.

For a marginally stable turbine, the moment arm induced by the flow about B will equal the stabilizing moment produced by its foundation weight. The minimum mass required to stabilize a spinning turbine is given by

$$M = \frac{\boldsymbol{F_O} h}{rg\cos(\theta) - z_c g\sin(\theta)} \quad (2)$$

such that the foundation mass is a function of two spatially- and time-varying parameters: the overturning moment ($\boldsymbol{F_O}h$) and stream-wise seabed slope (θ).

The overturning force, $\boldsymbol{F_O}$, is found by taking the L-2 norm of the lift and thrust force vectors ($\boldsymbol{F_L}$ and $\boldsymbol{F_T}$) acting on the turbine rotor, given by

$$\boldsymbol{F_L} = C_L \frac{1}{2} \rho A U_{avg}^2 \quad (3)$$

$$\boldsymbol{F_T} = C_T \frac{1}{2} \rho A U_{avg}^2 \quad (4)$$

where A is the projected area of the turbine, ρ is water density at 1020 kg/m^3, C_L and C_T are the coefficients of lift and thrust of the turbine (given in Table 1) and U^2_{avg} is the horizontal velocity across the rotor squared and averaged. To account for uncertainty in the FVCOM model, a turbulent gust multiplier of 1.3 and a model inaccuracy multiplier of 1.15 were applied to the horizontal velocity used to compute U^2_{avg}.

The resultant height of the overturning force (h) is given by

$$h = \frac{\int_{z_1}^{z_2} U^2(z) z dz}{\int_{z_1}^{z_2} U^2(z) dz} \quad (5)$$

where z is vertical distance above the seafloor in the direction of the rotor, z_1 is the height of the base of the turbine, z_2 is the height of the top of the turbine and $U^2(z)$ is horizontal velocity squared as a function of z.

Overturning moment and stream-wise seabed slope were computed at each time step and model grid point, yielding a spatially-varying representation of the minimum foundation mass required to resist overturning.

Overhead Clearance

Vessel traffic and permitting constraints impose a limit on the allowable distance between the top of the turbine and mean lower low water (MLLW) at Sequim Bay. The exact value of this limit is currently under negotiation with the United States Coast Guard, but is expected to be between 2 and 3 meters. Further, if the turbine is too close to the surface, it would aspirate (i.e. entrain air), which should be avoided.

Overhead clearance was evaluated by converting the datum of the model (NAVD 88) to MLLW and subtracting the height of the turbine system (2.74 m) at each model grid point [5].

Additional Considerations

Other priorities and parameters for micro-siting were considered and deemed either incidental or redundant.

Bottom slope was deemed redundant because its influence is explicitly included in foundation weight analysis. *Ebb/flood asymmetry* is incidental in this particular scenario because cross-flow turbines operate omnidirectionally and asymmetry is captured by ratio of maximum to mean power output. *Vertical velocity shear across the turbine rotor* may have implications for structural fatigue, but is sub-grid scale in the FVCOM model output. This will be evaluated from site survey data later in project development. Lastly, siting the turbine *proximal to the dock* and *within the pre-permitted zone* was deemed incidental due to generally short cable runs throughout the area and flexibility in the permitting process.

RESULTS

As shown in Figure 3, power output varies substantially throughout the channel. Ship-board acoustic Doppler current profiler (ADCP) and acoustic Doppler velocimeter (ADV) surveys will be conducted nearby three candidate locations to verify model estimates. These locations were selected due to relatively high mean power and relatively low max to mean power ratio. The latter has economic implications for turbine component sizing.

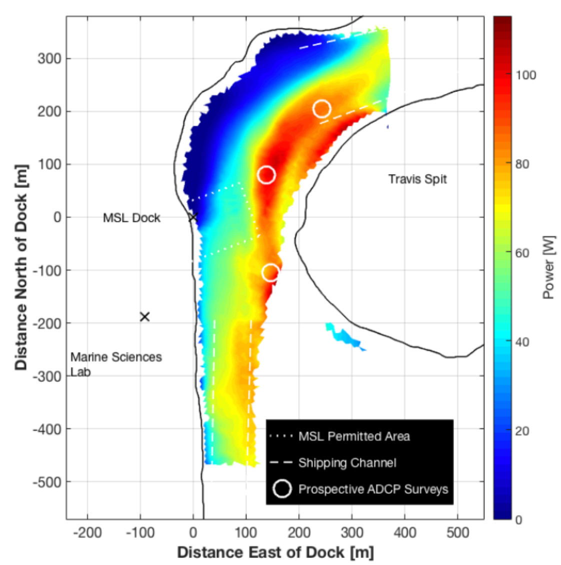

FIGURE 3. ESTIMATED MEAN TURBINE POWER OUTPUT [W]

Although an important consideration for lander design, the required foundation mass, shown in Figure 4, is generally within the limits of the deployment vessel. This is with exception to a small area northwest of Travis Spit. The stability of the turbine system can be improved by further optimizing lander geometry (e.g. increasing horizontal extent and lowering center of gravity). In general, foundation mass mirrors mean turbine power output (i.e., mass is driven by currents, not bottom slope), except immediately northwest of Travis Spit.

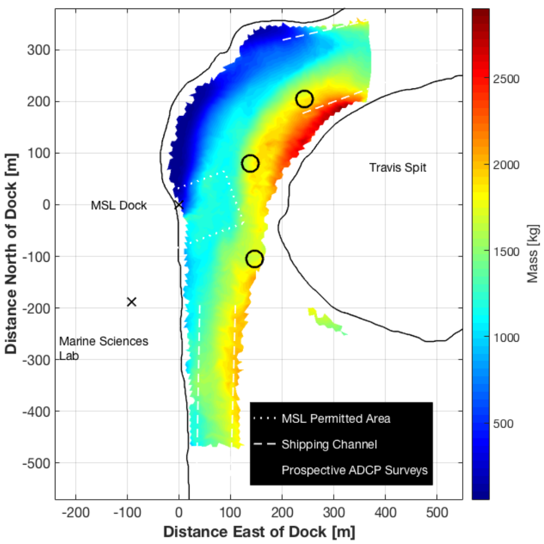

FIGURE 4. REQUIRED FOUNDATION MASS

As shown in Figure 5, overhead clearance substantially limits the candidate deployment locations. Permitting restrictions may require an overhead clearance between 2-3 meters.

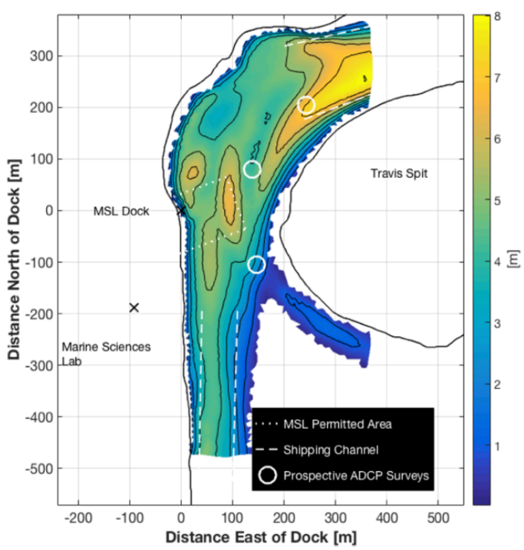

FIGURE 5. OVERHEAD CLEARANCE TO MLLW

CONCLUSIONS

The salient metrics explored in this analysis were power output, foundation mass and overhead clearance. Estimates of these parameters relied on output of an FVCOM model and a bathymetry survey. The results suggest three candidate locations that should be characterized by in-situ observations of current and seabed composition.

Next steps include further study of the prospective deployment sites, design of the turbine lander and refinement of the expected power and foundation weight calculations. In Spring 2018, ship-board ADCP and ADV surveys will be conducted nearby the three locations to measure water velocity. These results, in conjunction with testing of full-scale turbines and inclined turbines, will allow for further refinement of estimates of power output and required foundation mass.

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