Analysis of Tidal Turbine Arrays in Digby Gut and Petit Passage, Nova Scotia

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Abstract

The Nova Scotia government has approved tidal power Community-Feed-in-Tariffs for Digby Gut and Petit Passage, two passages along the coast of the Bay of Fundy. Digby Gut is a passage connecting the small, enclosed Annapolis Basin to the Bay of Fundy. On the other hand, Petit Passage is a passage between the large, open St. Mary's Bay and the Bay of Fundy. Altering the flow in Digby Gut strongly affects the surrounding tides, while altering the flow in Petit Passage does not. This significantly affects the resource assessment.

Using numerical simulations of the tides and tidal currents through the passages, we examine power extraction from the passages and the resulting impact on the flow. Using theories of power extraction, we examine how the numerical results can be extended to more realistic arrays of in-stream turbines. The results suggest Digby Gut has a high potential resource (180 MW) but that it will be difficult to realize this resource because of the weak flow in the passage. On the other hand, Petit Passage has a low potential resource (33 MW) but a significant portion of this (10 to 20 MW) could be realized with a reasonably sized turbine array.

Keywords: tidal power, resource assessment, Bay of Fundy

1. Introduction

The Bay of Fundy has the world's largest recorded tidal range, routinely reaching over 15 m in range within Minas Basin. Several passages along the coast of the Bay of Fundy have strong tidal currents that are suitable for the deployment of Tidal Energy Converters (TEC) that extract energy from the fast moving currents. In particular, Fundy Tidal Inc. (FTI) has been awarded Community Feed-in Tariffs (COMFITs) for the passages along Digby Neck (see Fig. 1). For the three passages–Digby Gut, Petit Passage, and Grand Passage–FTI has been given COMFITs of 1.95 MW, 0.5MW and 0.5 MW, respectively. At present, the maximum capacity of COMFIT projects is restricted by the annual minimum load on the local substation. But, the COMFIT is designed to promote the early development of distribution connected tidal power projects that may eventually lead to larger-scale, transmission-connected, commercial deployments. A critical aspect of these tidal power developments is an accurate assessment of the resource.

In this short paper, we use 2D numerical simulations of the tides and tidal currents to describe the flow through the passages, estimate the extractable power for each passage and estimate the impact of extracting power from each passage. We then use the tidal power theories to estimate what type of turbines and what size of arrays could be deployed in each passage.

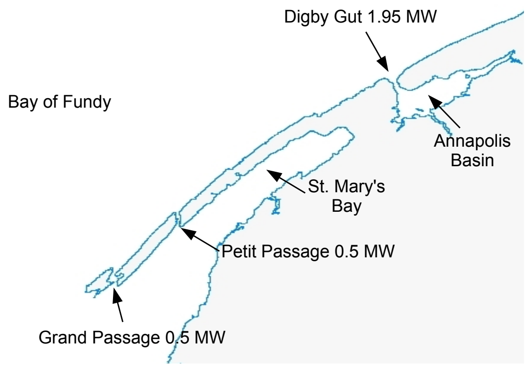

Fig. 1: A map of Digby Neck showing the three passages which FTI has been awarded COMFITs for the amounts shown. The Annapolis Tidal Power Plant lies at the right end of the Annapolis Basin

2. The Numerical Model

For the calculations in this paper, we simulated the tides and currents in the Bay of Fundy using the Finite Volume Coastal Ocean Model (FVCOM) [1]. The specific model grid was adapted from a grid developed by David Greenberg and Jason Chaffrey at the Bedford Institute of Ocean Sciences. The model domain covers the entire Gulf of Maine and Bay of Fundy with its open boundary beyond the continental shelf. The model is forced by specifying the amplitudes and phases of five tidal constituents at the open boundary. The model has been validated through comparisons to tide gauge data and recent current measurements from various locations around the Bay of Fundy. The simulations have a resolution of about 10 m in Digby Gut and Petit Passage. The simulations discussed here are 2D, that is, they calculate the depth-averaged velocities. This allows for many month-long runs to be completed in a reasonable amount of time.

In order to simulate turbines in the model, we used the simple approach of adding a quadratic drag term to the horizontal momentum equations over a region representing a turbine fence that extends across the cross section of the passage. There are several issues with this simplified model of turbines, but it serves the purpose of allowing us to extract power from the flow. After a simulation is complete, we calculate the mean extracted power associated with the fence drag and the mean flux through the fence. The reduction in flow through the passage is then computed by comparing the mean flux to the flux in the simulation with no turbine fence. For more details on the numerical model see [2,3,4].

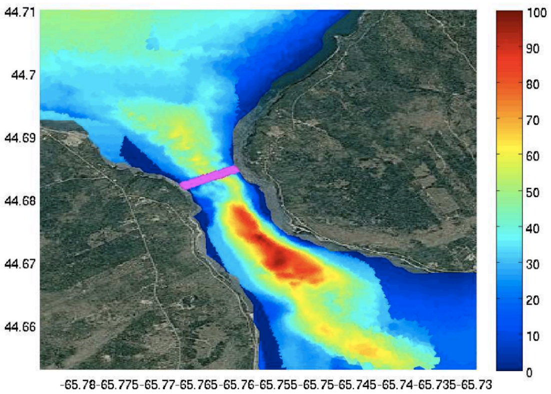

Fig. 2: The water depth (in metres) at mean tide in Digby Gut. The pink line is the location of the turbine fence.

3. Results for Digby Gut

Digby Gut is a deep passage that connects the Annapolis Basin to the Bay of Fundy as shown in Fig. 1. The passage is roughly 4 km long and 1 km wide, with water depths reaching almost 100 m, as shown in Fig. 2. Fig. 2 also shows the location of the turbine fence used to extract power in the numerical simulations. The fence has a cross-sectional area of roughly 20,000 m^2.

In Figs. 3 and 4, we plot the mean speed and mean power density for Digby Gut. The mean, depth averaged speed in Digby Gut rarely exceeds 1 m/s. The volume flux through the passage has a mean value of 1.7×10^4 m^3/s and reaches 4×10^4 m^3/s during the spring tide when the maximum speed reaches over 3.0 m/s. The power density rarely exceeds 1.2 kW/m^2 and reaches a maximum of just over 2 kW/m^2. Therefore extracting significant power from Digby Gut would require a TEC device that is cost effective at low flow velocities.

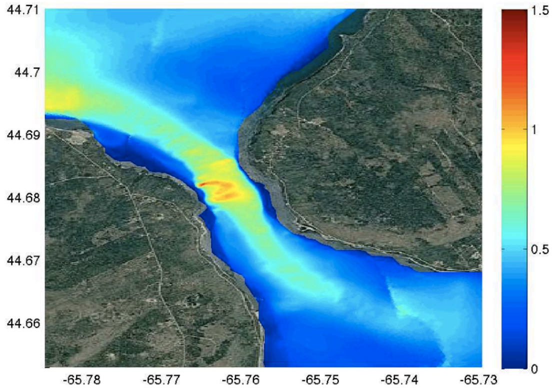

Fig. 3: The time-mean, depth-averaged speed in m/s for Digby Gut.

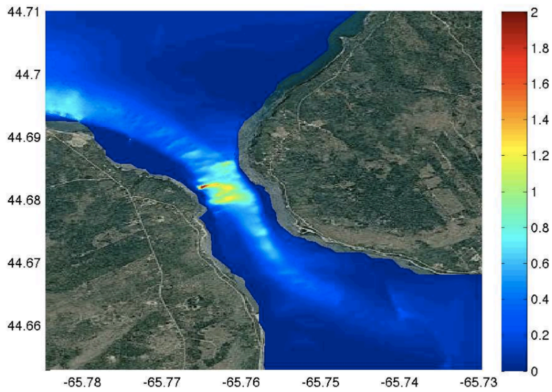

Fig. 4: The time-mean power density in kW/m^2 for Digby Gut.

Since Digby Gut connects the closed Annapolis Basin to the Bay of Fundy, the potential power in Digby Gut is related to the significant potential energy of the tides in the Annapolis Basin. To illustrate this, power was extracted using the turbine fence shown in Fig. 2. In Fig. 5, we plot the power extracted versus the reduction in the flow through Digby Gut. For a small channel, there is significant power that can be extracted (a maximum 180 MW) and notably significant extractable power with a small reduction in the flow through the passage (see values in Table 1).

It should be noted that any change in the flow through Digby Gut would have a direct impact on the tidal range in Annapolis Basin. This is important for ecological reasons, but also because the Annapolis Tidal Power Plant is located at the eastern end of Annapolis Basin. Therefore, one objective would be to keep the reduction in the flow through Digby Gut to a minimum, possibly below the 5% reduction highlighted in Fig. 5. The impacts of a 5% reduction in flow still need to be examined in more detail. And, as noted above and discussed below, the low speed of the tidal currents through Digby Gut may make realizing the large power potential difficult.

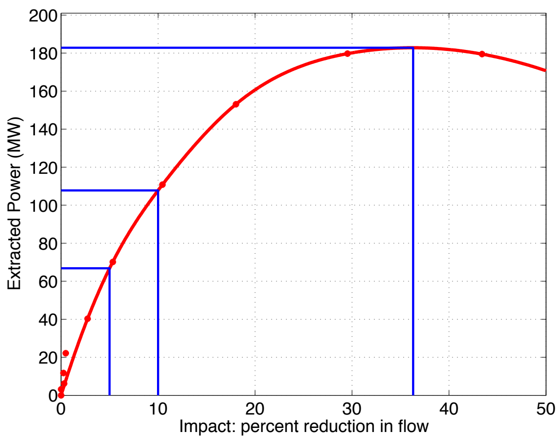

Fig. 5: Extracted power versus the reduction in flow through the turbine fence for Digby Gut. The blue lines highlight the values presented in Table 1. The dots are the values for the individual simulations.

4. Results for Petit Passage

Petit Passage is the passage between the Digby Neck peninsula and Long Island as shown in Fig. 1. The passage is roughly 4 km long and 0.5 to 1 km wide, with water depths reaching approximately 70 m, as shown in Fig. 6. Fig. 6 also shows the location of the turbine fence used to extract power in the numerical simulations. The fence has a cross-sectional area of roughly 10,000 m^2.

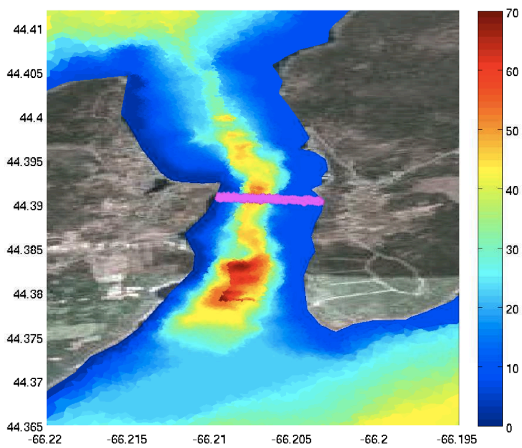

Fig. 6: The water depth (in metres) at mean tide in Petit Passage. The pink line is the location of the turbine fence.

In Figs. 7 and 8, we plot the mean speed and mean power density for Petit Passage. The time-mean, depth-averaged speed is between 2 and 2.5 m/s for a large fraction of the total area of the passage. The mean speed and volume flux through the fence are 1.6 m/s and 1.9x10^4 m^3/s. During the spring tide, the maximum velocity through the turbine fence was 5.7 m/s and the volume flux through the passage reaches 3x10^4 m^3/s. The mean power density routinely exceeds 8 kW/m^2 and reaches over 10 kW/m^2. These predicted values show Petit Passage to be a very energetic site.

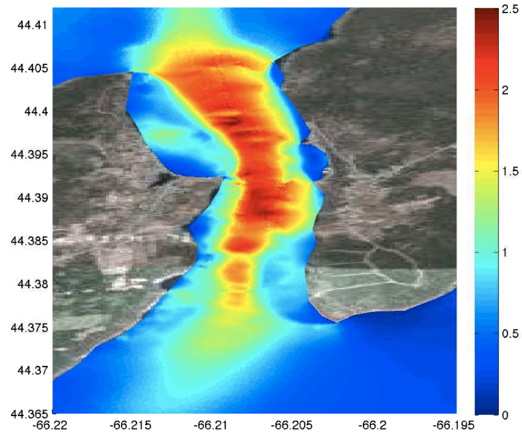

Fig. 7: The time-mean, depth-averaged speed in m/s for Petit Passage.

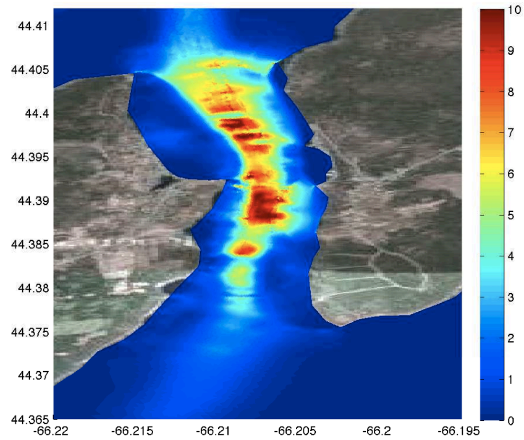

Fig. 8: The time-mean power density in kW/m^2 for Petit Passage.

However, since Petit Passage lies between two large bodies of water (St. Mary's Bay and the Bay of Fundy) it has different dynamics than Digby Gut. The flow through Petit Passage has very little impact on the tides in either St. Mary's Bay or the Bay of Fundy. This means that the extractable power for Petit Passage is proportional to the existing tidal head across the passage, not the potential energy of the full range of the surrounding tides. So, even though the volume flux through Petit Passage is similar to Digby Gut and the water speeds in Petit Passage exceed those of Digby Gut, the extractable power is almost an order of magnitude less.

Fig. 9 plots the extracted power versus reduction in flow for the Petit Passage turbine fence shown in Fig. 6. The curve has a similar shape to the curve in Fig. 5, but the maximum power of 33 MW is significantly smaller. Once again, significant portions of this power can be extracted with only small changes in flow through the passage (see Table 1).

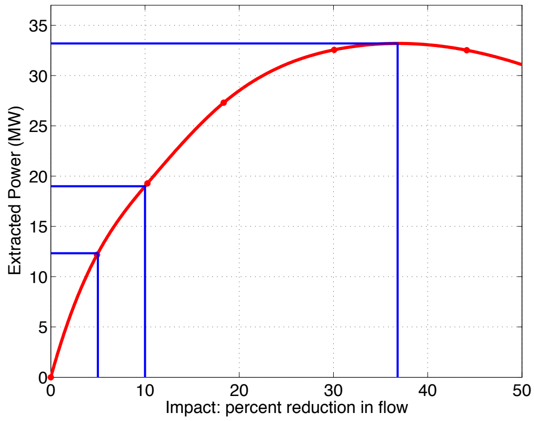

Fig. 9: Extracted power versus the reduction in flow through the turbine fence for Petit Passage. The blue lines highlight the values presented Table 1. The dots are the values for the individual simulations, the curve is found using an interpolating spline.

Since the flow through Petit Passage has little impact on the surrounding tides, it could be expected that a large reduction in flow (10% or more) would have little impact on adjacent intertidal zones. Of course, extracting power from the passage may still have other important environmental impacts.

It is worth noting the relative size of the effective turbine fence drag differs in the two passages. In Digby Gut, to generate 67 MW the effective turbine drag coefficient is roughly 6 times the natural drag coefficient. To generate 12 MW in Petit Passage, the effective turbine drag coefficient is only 0.5 times the natural drag coefficient. It is also worth noting that even though the passages are relatively close to each other, the power extraction from one passage has little effect on the other. When the extraction from Digby Gut is changed from 10 MW to 120 MW, the power extraction for a fence in Petit Passage changes only a small amount, from 19 MW to 17.5 MW. This is not surprising, since the power extraction from both these passages has little affect on the tides in the Bay of Fundy.

Location	Maximum	10% Impact	5% Impact
Digby Gut	180	110 (58%)	67 (35%)
Petit Passage	33	19 (58%)	12 (36%)

Table 1: Mean Power Extraction in MW. The impact is the reduction in flow through the passages. The percentage of the maximum power that can be extracted at each impact level is given in parenthesis.

5. Theoretical Assessment of Turbine Fences

Simulating the power potential of a partial fence of turbines in a channel can be difficult. Instead, the potential of a partial fence be estimated using Linear Momentum Actuator Disk Theory (LMADT). The theory uses momentum balances and Bernoulli equations to derive formulae for the flow past a turbine fence, see for example [5-7]. While LMADT calculates the power of a turbine fence, it does not determine the speed of the flow through the channel. But, LMADT can be combined with the power extraction theory (see [4,8]) to determine the power potential of a partial turbine fence in a given tidal flow, see [2,3,9]. Given a chosen blockage ratio (the ratio of the cross-sectional area occupied by turbines), turbine drag coefficient and the number of turbine rows, we can use LMADT to calculate the effective turbine-array drag on the entire channel flow. We can then use this drag to calculate the water speed in the passage using power extraction theory. And, finally, we can estimate the power potential of the turbine fence(s) and the reduction in flow through the passage, see [2,3] for details.

In our previous work, this has been applied to Minas Passage [2,3]. This analysis illustrated a couple of key points. First, that tuning the turbines (in this theory increasing the turbine drag coefficient) did not result in significant power increases for realistic arrays. We therefore choose to fix the turbine drag coefficient of each turbine to 1, the value that gives maximum power in Betz theory. Second, that in theory any value of extractable power up to the channel maximum power can be realized with partial fences by adding sufficient rows of these fences to the channel.

Here, we apply the theory of [3] to Digby Gut and Petit Passage. The power calculated is an idealized with a maximum power coefficient corresponding to the Betz limit. The parameters used in the theory are determined from the results of the numerical simulations. Possibly the most significant parameter is the potential tidal head. For Digby Gut, the potential tidal head is the amplitude of the tides at the head of the passage, 3.5 m. For Petit Passage the potential tidal head is the existing tidal head across the passage, about 0.8 m.

In order to illustrate the results of the theory we chose three blockage ratios: 0.1, 0.2, and 0.4. For Digby Gut, this roughly corresponds to fences of 5, 10, and 20 turbines, each with a cross-sectional area of 400 m^2. For Petit Passage, this roughly corresponds to fences of 2.5, 5, and 10 turbines.

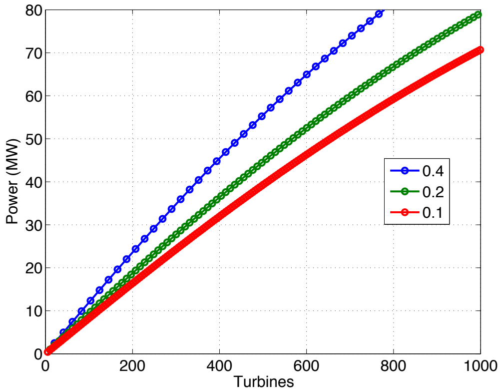

Fig. 10: Turbine power versus the number of turbines for Digby Gut, for the three different blockage ratios shown in the legend. Each dot represents an additional row of turbines.

First, we consider Digby Gut. In Fig. 10 we plot the turbine power versus the number of turbines. We see that the power increases almost linearly, but extremely slowly. Each turbine produces roughly 80 kW for a blockage ratio of 0.1, rising to 120 kW for a blockage ratio to 0.4. The low power generation per turbine requires large turbine arrays to generate significant power. To generate only 30 MW would require 250 to 400 turbines!

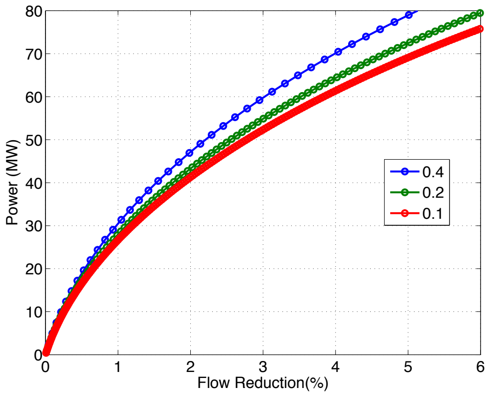

Fig. 11: Turbine power versus the flow reduction for Digby Gut, for the three different blockage ratios shown in the legend. Each dot represents an additional row of turbines.

In Fig. 11 we plot the turbine power versus the reduction in flow. The curves for the different blockage ratios are remarkably similar, implying that the different blockage ratios and number of fences do not drastically change the relationship between the power generated and the reduction in flow. For example, for a 4% reduction in flow, the power ranges from 60 to 70 MW. The generation of the first 30 MW will reduce the flow by only 1%.

Now we consider Petit Passage. In Fig. 12 we plot the turbine power versus the number of turbines. We see that the power increases much more quickly. Each turbine produces roughly 350 kW for a blockage ratio of 0.1, rising to 500 kW for a blockage ratio to 0.4. To generate 15 MW requires only 40 to 60 turbines. The power production per turbine falls off as the number of turbines increases, as we are pushing the system closer to the maximum extractable power.

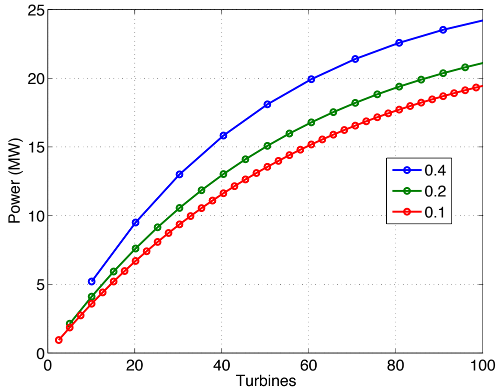

Fig. 12: Turbine power versus the number of turbines for Digby Gut, for the three different blockage ratios shown in the legend. Each dot represents an additional row of turbines.

In Fig. 13 we plot the turbine power versus the reduction in flow for Petit Passage. Once again the blockage ratio does not have a large effect. The generation of 15 MW will reduce the flow by 10 to 13%. The impacts are larger for Petit Passage, but since the flow through the passage does not have a direct affect on the surrounding tides, it is possible that a large reduction in flow through the passage may be acceptable.

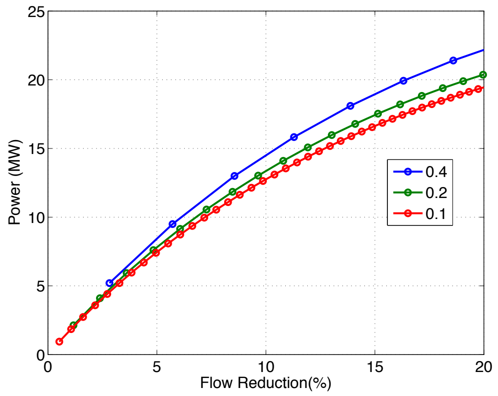

Fig. 13: Turbine power versus the flow reduction for Petit Passage, for the three different blockage ratios shown in the legend. Each dot represents an additional row of turbines.

6. Conclusions

In summary, Digby Gut and Petit Passage, two passages only 50 km apart and with similar flow volume, have very different dynamics and consequently very different tidal resources.

Significant power can be extracted from Digby Gut with only a small reduction in flow because the potential power is related to the potential energy of the tides in Annapolis Basin. But, because the flow through Digby Gut is relatively slow, this potential power can only be realized with a very large number of low-flow turbines. As well, the impact of even a low reduction in the flow through Digby Gut will have a direct impact on the tides throughout Annapolis Basin. It should be noted that there are specific locations with stronger flow in Digby Gut (see Fig. 3). These sites should be able to support standard tidal turbines and extract several MW of power with virtually no impact on the flow.

On the other hand, the potential extractable power from Petit Passage is low compared to Digby Gut, as it is related to the small tidal head across the passage. But now, because of the high flow speed, the extractable power in Petit Passage can be realized with a reasonable number of standard turbines. Here, the reduction in flow through the passage will be larger but the impact on surrounding tides minimal.

These differences between the two passages reinforce the conclusion that each site considered for tidal power development needs to be assessed carefully in terms of its particular dynamics.

Acknowledgements

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