Report to OEER/OETR for

Tidal Energy Resource Assessment Map for Nova Scotia

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Summary

This report presents an update on the extractable power potential of tidal currents in a number of passages around Nova Scotia. Since initial reports by EPRI [1] and the Triton [2] were produced, we have gained a better understanding of how the extraction of power from tidal currents affect the tidal system. This report uses numerical simulations and theoretical calculations to predict not only the power that can be extracted but also the resulting reduction in flow through the passage. As such, it gives power estimates along with a first measure of the environmental impact of extracting tidal energy from the system. In particular, the new power estimates are considerably higher for two passages, Minas Channel and Digby Gut, while the estimates for other passages are similar to previous results. Overall, we estimate potential power extraction of 2000 MW in the Minas Channel, 50 to 100 MW in the Digby Neck region and 1 to 2 MW in Cape Breton.

In Minas Channel, the mean extractable power is estimated to be 7200 MW, of which 3500 MW can be extracted with a 10% reduction in flow through the channel and 2000 MW can be extracted with a 5% reduction in flow. It should be stressed that Minas Channel, which includes Minas Passage, forms one tidal system with Minas Basin, that is, it is one source of energy and one system that will be changed if energy is extracted. The extractable power from Minas Channel is a reflection of the potential energy in the world's highest tides of the Minas Basin. A reduction in flow through Minas Channel will result in a corresponding reduction in the tides in Minas Basin. This will have important impacts on the intertidal regions that surround the basin. As such, we suggest the 2000 MW power estimate, which limits the reduction in flow to 5%, is the best estimate for the power potential of the Minas Channel region. Finally, it should be noted that the highest water speeds, and thus, highest power densities are found in Minas Passage. As such, it is Minas Passage that has the greatest potential for the development of commercial-scale, tidal turbine arrays.

The passages of the Digby Neck region offer the potential of significant tidal power. In particular, the Digby Gut/Annapolis Basin system has a much larger potential than previously estimated. The mean extractable power is 180 MW, of which 67 MW can be extracted with only a 5% reduction in the flow through Digby Gut. However, this estimate comes with the caveat that the flow speed and power densities in Digby Gut are low. Realizing a significant portion of the potential power will require technology that can extract power from flows with speeds of 1 to 2 m/s.

On the other hand, Petit and Grand Passages have higher velocities and power densities - similar to those found in Minas Passage. However, these passages lie between two large, open bodies of water. The flow through these small passages is not important in determining the tides in these waters. As such, they only have moderate potential power extraction - 33 MW for Petit Passage and 16 MW for Grand Passage. But, it is expected that a reduction in flow through these passages will have a small impact on the surrounding tides. Therefore,

power extraction that reduces the flow by 10% (or possibly higher) could be acceptable giving power estimates of 19 MW for Petit Passage and 8.9 MW for Grand Passage.

The passages of the Bra D'Or Lakes have a small potential for power extraction - 4.6 MW for Great Bra D'Or Channel and 2.2 MW for Barra Strait. The water exchange between the Bra D'Or Lakes and the ocean is a complicated process that supports the ecology of the region. Any power extraction of power should minimize the changes to these exchanges, and therefore we suggest the change in flow through the passages be limited to a 5% reduction, giving power estimates of 1.1 MW for Great Bra D'Or Channel and 0.6 MW for Barra Strait.

At this point, we have examined no other sites in Nova Scotia that have the strong tidal currents in a region suitable for large scale tidal power extraction. Ongoing research along the South West Nova Scotia coastline has identified locations suitable for community scale tidal development. These will be reported on in a later report.

Finally, estimating the portion of extracted energy that can be converted into useable electricity supplied to the grid is a difficult process. Tidal energy technology is still under development and changes in turbine technology and the design of turbine arrays will affect how much power can be generated. For this report, we only use a very basic model to estimate that 40% of the extractable power can be converted into electricity. We also estimate that the installed capacity necessary to generate this power to be 70% the extractable power. Therefore, the estimated mean extractable power are moderate overestimates of the potential installed capacity of turbine arrays for each passage.

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Chapter 1

Introduction

Nova Scotia has significant tidal energy resources. The Bay of Fundy has the world's highest tides, routinely reaching over 15 m in range in 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. A critical aspect of tidal power development is an accurate assessment of the power resource. Initial assessments of Nova Scotia's resource made by Triton Consultants for the Canadian Hydraulics Centre [2] were based on estimates of the kinetic energy flux. They estimated a potential of 2122 MW for Nova Scotia, with the majority in Minas Passage. EPRI [1] used similar calculations, with data on water speeds from charts, but also estimated mean extractable power as only 15% of the maximum potential power. They estimated a total resource of 331.9 MW for Nova Scotia, again with the majority from Minas Channel. Since these estimates were made, there has been considerable research done on the power potential of tidal currents. In particular, Garrett and Cummins [3] found that "there is no simple relationship between the maximum average power and the average kinetic energy flux in the undisturbed state." Their research brought into question all estimates that are based on the kinetic energy flux. Since then a number of studies have further expanded the Garrett and Cummins theory [4, 5, 6, 7, 8] and successfully compared the theory to numerical simulations [9, 5, 10]. In particular, Karsten, McMillan, Lickley and Haynes (hereafter KMLH) [5] illustrated through application of the theory and numerical simulations that the power potential of Minas Passage was considerably higher than previous estimates.

This report presents an updated resource assessment for tidal energy for the passages of the Bay of Fundy and the Bra D'Or Lakes passages based on the methodology used in KMLH. It will uses both theoretical analysis and numerical simulations to estimate the maximum extractable power from passages around the Bay of Fundy. For each location the extractable power will be plotted versus the resulting reduction in flow through the passages. Maps of the Bay of Fundy showing the maximum extractable power power and the extractable power that produces a 10% and 5% change in flow through the passages are given in section 2. In section 3, we examine each passage in more detail, presenting maps of the bathymetry, mean current speed and mean power density, in addition to a plot of extracted power versus the reduction in flow.

In section 4 we briefly describe the numerical and theoretical methods used in the calculations and illustrates that there is considerable agreement between the two. Finally, we present a brief discussion of how the extractable power can be connected to the potential electricity generation and installed capacity of a turbine array for a given passage.

Chapter 2

Nova Scotia's Tidal Energy Resource Maps

The following 7 maps and 3 tables summarize the results of this report. In each figure, the values given are calculated using numerical simulations for Minas Channel, Digby Gut, Petit Passage and Grand Passage as described in Section 4.1. Values for Great Bras D'Or Channel and Barra Strait are calculated using power extraction theory described in Section 4.2. The powers calculated are the time-mean power, that is ,the average power calculated from a month of data - the maximum power over a typical tidal cycle is roughly 1.5 times this mean value. Values shown are rounded to two significant digits - this does not reflect the accuracy of the values but is done for simplicity. As discussed in the methods section, all values should be considered the best available estimates at this time. There remains considerable uncertainty in understanding the details of tidal currents and how effectively tidal turbines can extract power from these currents. As well, understanding the impact of extracting power from tidal currents requires understanding the complex relationship between tides and ecology, which is unique to each specific location. Here, we have chosen a simple measure of the impact, the reduction in flow through the passage, because this is easily calculated in our numerical simulations and theory.

Figure 2.1 gives the maximum, time-averaged power that can be extracted from each passage. Figures 2.2 and 2.3 give the mean extractable power for a 10% and 5% reduction in flow, respectively. Figures 2.4 and 2.5 show the values for the 5% reduction in flow on larger-scale maps for Digby Neck and Cape Breton, respectively. These values are also summarized in Table 2.1, which also shows that the percentage of the maximum power that can be extracted with the specified reduction in flow. This percentage varies with location since the dynamics of the tidal currents varies with location (see Section 4.2) In Table 2.2, the mean extractable power values calculated in this report are compared to the mean power potential calculated in the Canadian Ocean Energy Atlas. This comparison is presented to emphasize that in the case of passage–tidal basin systems, like the Minas Channel–Minas Basin system and the Digby Gut–Annapolis Basin system, the power estimates based on the kinetic energy flux substantially underestimate the power.

As noted in Section 3, a 10% or 5% reduction in flow will result in different environmental impacts for each location. Since the Petit and Grand Passages do not have a direct impact on the local tidal range, we assume a 10% reduction in the flow through these passages will be acceptable. For all the other passages, the reduction in flow is expected to have a direct impact on both the tidal range and the water exchange of the associated basin and therefore chose to limit the reduction in flow to 5%.

The values of extracted power listed on each figure are the power that has been removed from the flow through the passage and do not correspond to the electricity that could be generated by a particular Tidal Energy Converter (TEC). The fraction of the extracted power that could be converted into electricity depends on many factors: the design of the TEC, the exact deployment location, the size and arrangement of the array of TECs, the limitations of the supporting infrastructure, etc. In Section 4.3, we use an analysis of an idealized turbine to estimate that 40% of the mean extracted power can be converted into electricity. We also estimate that the installed capacity would be 70% of the mean extracted power. In Figures 2.6 and 2.7, we give the potential mean electricity generation and required installed capacity for each passage. These numbers are summarized and compared to EPRI calculations in Table 2.3.

Location	Maximum	10% Reduction in Flow	5% Reduction in Flow
Minas Channel (including Minas Passage)	7200	3500 (49%)	2000 (28%)
Minas Passage (alone)	5800	2900 (50%)	1600 (28%)
Digby Gut	180	110 (58%)	67 (35%)
Petit Passage	33	19 (58%)	12 (36%)
Grand Passage	16	8.9 (55%)	5.4 (33%)
Great Bras d'Or Channel	4.6	2.1 (44%)	1.1 (24%)
Barra Strait	2.2	1.0 (46%)	0.6 (25%)

Table 2.1: Average Power Extraction in MW versus the reduction in flow through the passage. The percentages shown are the percentage of the maximum power that can be extracted at each reduction in flow. The values are calculated using numerical simulations for Minas Channel, Digby Gut, Petit Passage and Grand Passage as described in Section 4.1. Values for Great Bras D'Or Channel and Barra Strait are calculated using power extraction theory described in Section 4.2. Minas Channel includes the power potential of Minas Passage, which is listed separately because of the specific interest in Minas Passage.

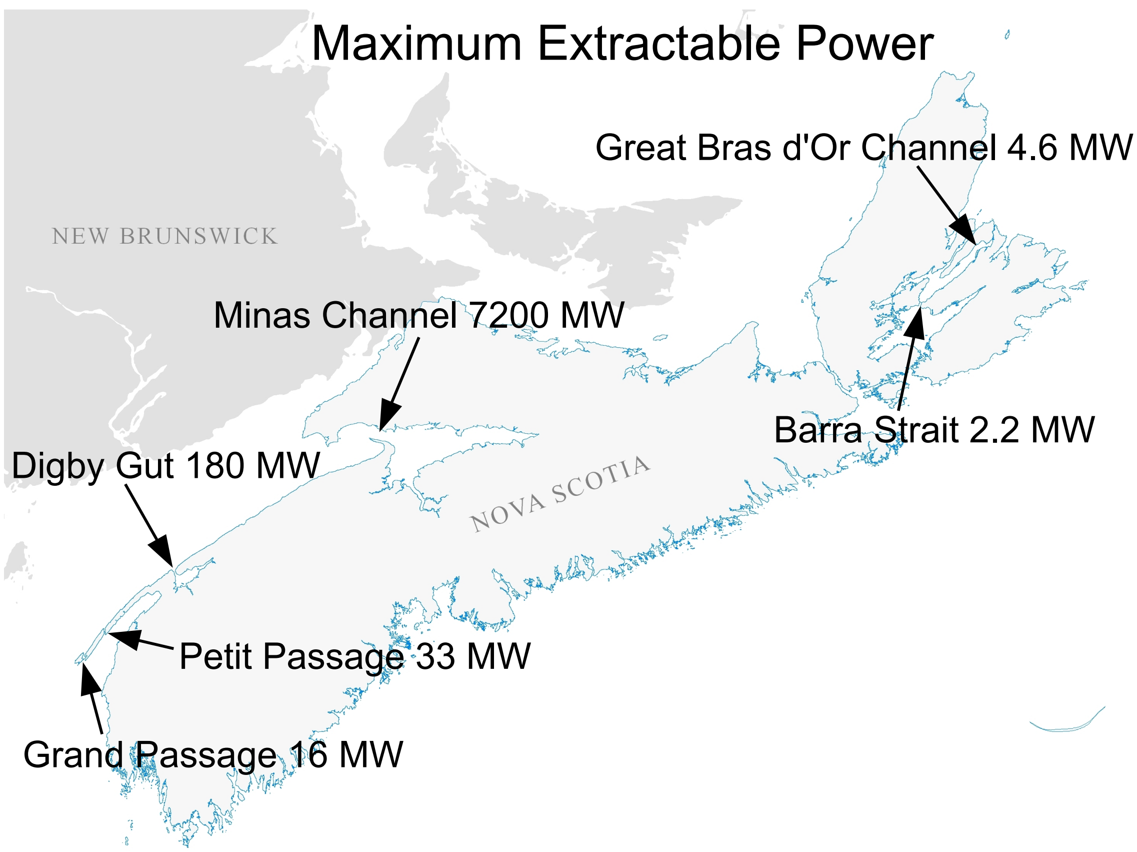


Figure 2.1: The maximum power that can be extracted from Nova Scotia tidal passages. The values are calculated using numerical simulations for Minas Channel, Digby Gut, Petit Passage and Grand Passage as described in Section 4.1. Values for Great Bras D'Or Channel and Barra Strait are calculated using power extraction theory described in Section 4.2.

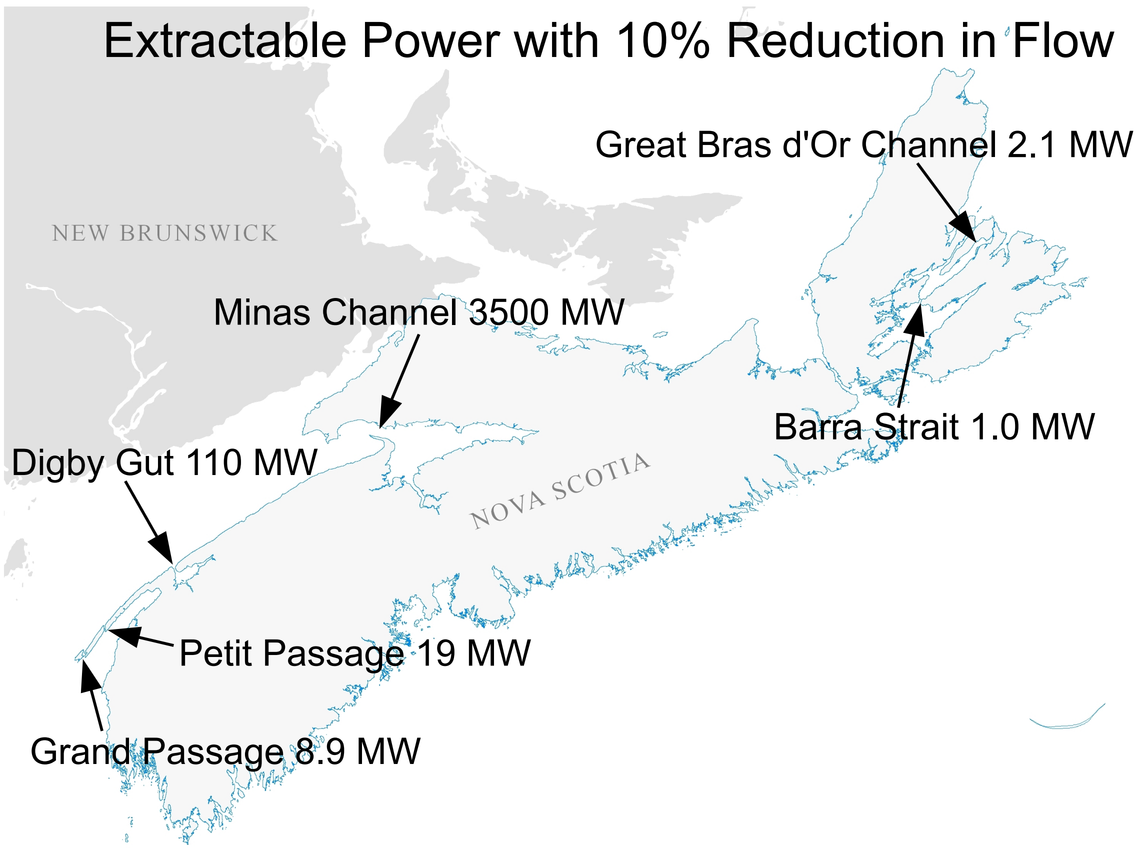


Figure 2.2: The power that can be extracted from Nova Scotia tidal passages while only reducing the flow through the passage by 10%. The values are calculated using numerical simulations for Minas Channel, Digby Gut, Petit Passage and Grand Passage as described in Section 4.1. Values for Great Bras D'Or Channel and Barra Strait are calculated using power extraction theory described in Section 4.2.

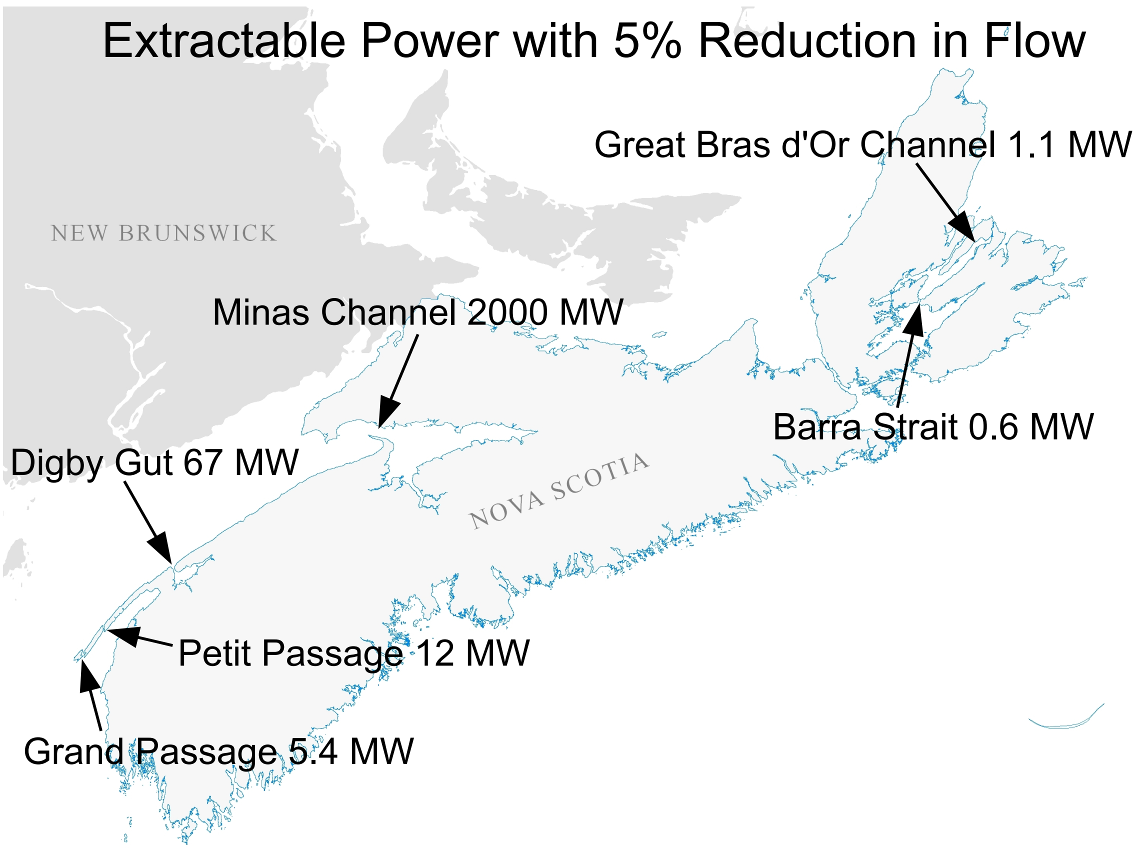


Figure 2.3: The power that can be extracted from Nova Scotia tidal passages while only reducing the flow through the passage by 5%. The values are calculated using numerical simulations for Minas Channel, Digby Gut, Petit Passage and Grand Passage as described in Section 4.1. Values for Great Bras D'Or Channel and Barra Strait are calculated using power extraction theory described in Section 4.2.

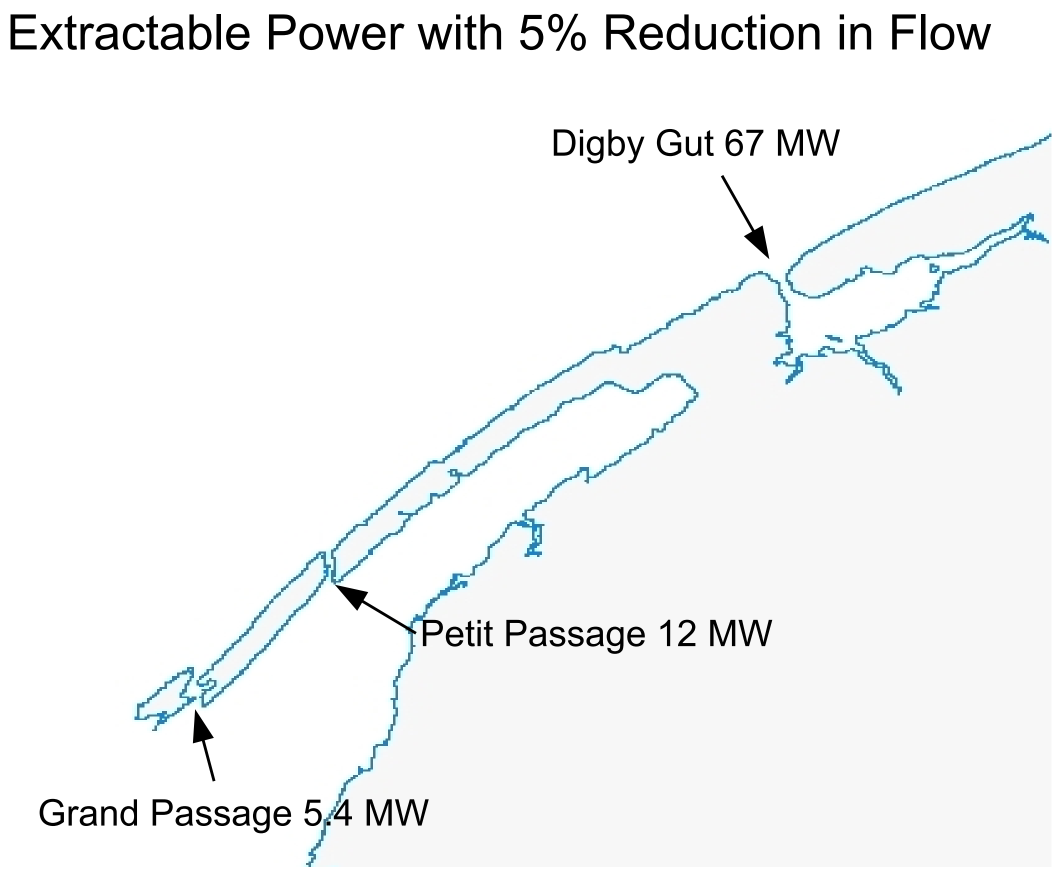


Figure 2.4: The mean power that can be extracted from the tidal currents through the Digby Neck passages while only reducing the flow through the passage by 5%. The values are calculated using numerical simulations as described in Section 4.1.

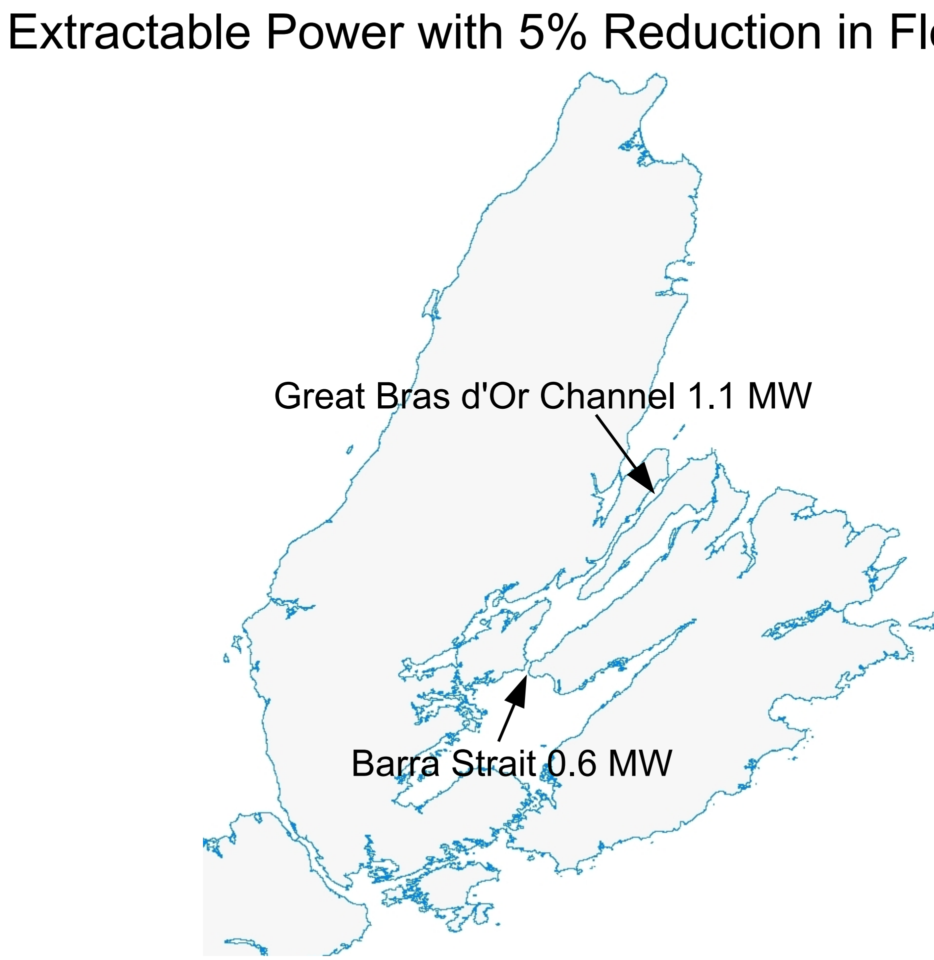


Figure 2.5: The mean power that can be extracted from the tidal currents through Cape Breton passages while only reducing the flow through the passage by 5%. The values are calculated using power extraction theory described in Section 4.2.

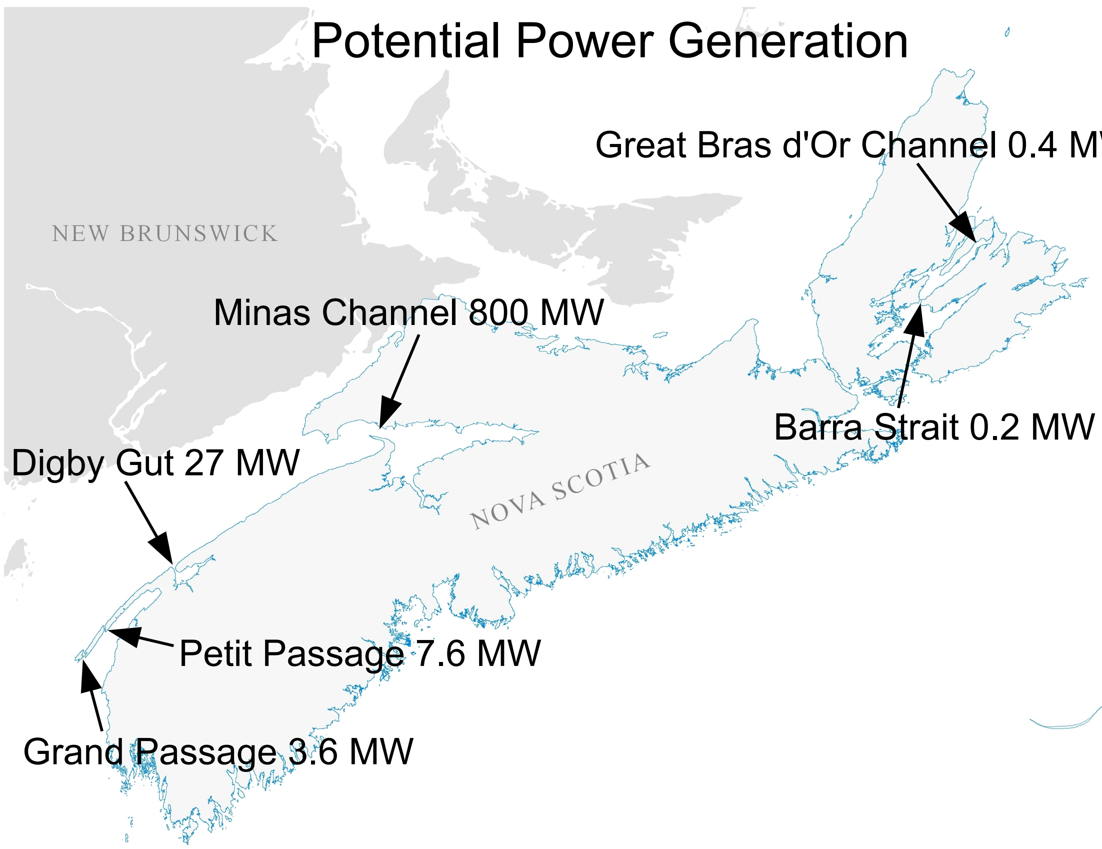


Figure 2.6: The potential mean power generation for Nova Scotia tidal passages while only reducing the flow through the passage by 5% for Minas Channel, Digby Gut, Great Bras D'Or Channel and Barra Strait, and by 10% for Petit Passage and Grand Passage. The relationship between power generation and extracted power is described in Section 4.3.

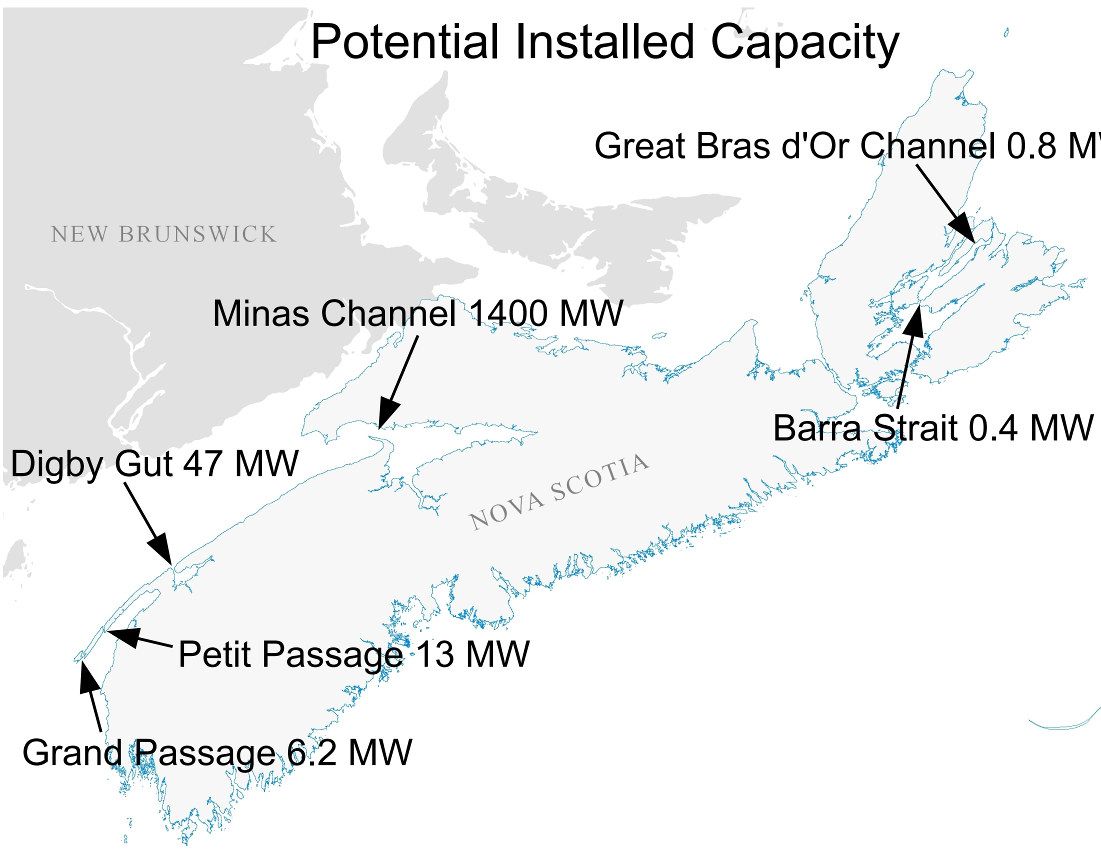


Figure 2.7: The installed capacity for Nova Scotia tidal passages required to generate the power shown in Figure 2.6. The relationship between power generation and installed capacity is described in Section 4.3.

Location	Canada Ocean Energy Atlas	This Report
Minas Channel	1903	7200
Digby Gut	21	180
Petit Passage	24	33
Grand Passage	15	16
Great Bras d'Or Channel	3	4.6
Barra Strait	3	2.2

Table 2.2: Maximum Mean Power in MW. The first column values come from the Canada Ocean Energy Atlas [2] and is calculated using the power density and cross-sectional area of the passage. The second is the extractable power calculated in this report.

Location	Mean Extracted Power	Mean Power Generation	Installed Capacity	EPRI Power Generated	EPRI Installed Capacity
Minas Channel	2000	800	1400	297	595
Digby Gut	67	27	47	4.9	9.8
Petit Passage	19	7.6	13	9.2	18
Grand Passage	8.9	3.6	6.2	6.6	13
Great Bras d'Or Channel	1.1	0.4	0.8	1.4	2.8
Barra Strait	0.6	0.2	0.4	-	-

Table 2.3: The extractable power in MW with a low reduction in flow through the passages (10% for Petit and Grand Passages, 5% for the rest), the potential power generation in MW (40% of extractable power) and the necessary installed capacity in MW (70% of extractable power) for Nova Scotia tidal passages. An explanation of the power generation and installed capacity is given in Section 4.3. The final two columns give the potential power generation and installed capacity given by EPRI [1].

Chapter 3

Detailed Analysis of Each Passage

3.1 Minas Channel and Minas Passage

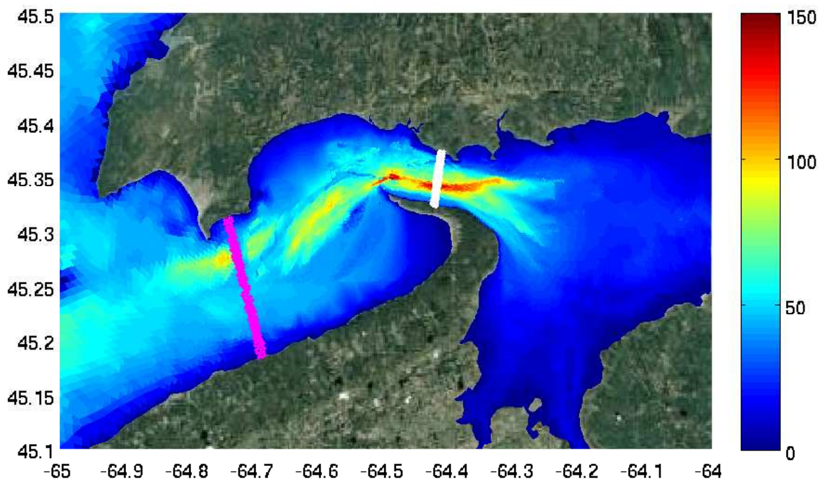


Figure 3.1: The bathymetry of Minas Channel used in the numerical simulations. The colours are the the mean water depth in metres. The pink line is the location of the Minas Channel turbine fence; the white line is the location of the Minas Passage turbine fence.

Minas Channel, as shown in Figure 2.1 and 3.1, connects Minas Basin to the Bay of Fundy. It is some 50 km in length, with a width of 20 km in the outer channel that reduces to only 5 km in Minas Passage. The water depths are 50-100 m in the outer channel increasing to 150 m in Minas Passage, see Figure 3.1. It has some of the strongest tidal currents in the Bay of Fundy, particularly in Minas Passage where water speeds can reach over 5 m/s. The volume flux through the passage can reportedly reach 1×10^6 m^3s^{-1} during the largest spring tides.

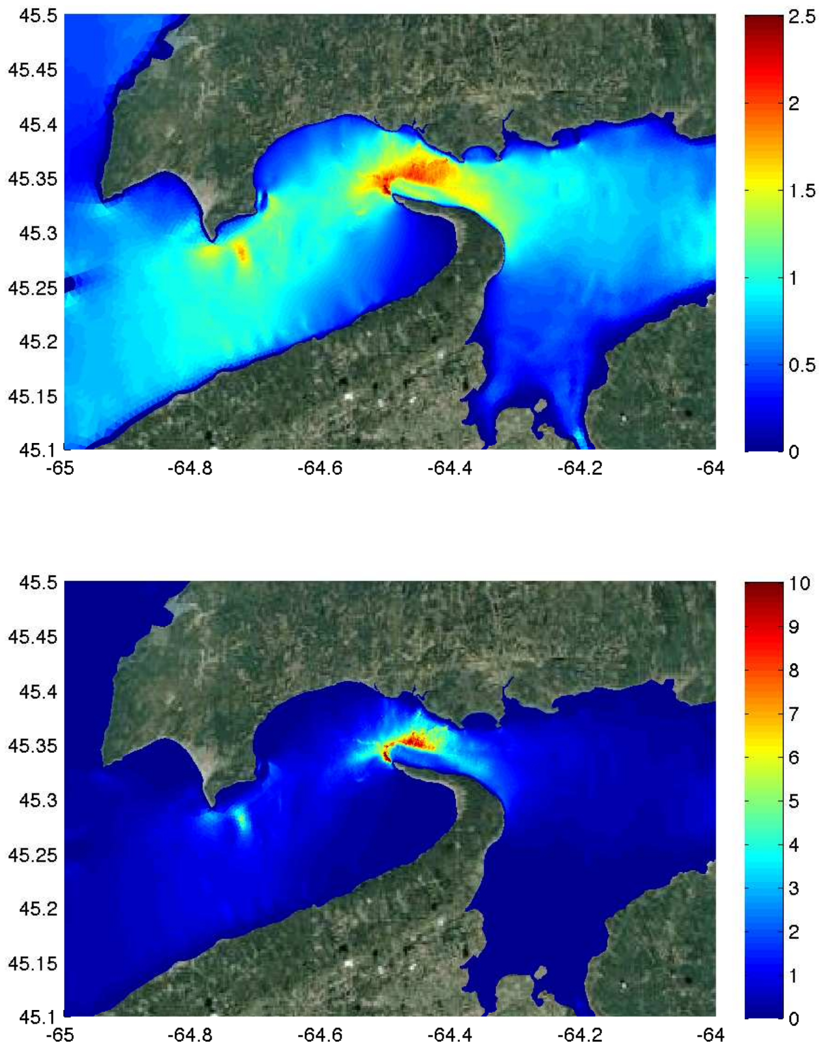


Figure 3.2: The mean depth-averaged speed in m/s (top) and mean power density in kW/m^2 (bottom) for Minas Channel.

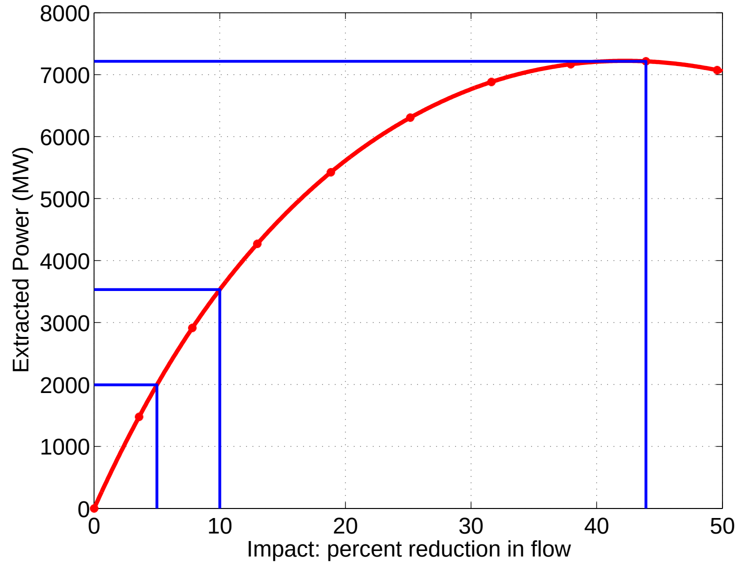


Figure 3.3: Minas Channel: Extracted power versus the reduction in flow through the turbine fence. The blue lines highlight the values presented in the resource maps. The dots are the values for the simulations, the curve is found using an interpolating spline.

During the numerical simulation used here, the volume flux reached a maximum of 8.3×10^5 m^3s^{-1}.

In Figure 3.2 we plot the mean speed and mean power density for Minas Channel. It illustrates that throughout much of Minas Passage the mean, depth-averaged speed exceeds 2 m/s–maximum depth average speeds are between 3 and 4 m/s. The power density in Minas Passage often exceeds 8 kW/m^2–at this power density, a 10 m diameter turbine would produce a mean power of 0.6 MW and a maximum power of about 1.0 MW. The outer Minas Channel has considerable slower flow, with mean speeds around 1 m/s with a small region where the mean speed exceeds 1.5 m/s. As such the power densities in the outer channel are much less, for most of the area below 4 kW/m^2. Therefore extracting significant power from the outer channel would require a low flow TEC.

It is important to keep in mind that Minas Channel and Minas Basin form a single tidal system. The power that drives the flow through Minas Channel is the tidal head across the channel - the difference in tidal elevation between the opening of Minas Channel and Minas Basin. The maximum extractable power from the channel is roughly equivalent to the potential energy in the tides of Minas Basin. In order to calculate the power potential of the channel, numerical simulations were run with a fence of turbines at two different locations as shown in Figure 3.3. The turbine fences extend across the entire channel at each location. For each simulation the drag coefficient of the fence is altered and the mean power extracted by the fence and mean volume flux through the fence are calculated. The extracted power

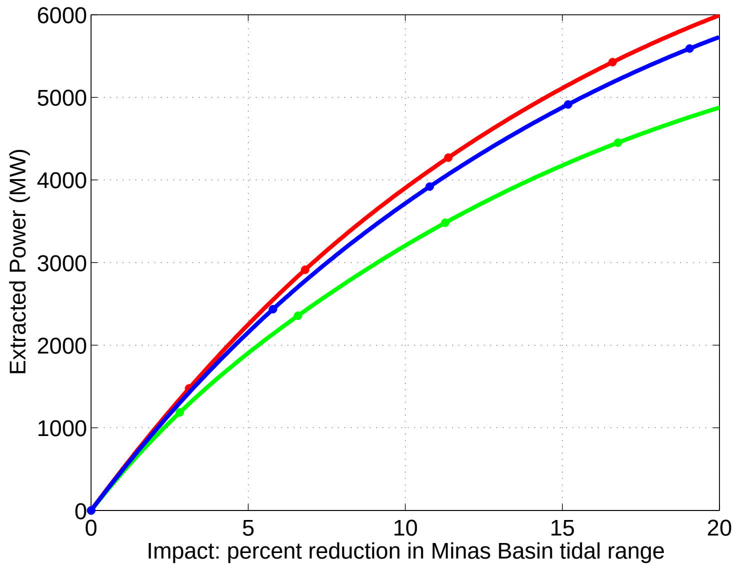


Figure 3.4: Minas Channel: Extracted power versus the reduction in the tidal range in Minas Basin. The red curve is power extracted using only the Minas-Channel fence ; the green curve is power extracted using only the Minas-Passage fence; the blue curve is the case of roughly equal power extracted both fences (56% MC and 44% MP). See Figure 3.1 for the location of the two fences.

versus reduction in volume flux can be plotted, as in Figure 3.3. This curve is for the outer Minas Channel fence shown in pink in Figure 3.1. The figure shows how the extracted power increases rapidly for a relatively small reduction in the flow through the passages. As the power extraction increases, the reduction in flow becomes greater until a maximum power extraction is reached.

In Figure 3.4, we illustrate how the power/impact curve shown Figure 3.3 changes if power is extracted from different locations in Minas Channel. In this figure, the impact of the power extraction is measured as the reduction in the tidal range of the tides in Minas Basin. The power curve changes very little if the power is extracted at different locations. The power available in Minas Passage is only 80% of the total available at the outer channel location, since the turbine fence in Minas Passage can not extract power from the significant tides in the outer Minas Channel. If power is extracted from both the fence in the outer channel and in Minas Passage, in roughly equal proportions (56% to 44%), the power curve lies between the two previous curves. Any combination of turbine fences in Minas Channel will produce a power/impact curve that will lie in the range of the red and green curves on this graph.

Figure 3.4 does suggest that more power can be extracted from the outer Minas Channel than from Minas Passage for the same reduction of Minas Basin tides. However, since the power densities in the outer Minas Channel are significantly lower than the values in Minas Passage (see Figure 3.2), extracting this power may require a technology that works at lower flow and will require significantly more and/or significantly larger turbines.

Finally, it should be emphasized that any reduction in flow through Minas Channel will directly reduce the tidal range in Minas Basin. A 5% reduction in flow through Minas Channel will result in a 5% reduction in the range of the tides in Minas Basin. A 5% change in the tidal range in Minas Basin could have significant impacts on the intertidal zones, with significant areas along the coast that no longer flood regularly during high tide or no longer dry at low tide. Calculating these changes require numerical simulations with improved coastal bathymetry and much higher resolution in the intertidal zones.

3.2 Digby Neck

For the three passages of Digby Neck, numerical simulations were run using a grid with particularly high resolution in Digby Gut, Petit Passage and Grand Passage. The location of Digby Neck and the passages are shown in Figures 2.1 and 2.4.

3.2.1 Digby Gut

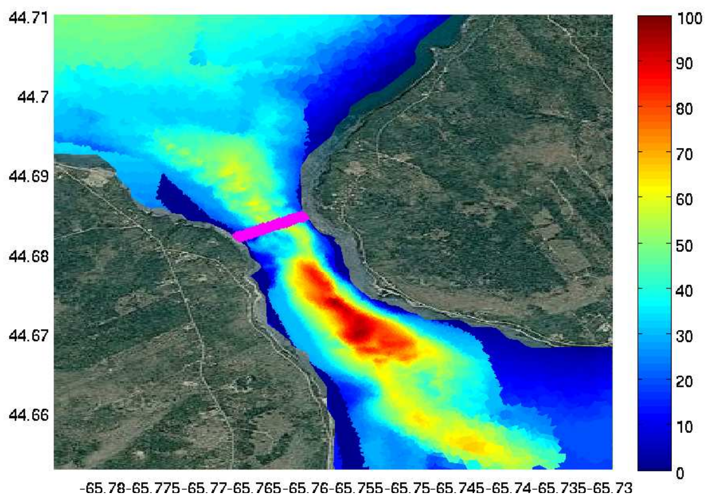


Figure 3.5: The bathymetry of Digby Gut used in the numerical simulations. The colours are the mean water depth in metres. The pink line is the location of the Digby Gut turbine fence.

Digby Gut is a deep passage that connects the Annapolis Basin to the Bay of Fundy as shown in Figure 2.4. The passage is roughly 4 km long and 1 km wide with water depths

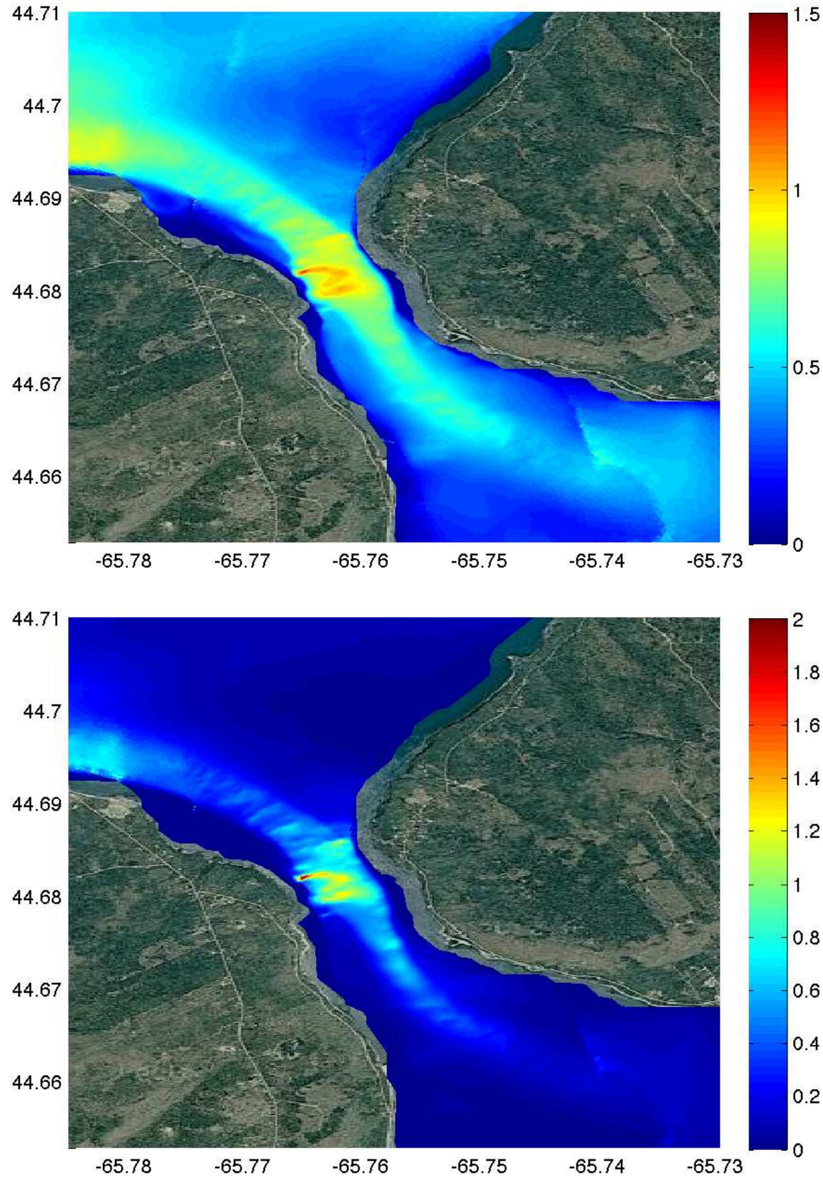


Figure 3.6: The mean depth-averaged speed in m/s (top) and mean power density in kW/m^2 (bottom) for Digby Gut.

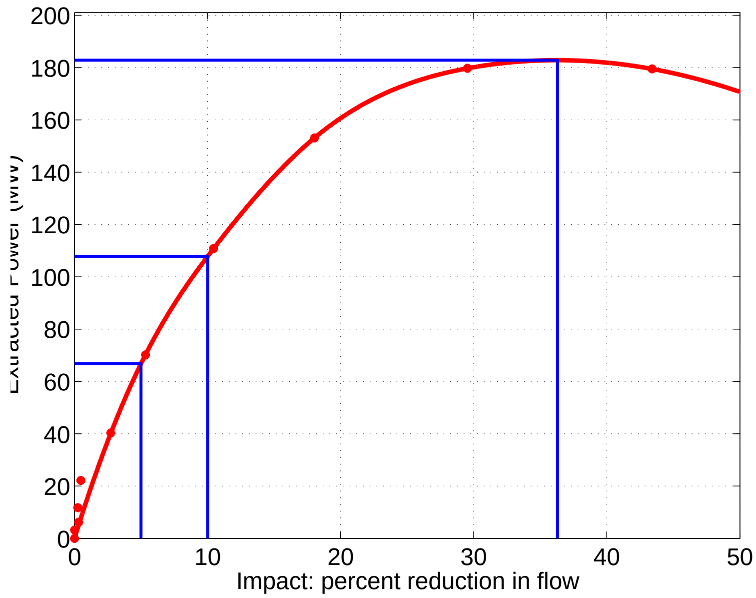


Figure 3.7: Digby Gut: Extracted power versus the reduction in flow through the turbine fence. The blue lines highlight the values presented in the resource maps. The dots are the values for the individual simulations, the curve is found using an interpolating spline.

reaching almost 100 m, as shown in Figure 3.5. Figure 3.5 also shows the location of the turbine fence used to extract power in the numerical simulations.

In Figure 3.6, we plot the mean speed and mean power density for Digby Gut. It illustrates that the mean, depth-averaged speed in Digby Gut rarely exceeds 1 m/s. In our numerical simulations, the volume flux through the passage reaches 4×10^4 m^3s^{-1} during the spring tide. 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 the Digby Gut would require a low flow TEC. Since the Gut connects the closed Annapolis Basin to the Bay of Fundy, it has similar dynamics to the Minas Channel/Minas Basin system. The potential power in Digby Gut is related to the significant potential energy of the tides in the Annapolis Basin.

The extractable power was calculated using the turbine fence shown in Figure 3.5. The resulting power curve, shown in Figure 3.7, has a similar form to the curve for Minas Channel. For a small channel, there is significant power (180 MW) that can be extracted, and notably significant power with small changes in flow through the passage. But, as with Minas Channel, small changes in the flow through Digby Gut will have direct impacts on the tidal range in Annapolis Basin. These impacts need to be examined more closely. It should be noted that the simulations that were run that extracted up to 20 MW from Digby Gut showed essentially no change in the flow through the Gut – at least within the accuracy of the numerical model. Again, as noted above, the tidal currents through the Digby Gut have a relatively low speed, in comparison to other passages discussed here. Therefore, to

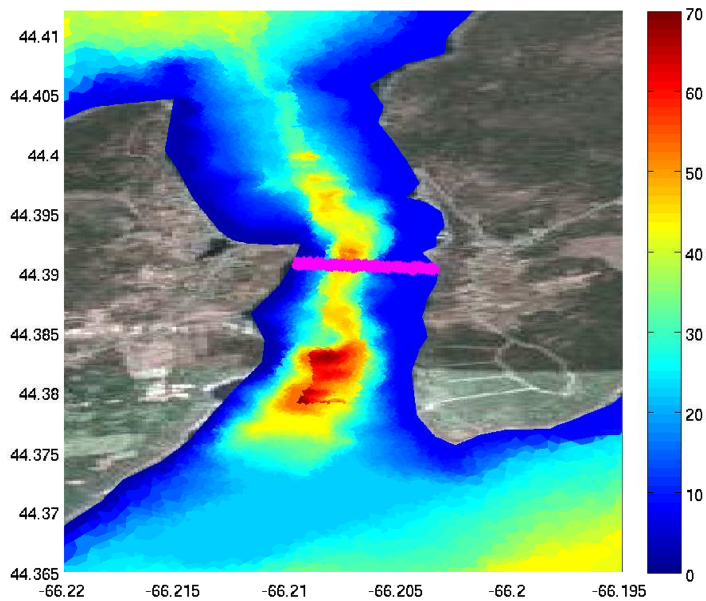


Figure 3.8: The bathymetry of Petit Passage used in the numerical simulations. The colours are the mean water depth in metres. The pink line is the location of the Petit Passage turbine fence.

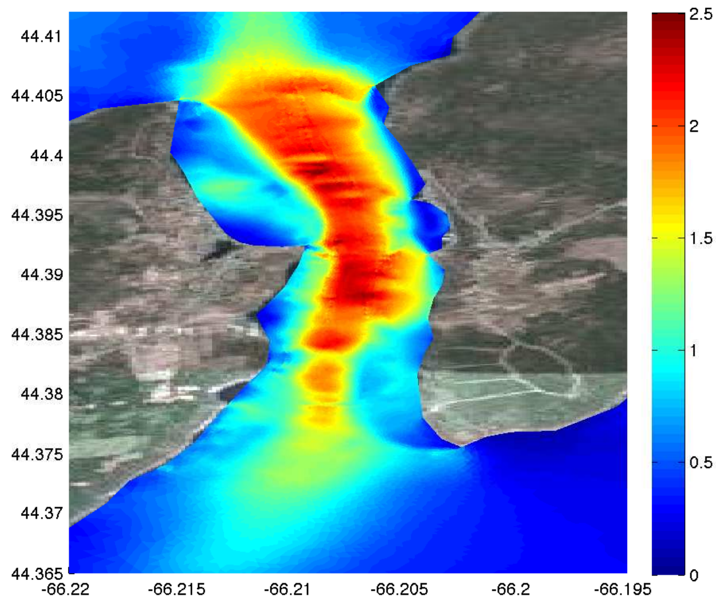
realize the large power potential will require TEC technology that works at moderate current speeds.

3.2.2 Petit Passage

Petit Passage is the passage between the Digby Neck peninsula and Long Island as shown in Figure 2.4. The passage is roughly 4 km long and 0.5 to 1 km wide with water depths reaching 70 m, as shown in Figure 3.8. Figure 3.8 also shows the location of the turbine fence used to extract power in the numerical simulations.

In Figure 3.9 we plot the mean speed and mean power density for Petit Passage. It illustrates that the mean, depth-averaged speed in Petit Passage is mostly between 2 and 2.5 m/s. In our numerical simulations, the volume flux through the passage reaches 3×10^4 m^3s^{-1} during the spring tide. The power density routine exceeds 8 kW/m^2 and reaches over 10 kW/m^2. These values exceed those in Minas Passage, though it should be noted that these simulations use a higher resolution grid which allow higher water speeds. Thus, the flows in Petit Passage will allow high energy TEC to produce a large amounts of power.

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 Minas Channel or Digby Gut. The flow through Petit Passage has little impact on the tides of either St. Mary's Bay or the Bay of



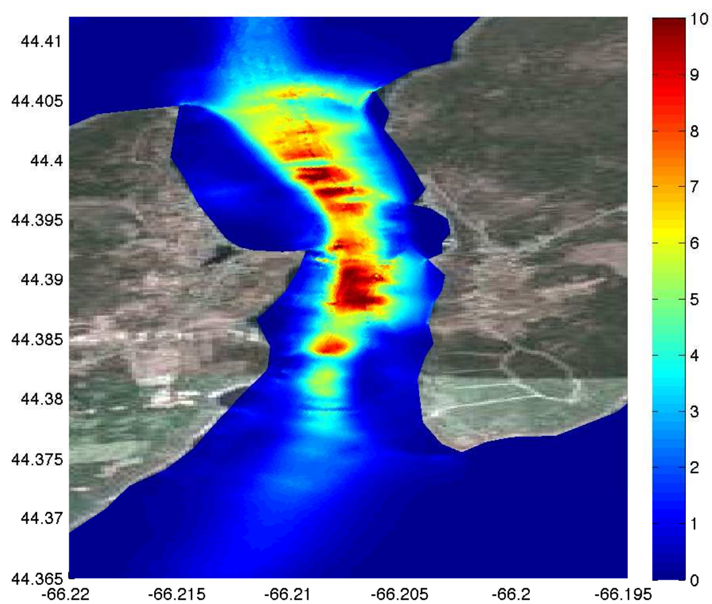


Figure 3.9: The mean depth-averaged speed in m/s (top) and mean power density in kW/m^2 (bottom) for Petit Passage.

Fundy. As discussed in Section 4.2, 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 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 an order of magnitude less. The power curve for Petit Passage, shown in Figure 3.10, has a similar shape to the previous power curves, but the maximum power is significantly smaller. The maximum power is only 33 MW but one again a significant portion of this power can be extracted with only small changes in flow through the passage. Now, since flow through Petit Passage has little impact on the surrounding tides, it could be expected that a 10% reduction in flow will have little impact on surrounding intertidal zones. Of course, extracting power from the passage may still have other important environmental impacts.

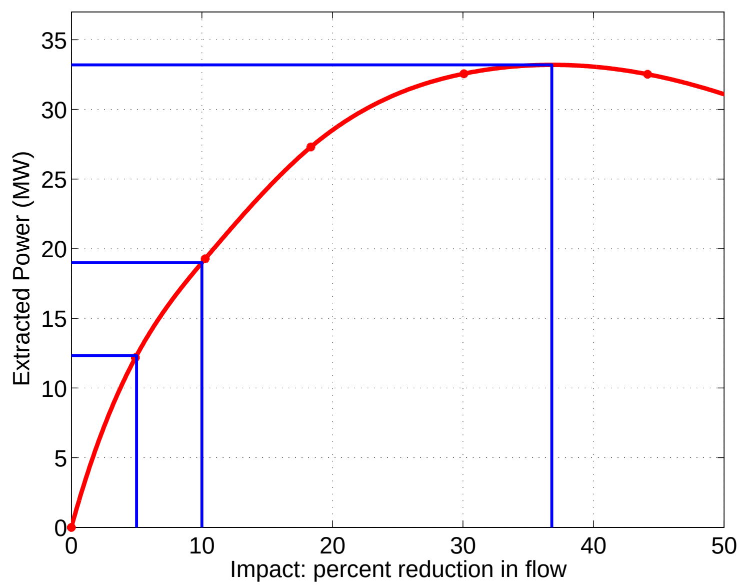


Figure 3.10: Petit Passage: Extracted power versus the reduction in flow through the turbine fence. The blue lines highlight the values presented in the resource maps. The dots are the values for the individual simulations, the curve is found using an interpolating spline.

3.2.3 Grand Passage

Grand Passage is the passage between Long Island and Briar Island as shown in Figure 2.4. The passage is roughly 4 km long and 0.5 to 1 km wide but is quite shallow with water depths reaching only 35 m, as shown in Figure 3.11. Figure 3.11 also shows the location of the turbine fence used to extract power in the numerical simulations.

In Figure 3.12 we plot the mean speed and mean power density for Grand Passage. It illustrates that the mean, depth-averaged speed in Grand Passage is mostly between 1.5 and

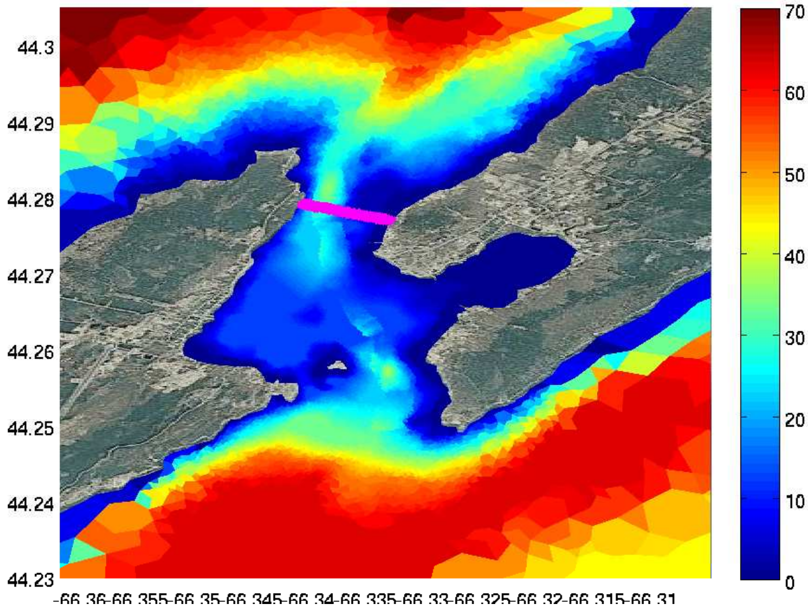


Figure 3.11: The bathymetry of Grand Passage used in the numerical simulations. The colours are the mean water depth in metres. The pink line is the location of the Grand Passage turbine fence.

2 m/s. In our numerical simulations, the volume flux through the passage reaches 2×10^4 m^3s^{-1} during the spring tide. Since the flow through Grand Passage is significantly less than that of Petit Passage, the power potential is similarly reduced. The power density occasionally reaches 8 kW/m^2, and has large areas between 4 and 6 kW/m^2. Thus, the flows in Grand Passage will not be suitable for high energy TECs, but could be ideal for moderate energy TECs or for testing high energy TECs.

Like Petit Passage, Grand Passage lies between St. Mary's Bay and the Bay of Fundy and thus has very similar dynamics. The power curve for Grand Passage, shown in Figure 3.13, has a similar shape to the previous power curves, but the maximum power is significantly smaller. The maximum power is only 16 MW but one again a significant portion of this power can be extracted with only small changes in flow through the passage. As with Petit Passage, the flow through Grand Passage has little impact on the surrounding tides and it could be expected that a 10% reduction in flow will have little impact on surrounding intertidal zones. And, as mentioned before, extracting power from the passage may still have other important environmental impacts.

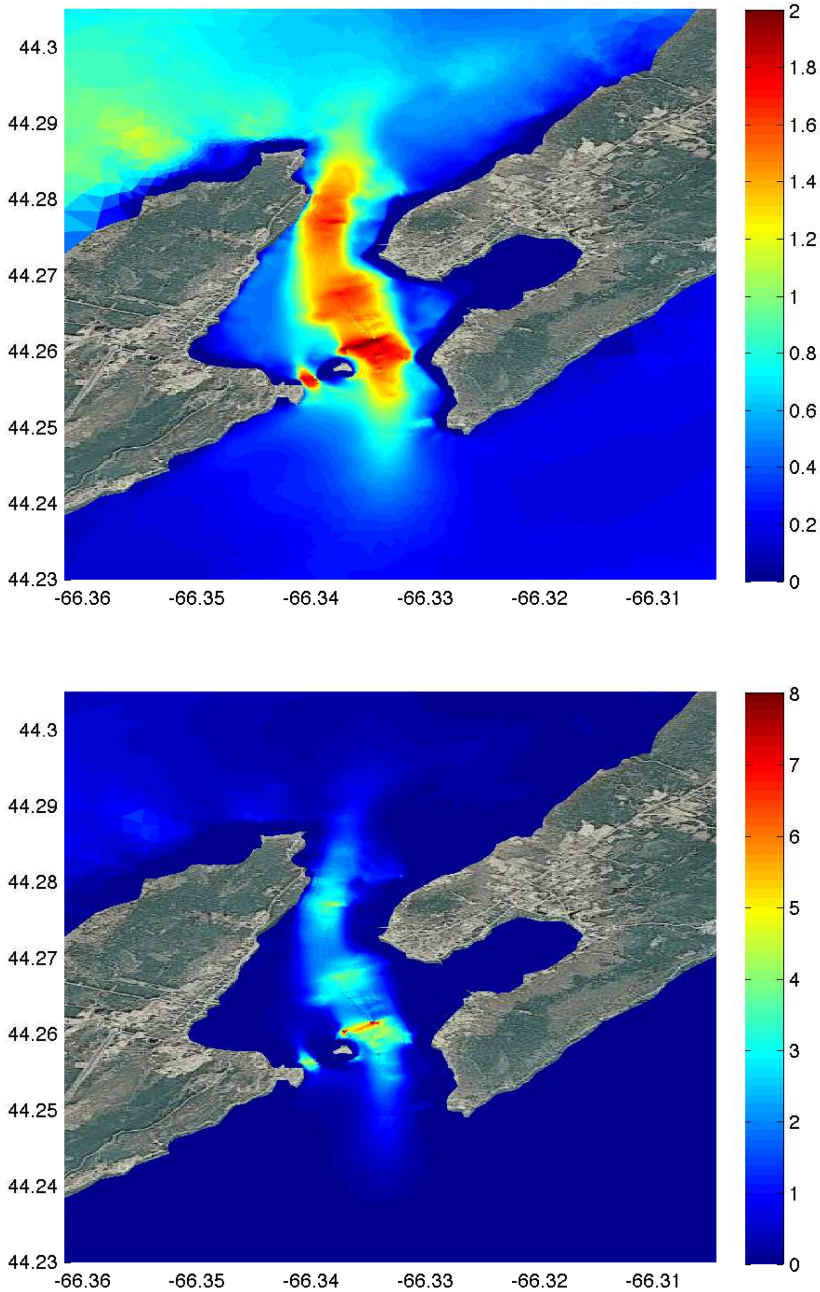


Figure 3.12: The mean depth-averaged speed in m/s (top) and mean power density in kW/m^2 (bottom) for Grand Passage.

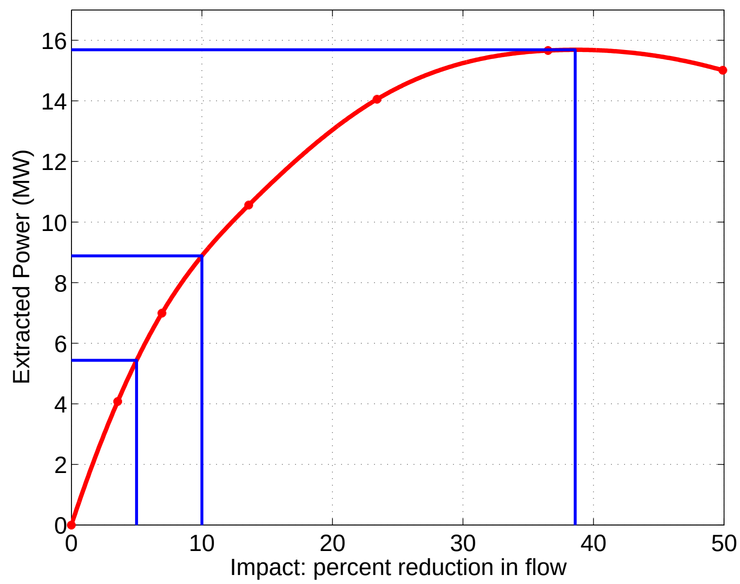


Figure 3.13: Grand Passage: Extracted power versus the reduction in flow through the turbine fence. The blue lines highlight the values presented in the resource maps. The dots are the values for the individual simulations, the curve is found using an interpolating spline.

3.2.4 Inter-passage impact for Digby Neck

Finally, we examine how the extractable power changes when power is extracted from several passages at the same time. For all these simulations, the drag value of the turbine fences in Grand and Petit Passages were held at a constant value that would result in a 10% reduction in flow if power was only extracted from these passages. In the first set of simulations, an increasing amount of power was extracted from Digby Gut. The results are shown in Table 3.1. As the power from Digby Gut is increased from near zero to over 100 MW the change in Petit and Grand Passages is only a small decrease in power and a small increase in impact. We conclude that projects in the 3 passages can be developed simultaneously without impacting each other.

In the second set of simulations, the Digby Neck fences were kept at the same drag values used in the final simulation shown in Table 3.1 while an increasing amount of power was extracted from Minas Passage. The results are shown in Table 3.2. As the power from Minas Passage is increased from 0 to over 6000 MW we see little change in the performance of the Digby Gut fence, in fact it generates a small increase in power with a small decrease in impact. On the other hand, in Petit and Grand Passages there is a small decrease in power and an increase in impact when significant power is extracted from Minas Passage. These results are consistent with our previous results [5] where extracting power from Minas Passage had little impact on the tides in the Digby Neck region. Since we expect that the

Location	Power (Flow Reduction)	Power (Flow Reduction)	Power (Flow Reduction)
Digby Gut	<12 (<1%)	75 (5.9%)	117 (11.4%)
Petit Passage	19.0 (10%)	17.7 (10.1%)	17.5 (10.2%)
Grand Passage	8.88 (10%)	8.61 (10.5%)	8.63 (10.3%)

Table 3.1: Extracted power in MW and the resulting reduction in flow for the three Digby Neck passages. The results highlight the affect of extracting increasing power from Digby Gut on the other two passages.

power extracted from Minas Passage will be less than 2300 MW for the near future, we conclude that projects in Minas Passage and Digby Neck can be developed simultaneously without significantly impacting each other. In conclusion, the modelled impacts of the turbine fences in the different passages on each other are smaller than other uncertainties in our calculations.

Location	MP 0 MW	MP 2300 MW	MP 3700 MW	MP 6600 MW
Digby Gut	117 (11.4%)	116 (11.7%)	115 (11.8%)	119 (10.9%)
Petit Passage	17.5 (10.2%)	17.0 (11.2%)	16.7 (12.0%)	15.1 (15.1%)
Grand Passage	8.63 (10.3%)	8.37 (11.3%)	8.08 (12.3%)	7.47 (15.2%)

Table 3.2: Extracted power in MW and the resulting reduction in flow for the three Digby Neck passages when different power levels are extracted from Minas Passage. The results highlight the affect of extracting increasing power from Minas Passage on the Digby Neck passages.

3.3 Cape Breton

The Bras D'Or lakes in Cape Breton are connected to the Atlantic Ocean by a series of passages as shown in Figure 2.5. The tidal head that develops between different parts of the lakes and the ocean creates passages with significant tidal currents. We have not developed the numerical models to simulate power extraction from these passages. To examine the potential power extraction and impact on the flow, we use the power extraction theory described in Section 4.2 and the characteristics of the passages from previous observations and modelling projects [11].

3.3.1 Great Bras D'Or Channel

Great Bras D'Or Channel is a 30 km long, relatively thin passage (average width 1.3 km) that connects the Bras D'Or lakes to the Atlantic Ocean at Sydney Bight, see Figure 2.5. The passage is relatively shallow with an average depth of about 20 m, although the depth does reach a maximum of 95 m [11]. The importance of the channel and the constriction it presents, is noted in [11] "The most severe restriction is at the mouth of the channel where it opens onto Sydney Bight. There the width is only 320 m, the maximum depth is 16.2 m, and the cross-sectional area is 2400 m^2. Most of the water exchange between the Lakes and the ocean must occur through this small opening." The measured and model currents in the passage routinely exceed 1 m/s, but there is little evidence that the speed exceeds 2m/s.[11].

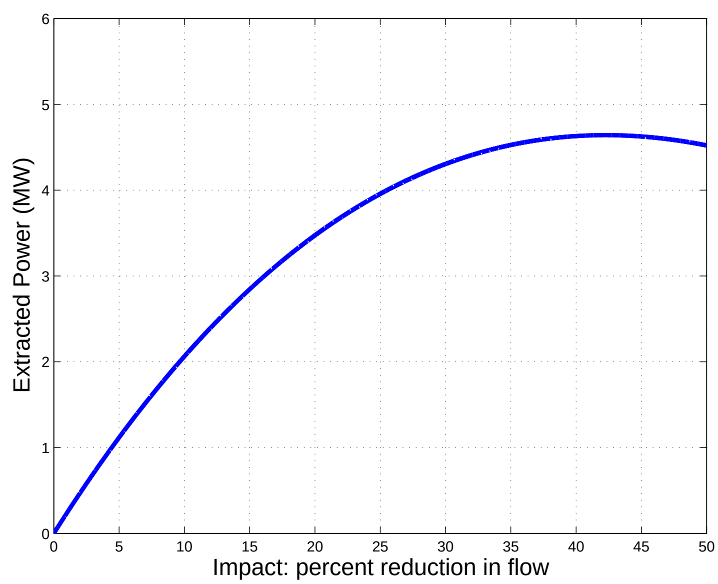


Figure 3.14: Great Bras D'Or Channel: Extracted power versus the reduction in flow through the turbine fence calculated using power extraction theory.

The theoretical power extraction results for the Great Bras D'Or Channel are shown in Figure 3.14. The predicted maximum extractable power is 4.5 MW while 2 MW and 1 MW can be extracted with a 10% and 5% reduction in flow respectively. It should be noted that because the Great Bras D'Or Channel is very long, 30 km, compared to it's width, 500 m, it is a rather unique case. The tidal flow through the channel has very little impact on the tides in Bras D'Or Lake. The phase lag in the tides from one end of the passage to the other, about 75°, is significantly larger than all the other passages. In the power extraction theory, a large phase lag results in a greater reduction in flow through the passage as power is extracted. As well, it should be noted that the Great Bras D'Or Channel is the main water exchange between the relatively fresh Bra D'Or Lakes and the open ocean. While a reduction in flow through the channel will not cause a large change in the tides of the lakes, it could have an important effect on the salinity of the lake and other water properties.

3.3.2 Barra Strait

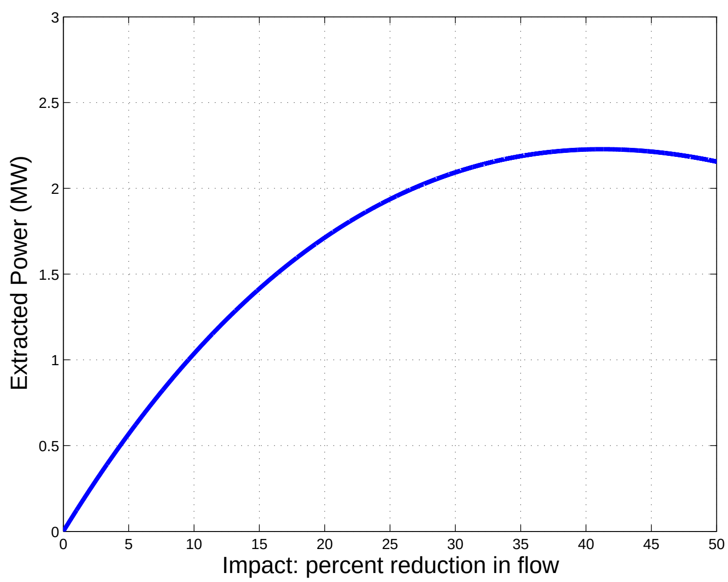


Figure 3.15: Barra Strait: Extracted power versus the reduction in flow through the turbine fence calculated using power extraction theory.

The Barra Strait is an inner passage connecting the northern and southern basins of the Bras D'Or Lakes. It has a sill depth of about 20 m and a minimum width of about 500 m. [12] The model currents in the passage rarely exceed 1 m/s. For example the amplitude of dominant M_2 tidal currents in Barra Strait ranged from about 0.5 to 0.8 m/s in current meter data from the early 1970s [11]. Modelled currents were even lower [11]. As discussed in [12] and [11] it is expected that the residual flow through the passage plays an important role in the water exchange between the northern and southern basins.

The theoretical power extraction for the Barra Strait is shown in Figure 3.15. The predicted maximum extractable power is 2.2 MW while 1.0 MW and 0.6 MW can be extracted with a 10% and 5% reduction in flow respectively. Despite the short length of Barra Strait, there is a large phase lag in the tides across the passage, about 40°, with a small tidal head. The result is a large reduction in flow through the passage as power is extracted. And, as with the Great Bras D'Or Channel, the impact of changing the flow through Barra Strait will likely not be seen as a change in the local tides, but in the impact of limiting the water exchange across the passage. These potential impacts require further research.

A complete analysis of power extraction and the impact on the residual flows through the Bras D'Or passages is required. As a first step, the model used in [11] could be adapted to run numerical simulations with turbine fences.

3.4 Other locations

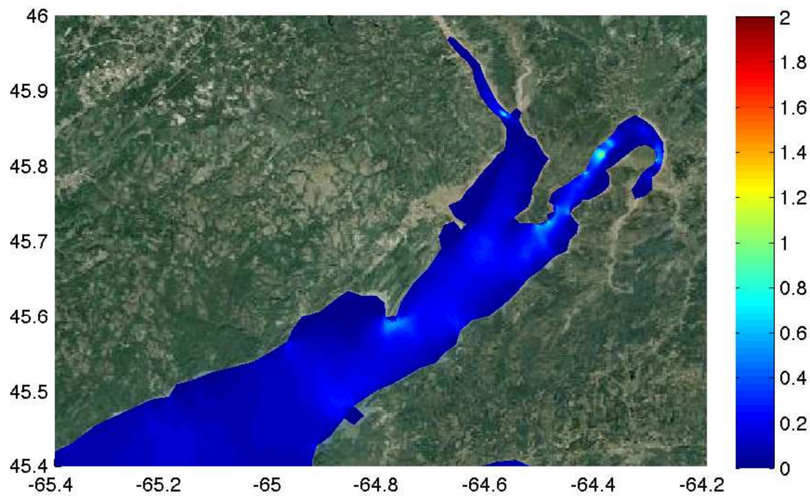


Figure 3.16: The mean power density in kW/m^2 for Chignecto Bay

This report has focused on the Nova Scotia locations that have shown the most promise for substantial power extraction and locations that have ongoing development. Other reports have listed a number of locations in Chignecto Bay and off the southwest coast of Nova Scotia. In Figures 3.16 and 3.17 we plot the mean power densities for these regions as calculated from our numerical simulations. In Chignecto Bay, there are no regions that exceed 1 kW/m^2. Off the coast of Southwest Nova Scotia, the only region that has a moderate power density of

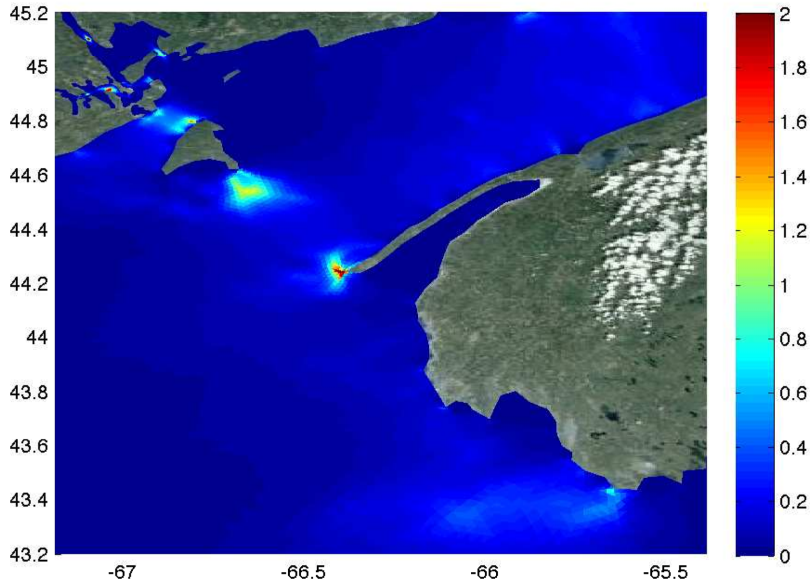


Figure 3.17: The mean mean power density in kW/m^2 off the southwest coast of Nova Scotia.

about 2 kW/m^2 is around Briar Island. This region may have tidal currents strong enough to generate tidal energy. However since it is not a passage but open ocean, it is much more difficult to estimate the power potential. As well, since it is not a passage, the tidal currents are more likely to have more variable directions requiring a TEC that actively yaws. It is a region that requires further analysis. Most of the other regions with power densities less than 1 kW/m^2 are also open ocean regions and would have similar challenges.

It should be noted that our numerical model was not designed to examine these areas in detail. Recent observations gathered from passages and channels in southwest Nova Scotia have found strong tidal currents that could be suitable for small tidal power projects. These passages will be examined in future research.

Chapter 4

Methods

4.1 Calculating extractable power using numerical simulations

For the calculations in this report we simulated the tides and currents in the Bay of Fundy using a 2D version of the Finite Volume Coastal Ocean Model (FVCOM). FVCOM was developed by Changsheng Chen and Geoffrey Cowles from the University of Massachusetts-Dartmouth, along with Robert C. Beardsley from Woods Hole Oceanographic Institution [13, 14]. The specific model grids were adapted by Mitchell O'Flaherty-Sproul and Joel Culina at Acadia from grids developed by Triton Consultants and David Greenberg and Jason Chaffrey at the Bedford Institute of Ocean Sciences. The model domains covers the entire Gulf of Maine and Bay of Fundy for most simulations, and only the upper portion of the Bay of Fundy for simulations focusing on the Minas Channel and Minas Basin. The model is forced by specifying the tidal amplitude and phases at the open boundary. The model has been validated through comparisons to tide gauge data and recent current measurements from various spots around the Bay of Fundy. The simulations for Minas Channel have resolution that reaches 50 m in Minas Passage. The simulations for the Digby Neck have resolution of about 15 m in each of the Digby Neck passages. Changes in resolution can affect the calculated values by up to 10%, but do not change the qualitative results. It should be noted that the development of these models is an ongoing process. The models are being continually improved as we receive more data on the bathymetry, tidal elevations, and tidal currents from the Bay of Fundy, as we better understand the fluid dynamics of the tidal flow–in particular, how the bathymetry affects tidal currents–and as we increase the resolution of the models. More details of the model and the domain can be found in other publications [5, 10, 8].

In order to model turbines in the 2D model, we used the simple approach of adding a quadratic drag term to the horizontal momentum equations i.e., the u-momentum equation would have the additional forcing term

$$-\frac{C_D}{W} u\sqrt{u^2 + v^2}\,, \tag{4.1}$$

where u and v are the north-south and east-west depth-averaged velocities, respectively; C_D is the drag coefficient of the turbines; and W is the thickness of the turbine fence along the direction of flow. This is the most natural extension of the work in KMLH and is easy to employ in a finite-element model where we wish to change the locations of the turbines without altering the numerical grid. The major disadvantage of this approach is that it represents relatively thin turbines with a large region of high drag. In fact, due to the grid resolution, the thickness of the turbine region can be several hundred metres. One could raise many other issues with this model of turbines, but it serves the purpose of allowing us to extract power from the flow anywhere in the numerical grid.

After a simulation has been completed, the power extracted by the fence can be calculated as

$$P(t) = \frac{\rho C_D}{W} \int h \left(u^2 + v^2\right)^{3/2} dA\,, \tag{4.2}$$

where h is the depth of the water (which varies with the tides) and the integral is over the grid elements of the turbine fence. The flux through the fence is

$$Q(t) = \frac{\rho}{W} \int h \left(u^2 + v^2\right)^{1/2} dA\,. \tag{4.3}$$

The mean extracted power and mean flux are $P(t)$ and $Q(t)$ averaged over the length of the simulation. 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.

4.2 Extractable power theory

In this section we lay out the theory used to calculate the extractable power and reduction in flow of a tidal passage. The theory was first introduced by Garrett and Cummins [3] for a channel connecting two large bodies of water and was adapted by others [4, 5] to the case of a channel connecting a tidal basin to the ocean. These papers derived a formula for the maximum mean extractable power given by

$$P_{\text{avg}} = \gamma \rho g a Q_0\,, \tag{4.4}$$

where a is the amplitude of the potential tidal head across the channel, g is the acceleration due to gravity, and Q_0 is the maximum volumetric flow rate through the channel in the undisturbed state. The parameter γ only varies over the small range between 0.19 and 0.25 [4, 5].

The formula (4.4) includes the tidal forcing through a, the potential tidal head. For a passage between two large bodies of water where the tides are not influenced by the flow through the passage, the potential tidal head is simply the maximum tidal head across the passage in the undisturbed state. For a passage that connects the ocean to a tidal basin the situation is different. Here, the tides are completely dependent on the flow through the passage. If the speed of the flow through the passage is reduced by extracting power, the

Location	a (m)	Q_0 (10^3 m^3/s)	ϕ (degrees)	$\gamma\rho g a Q_0$ (MW)
Minas Passage	4.5	620	12.4	6200
Digby Gut	3.5	22	2.9	190
Petit Passage	0.84	24	20	43
Grand Passage	0.46	15	20	15
Great Bras d'Or Channel	0.5	4.8	75	4.6
Barra Strait	0.3	3.8	40	2.2

Table 4.1: The parameters used in the extractable power theory: potential tidal head across the channel a, volume flux through the channel Q_0, phase lag of the tides across the channel ϕ and the theoretical maximum extractable power $\gamma\rho g a Q_0$.

tidal head will increase until it reaches the amplitude of the tidal oscillation – equal to 1/2 the tidal range. Thus, the potential tidal head is the amplitude of the tides at the mouth of the passage in the undisturbed state.

The difference between these two cases is significant, as shown in Table 4.1 where the values for a for the Nova Scotia passages are listed. In the cases of a tidal basin, Minas Channel and Digby Gut, the value of a is 5 to 10 times as large as the values for passages where the current does not impact the surrounding tides, Petit Passage and Grand Passage.

It is also important to note that the formula (4.4) depends linearly on the current speed through the flow rate, Q_0. Since the power depends only on the volumetric flow rate, the formula does not differentiate between thin channels with strong flow and wide channels with weaker flow. And, since the formula depends linearly on the flow rate, the power does not increase rapidly as the flow rate increases.

Finally, as previously emphasized, the formula has no simple connection to the kinetic energy flux or the power density. Thus, a passage with low power density like Digby Gut can have a much higher extractable power than a passage with high power density like Petit Passage. These two passages have a similar volume flux, but because Digby Gut is a passage connected to the enclosed basin, its potential tidal head is over 4 times as large as the head of Petit Passage, see Table 4.1. As result, the extractable power for Digby Gut is over 4 times as large as the extractable power for Petit Passage.

Here, we summarize the description of the theory found elsewhere in more detail, see [5, 8]. The theory calculates the power generation of a turbine fence covering the entire cross-section of a tidal passage. In doing so, it calculates the volume flux through the passage and, thus, can be used to determine the reduction in flow through the passage as power is extracted.

The effect of a turbine fence on the flow is represented as a quadratic drag with a drag coefficient C_{D_F}. In the theory, we introduce the non-dimensional drag ratio

$$\lambda_T = \frac{C_{D_F}}{C_{D_0}}\,, \tag{4.5}$$

where C_{D_0} is the natural drag coefficient of the passage; that is, C_{D_0} is the drag coefficient

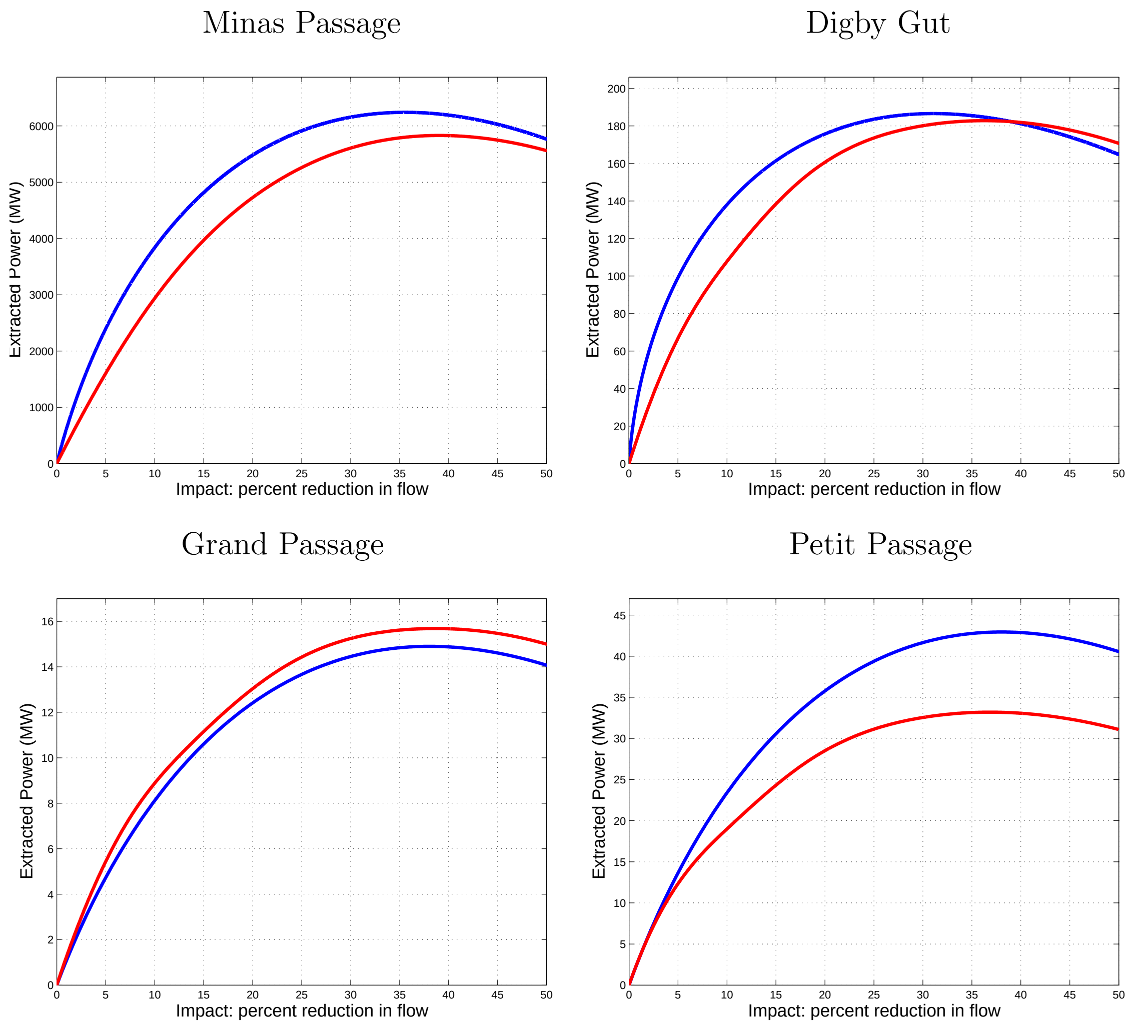


Figure 4.1: Extracted power versus the reduction in flow through the turbine fence for four passages. The red curve is from numerical simulations, the blue curve is from power extraction theory.

of momentum lost through bottom drag and nonlinear inertia. Therefore, λ_T represents the ratio of the turbine drag to the natural drag in the system.

The flux through the passage with a turbine fence is

$$Q(\lambda_T) = R(\lambda_T)Q_0\,, \tag{4.6}$$

where Q_0 is the undisturbed volume flux through the passage, which can be estimated from observations or numerical simulations. Following KLMH, the reduction in flow factor, R, is given by

$$R(\lambda_T) = \left(\frac{1+\sqrt{1+\delta}}{1+\sqrt{1+\delta(1+\lambda_T)^2}} \right)^{1/2} . \tag{4.7}$$

The parameter δ in the formula is determined by the geometry of the system and the natural drag in the basin. Adapting the formulas in KLMH, δ can be written in terms of the phase lag of the tides across the undisturbed passage, ϕ, as follows:

$$\delta = \frac{4\sin^2\phi}{\cos^4\phi} . \tag{4.8}$$

The power extracted from the flow by the turbine fence is given by

$$P_{\mathrm{ext}}(\lambda_T) = \frac{\lambda_T \sin\phi}{2} [R(\lambda_T)]^3 \rho g a Q_0 . \tag{4.9}$$

In Figure 4.2, we compare the extracted power and reduction in flow calculated using the above theory with the results of the numerical simulations discussed in Chapter 4.1. For these comparisons, the volume flux, Q_0, the tidal head amplitude, a, and phase lag across the passage were estimated from a month-long numerical simulation. The maximum volume flux, Q_0 was taken to be 1.3 times the month-long-mean volume flux through the passages. Table 4.1 shows the values for all the parameters used for each passage. For three of the four passages, the theory and numerical simulations agree very well. For Petit Passage, the theory over predicts the power by about 25%. Overall this gives us confidence that the theory can be used to give a good first estimate of the relationship between the power that can be extracted from a passage and the resulting reduction in flow that results. We therefore use the extractable power theory to calculate the extractable power and flow reduction for the Cape Breton passages, as shown in Figures 3.14 and 3.15.

4.3 Relating extracted power to power generation and installed capacity

In this section we present a simple approach to relating the extracted power to potential power generation. Calculating this relationship precisely is not an easy task. It would require precise knowledge of the TEC and its supporting structure as well as detailed knowledge of the flow and the TEC response to variations in the flow. The calculation becomes more difficult as turbines are placed in arrays and the effects of the turbines on each other as well as their cumulative effect on the flow must be determined.

Here we only provide a simple extension of Betz theory to get a rough estimate of the percentage of the extracted power that could be converted into electricity. Betz theory tells us that for an idealized, isolated turbine the power available for electricity generation is 2/3 of the power extracted from the flow when the turbine is tuned to produce maximum power, that is, when the axial induction factor is 1/3. At lower values of the axial induction factor,

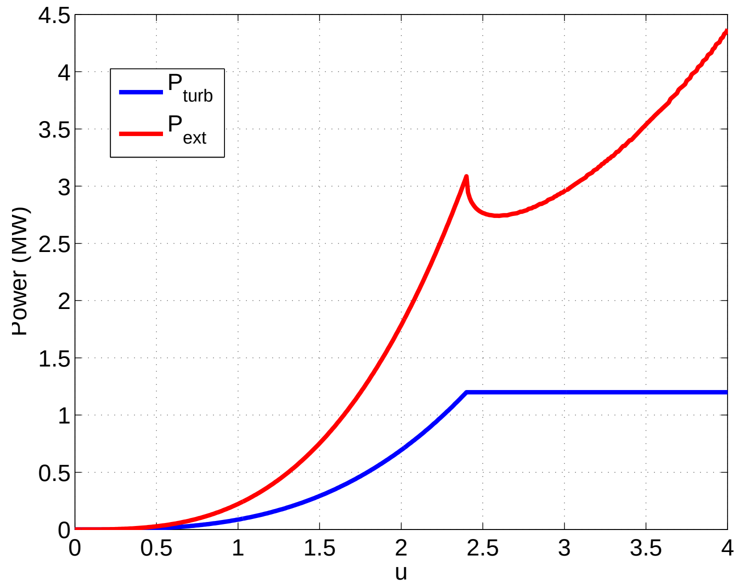


Figure 4.2: An idealized turbine power curve versus the calculated extracted power curve. The turbine is rated to produce 1.2 MW at a water speed of 2.4 m/s. The extracted power includes the turbine power, the power lost in the generation of electricity, the power lost in turbine wake mixing, and the power lost to the drag of the supporting structure.

the ratio of power available for electricity generation to the power extracted from the flow actually rises even though the turbine extracts less power from the flow.

For a realistic turbine, the extracted power must also account for the supporting structure of the turbine, which will also extract power from the flow. To construct a more realistic turbine, we consider a turbine that is a rough model of the Marine Current Turbines' Sea Gen turbine. The turbine blade area is set to 400 m^2. The turbine is rated as producing 1.2 MW at a water speed of 2.4 m/s, which corresponds to a power coefficient 0.42. Up to the rated speed it is assumed that the turbine is operating with an axial induction factor of 1/3 and that at speeds above the rated speed the axial induction factor is reduced to produce the rated power. The supporting structure is considered to have an area of 200 m^2 with a drag coefficient of 0.2. The power curve and resulting extracted power curve are plotted in Figure 4.2. For this turbine, up to the rated speed the turbine converts 39% of the extracted power into electricity. For this idealized turbine at the rated speed, 16% of the extracted power is lost to the inefficiency of the turbine, 18% is lost to the drag of the supporting structure and 27% is lost in the wake mixing. Above the rated speed, the turbine actually becomes more efficient, converting up to 43% of the extracted power until at higher speeds the power lost due to the drag on the supporting structure make the turbine less efficient.

In Figure 4.3, we illustrate the results of applying such a power curve to a time series of water speed for simulated flow through Minas Passage. The water speed, the calculated

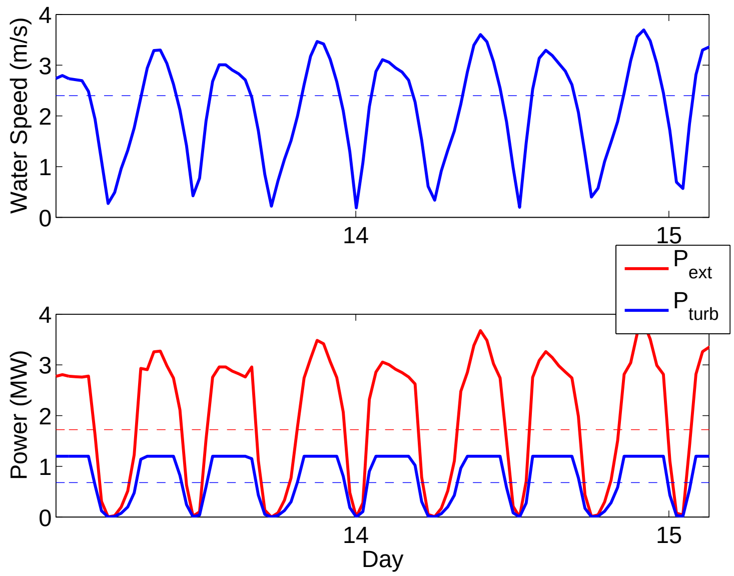


Figure 4.3: (top) A time series of water speed in m/s at a location in Minas Passage (from our numerical simulation). The dashed line is the rated water speed – 2.4 m/s. The resulting extracted power and generated power in MW found using the power curves in Figure 4.2. The dashed lines are the time means – 0.7 MW for generated power and 1.7 MW for extracted power.

extracted power, and the calculated electricity generated are plotted. When averaged over the month long run, the mean electricity generated (0.7 MW) is roughly 40% of the extracted power (1.7 MW). As well, the installed capacity of the turbine, 1.2 MW, is roughly 70% of the mean extracted power. Therefore, we conclude that a turbine array with an installed capacity of 70% of the mean extracted power should be able to convert 40% of the extracted power into electricity.

It should be stressed that the calculation of installed capacity assumes that the rated speed of the turbine is chosen appropriately for the given flow speeds. In the given example, the flow speeds exceeds the rated speed for a significant portion of the time and so the turbine operates at its rated capacity for a majority of the time. It would not be sensible to deploy this turbine in flows that did not exceed 2 m/s and quote its installed capacity as 1.2 MW.

Admittedly, this is an idealized and simplified analysis of a complex process and further analysis into this issue is required. The analysis is presented here to stress the difference between extracted power, generated power, and installed capacity. The only value that has been robustly calculated in this report is the extracted power. The simple calculations for the generated power and installed capacity rare presented to emphasize that these values will be only a portion of the extracted power.

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