

Tidal Energy Resource in Larantuka Straits, Indonesia

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Abstract

Located in between the Flores and Adonara islands, Larantuka strait has one of the strongest tidal currents in Indonesia. An 810 m length bridge is planned to be constructed across the strait to connect the islands. Commencing in 2019, the Palmerah Bridge Project is planned to be the first combined tidal energy/bridge project worldwide. By combining the installation of turbines with bridge construction, the project is intended to achieve certain economies. However, the financial viability would depend on the power production at this site. This study is an independent assessment regarding the tidal energy resources, estimating the average power available at possible array locations in the area of the Palmerah Tidal Bridge. This paper examines alternative locations for turbine deployment along the strait as well. Moreover, this paper also discusses the flow field change and its effects on the Indonesian Throughflow (ITF) in the region. Assessments with realistic turbine deployments as well as idealised cases are conducted. The project promises to deliver power capacity of 18 to 23 MW at the first stage and may be followed by an extension to a capacity of 90 to 115 MW. It is unclear whether these figures are the average or maximum power. This paper finds that the available power from this site is lower than the output that has been predicted for this project. However, if the prediction is the maximum (as opposed to average) power available for the subsequent stages, this study finds that numbers are achievable.

Keywords from ICE Publishing list

Energy; Maritime engineering; Renewable energy, Coastal engineering

Notation

A_c	hydrostatic area of the channel
A_t	area of turbine
B	blockage ratio
B_E	blockage a ratio at an element
B_N	blockage a ratio at a node
D	diameter of turbine
F_r	Froude number
$F_{x,y}$	additional forces in the shallow water system such as tidal potential forces, wind or wave radiation stresses in x- and y-directions
H	total depth of the water column

c_f	empirical bed friction coefficient
f	Coriolis force
h	bathymetric depth of the water column below the geoid
l_E	length of element
s	spacing between turbines
u, v	the depth averaged velocity components in x- and y-directions
α_4	wake coefficient
β_4	bypass flow coefficient
ρ	water density

1 **1 Introduction**

2 Providing alternative and clean energy is a future challenge for the world, including Indonesia.

3 Renewable energy is expected to address the problem of energy deficit and support the

4 improvement of environmental conditions in the future. As the largest archipelagic country,

5 energy from the ocean such as tidal, wave and Ocean Thermal Energy Conversion (OTEC) is

6 an appealing option for Indonesia. Tidal current energy, in particular, has been receiving more

7 attention due to its unique characteristics. Unlike wind and wave energy, which are more

8 uncertain due to their stochastic nature, tidal stream energy systems are more deterministic.

9 Moreover, tidal energy extraction systems are relatively cheap compared to OTEC. There are a

10 number of possible sites in Indonesia where tidal current schemes may be viable, and this

11 paper examines the power available from the Larantuka strait, located between the Flores and

12 Adonara islands, which has one of the strongest tidal currents in Indonesia. An 810 m length

13 bridge is planned to be constructed across the strait to connect the islands. Commencing in

14 2019, the Palmerah Bridge Project is planned to be the first combined tidal energy/bridge

15 project worldwide.

16 Unfortunately, there are few publicly available resource assessments for this site. Orhan et al.,

17 2015 investigated the potential tidal energy at Larantuka Straits using Delft3D developed by

18 Deltares, and found that power densities can exceed 6 kW/m^2 with velocities exceeding 4 m/s .

19 This research was continued in Orhan et al., 2016. Their analysis for the potential location is

20 based on the extractable power for a tidal in-stream energy conversion device, for which it is

21 claimed that it could generate power at a lower cut-in speed than other commercial devices.

22 Field measurements and further numerical modelling at Larantuka were reported by Ajiwibowo

23 et al. (2017), who use kinetic flux calculations to estimate an average power output of 59.7 kW

24 from a single D10 Sabella turbine. However, none of the above studies considers the interaction

25 between the turbine arrays and the flow. The extracted power is simply computed from the

26 undisturbed kinetic energy flux multiplied by the rotor and generator efficiencies.

27 The purpose of this paper is not to promote any particular scheme, but to conduct an

28 independent assessment of the tidal power potential within the Larantuka Strait.

2 The Palmerah Tidal Bridge Project

Larantuka Strait is located in Nusa Tenggara Timur (NTT) Province, Indonesia. The strait separates Larantuka and Adonara in the East Flores regency. The Pancasila Palmerah Bridge is planned to connect the islands, with a length of 810 m, linking the eastern tip of Flores Island and the smaller island Adonara.

Tidal Bridge BV, a joint venture between a Dutch engineering firm, Strukton International and venture capital fund Dutch Expansion, has been awarded the Palmerah Tidal Bridge project.

With an estimated investment of US\$200 million, this tidal power plant promises to deliver power capacity of 18 to 23 MW (see <https://www.eco-business.com/news/indonesia-to-build-worlds-largest-tidal-power-plant/>). As mentioned in the Strukton International website (see <https://www.struktoninternational.com/news/2017/feasibility-study-for-palmerah-tidal-bridge-project-by-tidal-bridge-bv/>) this project may be followed by an extension to a capacity of 90 to 115 MW (although this figure probably exceeds the current electrical demand in the region).

A series of turbines are planned to be installed beneath the bridge to generate electricity from the tidal current, with the aim of providing electricity for over 100,000 people in the region. As part of the NTT Provincial Government vision to develop the region further, a technical feasibility report has been delivered describing the project. Furthermore, the Palmerah Tidal Bridge project has National Strategic Project status, emphasizing the national interest.

The proposed location of the tidal bridge, based on the report, is shown in Figure 1. As mentioned in the report, the bridge alignment is determined based on the current conditions and technical aspects of bridge construction (see Jan-Vos et al., 2017). Unfortunately, the report does not discuss the resource assessment in detail.

3 Turbine representation and DG-ADCIRC Modelling

The tidal resources are assessed in this paper using the Discontinuous Galerkin version of the ADvanced CIRCulation Model (DG-ADCIRC) to solve the Shallow Water Equations to model the tidal hydrodynamics (see Kubatko et al. 2006). This numerical solver uses the governing equations that can be expressed as a time-dependent two-dimensional system of non-linear partial differential equations of hyperbolic type as shown in equations (1,2 and 3)

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(uH) + \frac{\partial}{\partial x}\left(Hu^2 + \frac{1}{2}g(Hu^2 - h^2)\right) + \frac{\partial}{\partial y}(Huv) = g\eta\frac{\partial h}{\partial x} - c_f u\sqrt{u^2 + v^2} + fv + Fx \quad (2)$$

$$\frac{\partial}{\partial t}(vH) + \frac{\partial}{\partial x}(Huv) + \frac{\partial}{\partial y}\left(Hv^2 + \frac{1}{2}g(Hv^2 - h^2)\right) = g\eta\frac{\partial h}{\partial y} - c_f v\sqrt{u^2 + v^2} + fu + Fy \quad (3)$$

Equation (1) is the mass conservation equation, where h is the bathymetric depth of the water column below the geoid, H is the total depth of the water column ($H = \eta + h$), η is the free surface elevation while the variables u and v represent the depth averaged velocity components in x- and y- directions. Equations (2) and (3) are the horizontal momentum conservation equations in x- and y directions respectively, where g is the gravitational acceleration, c_f is an empirical bed friction coefficient, f is the Coriolis force, and Fx and Fy represent additional forces in the system such as tidal potential forces, wind or wave radiation stresses.

The turbine is modelled using Linear Momentum Actuator Disk Theory (LMADT) as proposed by Houlby *et al.*, (2008, 2017). This actuator disk model expands the work of (Garrets and Cummins, 2005, 2007) to the case of open channel. The Power (P) removed from the flow in the open channel of LMADT implementation is calculated by the equation (4)

$$P = \frac{1}{2}\rho v^3 B A_c C_p \quad (4)$$

where v is the velocity of the tidal stream, is B blockage ratio and A_c hydrostatic area on the channel and C_p dimensionless power coefficient that is expressed by Houlby *et al.* (2008, 2017) as a function of α_4 , the turbine wake coefficient and β_4 , the bypass flow coefficient. The latter is in turn a function of α_4 , the upstream Froude number F_r and the Blockage Ratio B .

Note that this analysis does not take into account any possible effects of the bridge structure on the flow.

Following Adcock *et al.*, 2015, in order to minimize the effect of the turbine at the boundary, the model employs a very large domain as shown in Figure 2. This large domain is also necessary to capture the global current in the region.

The location of the project is shown as the red box in the model domain (Figure 2). Since Lantuka is located in an area of mixed diurnal/semidiurnal tides, the model is forced with 13 constituents on the boundary in order to estimate the power output (average and maximum).

The model incorporates bathymetry data obtained from three sources. The GEBCO Maps, bathymetric maps of the Java Sea, Banda Sea and Makassar Sea from DISHIDROS TNI-AL (a hydro-oceanographic Division of the Indonesian Navy), and bathymetric survey data provided by the Indonesia Centre of Marine Geology (P3GL) are incorporated for this model.

As described in Firdaus et al., 2019, the model is validated against three different data sets. Firstly the validation is conducted against principal semidiurnal and diurnal constituents (M_2 , S_2 , K_1 and O_1) obtained from admiralty tidal data. Secondly the model is validated against co-tidal charts from satellite observations (Ray et al., 2009). Lastly, the model is validated against survey data (tidal observations and ADCP measurements). Further details of the modelling, such as validation and sensitivity to the number of tidal constituents, are discussed in Firdaus et al., 2019.

4 Resource Assessment

4.1 Resource assessment at the tidal bridge

The mesh in the area of the turbines follows the alignment of the tidal bridge as shown in Figure 3. The idealised turbine model is run for three different wake coefficient (α_4) (see Schoenberg 1946), and each simulation represents a period of 62 days (four spring-neap cycles). Figure 4 shows the time series of power extraction for low blockage ratio.

As shown in Figure 4(a), the maximum powers differ from one two-week neap spring cycle to the next. Since the area is located in a region of mixed diurnal/semidiurnal tides, the power extraction shows a significant neap-spring cycle fluctuation. Moreover, the peak of power production is also different in each daily cycle (Figure 4(b)).

The optimum α_4 is obtained by interpolating the results using a cubic spline following the general approach of Adcock et al., 2013. As shown in Figure 5, the available mean power for the idealised case and low blockage is 4.67 MW. This number is far below 18 to 23 MW as promised for the first delivery.

The maximum power available, at $B = 0.1$ is 24.82 MW for same optimum value of $\alpha_4 = 0.38$ as for the average power (Figure 5). Whilst the maximum power extraction might reach 25 MW, this power is only achievable once or twice a month (see Figure 4). As this figure is close to the

capacity quoted for the first stage of the project (18 to 23 MW), presumably the quoted figures should be interpreted as the maximum power that can be extracted from the given site.

There is a planned extension to the project to deliver 90 to 115 MW. We therefore continue our analysis to investigate this figure. Hypothetically, the highest achievable blockage ratio is about $B = 0.4$. Therefore, the simulations are also run with this assumption. As in the previous simulations, those at high blockage ratio ($B = 0.4$) are also run with three different α_4 values (see Figure 6). Following the same method as for low blockage ratio, the optimum average gives 19.06 MW power extraction and the maximum power extraction is 87.09 MW, both at $\alpha_4 = 0.53$. Although this is still below the target of 90 to 115 MW, the target of 90 MW is almost reached.

However, the assessment using LMADT is an upper bound of the resources (see Adcock et al., 2013), and in reality the maximum achievable power is expected to be lower than 87.09 MW (see Chen et al., 2019). This means that the target of 115 MW is unlikely to be achieved. Moreover, the maximum power is not obviously the best metric for describing the resource, since this value is only available fortnightly or monthly. To assess whether the project target can be met, the assessments are further expanded to consider other possible locations.

4.2 Alternative locations for tidal turbine arrays

Based on the simulation results for the existing conditions (before the turbine arrays are introduced in the model), the average kinetic power per elevation area of flow in the Larantuka Strait is calculated using Eq. (5).

$$E = \frac{1}{2} \rho v^3 \quad (5)$$

Where E is power (W/m^2), ρ is seawater density (1025 kg/m^3) and v is the average velocity (m/s). This metric provides a useful initial indication of potentially productive sites, and as shown in Figure 7, potential locations near the proposed bridge alignment can be considered. The possible alignments of turbine fences follow the mesh arrangement as shown in Figure 7, where the mesh in the model is aligned perpendicular to the principal flow direction. This paper assesses five different locations including the proposed bridge position.

Following similar methods to those used above, the other sites are assessed in the same manner (runs at three different α_4 values and use of a cubic spline to obtain the optimum average power extraction). Here we also consider multi-fence schemes. The proposed location of the bridge is used as one of the fence positions.

The results of simulations for low blockage ratio are shown in Table 1. The first column of the Table shows the scheme simulated, thus for instance A1 indicates turbines installed only at location A1, whilst A1A2A3A4 indicates turbines installed simultaneously at each of the locations A1, A2, A3 and A4. The subsequent columns show the average power at each site for the given installation scheme. For the A1A2A3A4A5 scheme, for example, the results shown in columns A1 to A5 are the power extracted at each individual site, while the total power presented in the penultimate column is the total extraction achieved by the scheme. The final column shows the α_4 value at which this power is achieved. The Table shows for instance that the A4 fence gives ~5.4 MW power extraction. This is higher than the current proposed position of the fence at the bridge (A2) although the fence length for A4 is shorter than any other fence. As expected, the multi-fence schemes give lower extraction at each individual fence for a higher number of fences. For this low blockage scenario, however, the reductions for the multi-fence configurations are relatively small. Occupying all five arrays, for example, only reduces the average power extraction by around 25% from the sum of the individual fences operated alone.

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Table 1. Average Power Extraction for Low Blockage Ratio

Fence Length(m)	702	665	665	508	664	Total	
Cross Section(m ²)	16,480	13,900	13,708	12,337	16,117		
	A1	A2	A3	A4	A5	Power	α_4
	MW	MW	MW	MW	MW	MW	
A1A2A3A4A5	2.41	3.48	3.82	4.26	2.85	16.82	0.45
A1A2A3A4	2.52	3.62	3.97	4.42	-	14.54	0.44
A1A2	3.04	4.42	-	-	-	7.46	0.40
A2A3	-	4.13	4.52	-	-	8.64	0.41
A2A4	-	4.20	-	5.04	-	9.25	0.40
A2A5	-	4.43	-	-	3.63	8.06	0.40
A1	3.56	-	-	-	-	3.56	0.36
A2	-	4.67	-	-	-	4.67	0.38
A3	-	-	4.96	-	-	4.96	0.38
A4	-	-	-	5.40	-	5.40	0.38
A5	-	-	-	-	3.87	3.87	0.38

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Table 2. Average Power Extraction for High Blockage Ratio

Fence Length(m)	702	665	665	508	664	Total	
Cross Section(m ²)	16,480	13,900	13,708	12,337	16,117		
	A1	A2	A3	A4	A5	Power	α_4
	MW	MW	MW	MW	MW	MW	
A1A2A3A4A5	4.50	6.32	7.29	8.65	5.40	32.16	0.60
A1A2A3A4	5.28	7.43	8.58	10.20	-	31.49	0.60
A1A2	10.39	14.71	-	-	-	25.10	0.60
A2A3	-	12.13	14.17	-	-	26.30	0.60
A2A4	-	13.11	-	17.96	-	26.86	0.60
A2A5	-	14.07	-	-	11.26	25.33	0.60
A1	16.90	-	-	-	-	16.90	0.49
A2	-	19.06	-	-	-	19.06	0.53
A3	-	-	19.32	-	-	19.32	0.56
A4	-	-	-	22.52	-	20.29	0.60
A5	-	-	-	-	16.12	16.12	0.50

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Table 2 shows the average power extraction for high blockage ($B = 0.4$). As for the low

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blockage scenario, the A4 fence gives the highest average power output. Moreover, this site

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also performs better in the multi-fence schemes. At high blockage the interference between

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fences placed upstream-downstream of each other is greater. The reduction in power for five

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fences is about 66% of the sum of the powers from the individual sites each operated alone.

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The maximum power extractions are also analysed here. As presented in Table 3 for low

blockage and Table 4 for high blockage ratio, these show similar interactions for multi-fence configurations. Regarding the projected delivery of ~115 MW capacity, none of the low blockage schemes, including the multi-fence schemes, achieves the ~115 MW. Therefore, the final stage of this project could only be achievable with high blockage.

Table 3. Maximum Power Extraction for Low Blockage Ratio

Fence Length(m)	702	665	665	508	664	Total	
Cross Section(m ²)	16,480	13,900	13,708	12,337	16,117		
	A1	A2	A3	A4	A5	Power	α_4
	MW	MW	MW	MW	MW	MW	
A1A2A3A4A5	10.60	16.11	19.73	20.75	15.03	81.12	0.38
A1A2A3A4	11.02	16.73	20.66	21.78	-	69.97	0.38
A1A2	13.47	22.21	-	-	-	36.34	0.37
A2A3	-	20.50	24.15	-	-	45.18	0.37
A2A4	-	21.55	-	25.71	-	47.95	0.37
A2A5	-	23.13	-	-	19.96	43.77	0.37
A1	15.98	-	-	-	-	16.35	0.36
A2	-	24.85	-	-	-	25.41	0.37
A3	-	-	28.02	-	-	28.66	0.37
A4	-	-	-	29.51	-	30.12	0.37
A5	-	-	-	-	22.21	22.65	0.37

Table 4. Maximum Power Extraction for Low Blockage Ratio

Fence Length(m)	702	665	665	508	664	Total	
Cross Section(m ²)	16,480	13,900	13,708	12,337	16,117		
	A1	A2	A3	A4	A5	Power	α_4
	MW	MW	MW	MW	MW	MW	
A1A2A3A4A5	18.19	25.35	29.23	33.91	25.34	87.34	0.41
A1A2A3A4	21.23	29.59	35.25	40.88	-	86.76	0.41
A1A2	43.25	66.38	-	-	-	88.66	0.40
A2A3	-	48.65	63.31	-	-	86.02	0.40
A2A4	-	52.13	-	76.62	-	111.13	0.37
A2A5	-	61.80	-	-	50.25	91.03	0.40
A1	74.80	-	-	-	-	71.34	0.39
A2	-	87.71	-	-	-	77.97	0.40
A3	-	-	90.53	-	-	75.58	0.40
A4	-	-	-	103.92	-	91.36	0.37
A5	-	-	-	-	79.10	75.03	0.39

At high blockage, schemes with two or more arrays can give a maximum power output of about 115MW. Of the two fences schemes, the A2A4 scheme is the most promising, and the ~115MW target might be achieved with a high blockage, two fence scheme. If four or more fences were installed, the fences would only operate at 25-30% of individual capacities. Furthermore, high blockage ratio schemes also impact the global current in the region, as investigated further below.

4.3 Flow field change and its effect on global current

The flow field changes in the area are calculated by comparing the average flow at each node before and after the turbines are installed in the model. Figure 8 and Figure 9 show the flow change for a turbine fence is installed at the bridge position (scheme A2). The low blockage case is presented in Figure 8 and high blockage in Figure 9. Red indicates increased flow, and blue indicates decreased flow due to the deployment of turbines.

The figures show that high blockage causes the flow to divert to nearby channels or the Boleng and Alor Straits. These results also imply that a high blockage ratio such as 0.4 is not just hard to achieve in reality, but also counterproductive since the flow diversion might have a significant impact on the regional flows. For high blockage, therefore, the effect on global current should be considered.

At high blockage, the flow fields change significantly in the region. As discussed in Firdaus et al., 2019, the model considers the Indonesian Throughflow (ITF). The flow pattern of the ITF in the Bali-NTT islands chain follows the pattern described by Gordon 2005 as presented in Figure 10. Figure 11 presents flow changes in the relatively distant straits of Lombok, Alas, Sape, Linta and Molo (area of observation in Figure 11), where the flow at these sites slightly increases.

Such issues should be addressed, as the ITF is related to the so-called “Great Ocean Conveyor Belt” and this phenomenon is related to the global climate. Having high blockage at this site might affect the global ocean system.

5 Realistic Arrays

A uniform blockage array with varying water depths along the fence means that the size of the turbines would have to be varied as well. Therefore, uniform blockage arrays, as discussed previously, are somewhat unrealistic since a developer would prefer to deploy an array of

turbines of the same size. We therefore also analyse array performance for realistic arrays with uniform sized turbines.

5.1 Implementing realistic arrays in the model

In reality, the turbines do not occupy the entire cross section of the channel. There are always parts that do not meet the bathymetric constraints for the turbines. Figure 12 shows an illustration of a turbine array across the channel at the site of the bridge. The depth along the fence is taken from the DG ADCIRC model, in which the cross section is simplified.

As an example, a turbine of 10m diameter may require at least 10m + 2m + 5m depth, where the 2m is the clearance of the turbines to the seabed, and the 5m is the clearance for freeboard above the turbine to account for tidal elevation change. Thus, only the middle part of the channel at Larantuka has adequate depth for these turbines.

Although the assessment follows the previous array schemes, the array alignments in the realistic cases is slightly different from the previous simulations (see Figure 13). As seen in the figure, for each array the fence does not occupy the entire cross section of the channel. In each analysis at least two elements at the edge of the alignment are set up without any turbine.

The actuator disc theory incorporated in the DG-ADCIRC model calculates power output based on the blockage ratio. In the realistic scenario, the blockage at each node is calculated based on Eq. (6):

$$B_E = \frac{n_t A_t}{A_E} \quad (6)$$

where B_E is the blockage ratio for the element, A_t is the area of the turbine ($A_t = \frac{\pi D^2}{4}$), n_t is the number of turbines that can be installed in the area and A_E is the cross-sectional area of the element. The number of the turbines is determined by Eq. (7):

$$n_t = \frac{l_E}{D+s} \quad (7)$$

where l_E is the length of the element with adequate depth for the turbines, D is turbine diameter and s is the tip-to-tip spacing between turbines (see Figure 12). Since the DG-ADCIRC model implements the blockage at the nodes, the blockage at each node (B_N) is determined by the

231 average blockage ratio for the adjacent elements ($B_N = \frac{B_{E(i)} + B_{E(i+1)}}{2}$). For the nodes at the
232 edges, the blockage is that of the adjacent element ($B_N = B_E$).

233 5.2 Results

234 For the example realistic case considered, the tip-to-tip spacing between turbines is equal to the
235 turbine diameter (10 m). As for the uniform blockage simulations, the realistic case is run with
236 three different α_4 values and the optimum α_4 obtained for the average power production. The
237 results of all simulations are shown in Table 5.

238 Based on these results, the realistic case gives slightly higher average power output than the
239 uniform blockage ratio (low blockage cases), especially in the area of the tidal bridge (higher by
240 approximately 7%). All arrays except for A5 (that shows a 25% reduction) show higher power
241 compared to the uniform blockage scenario at low blockage ratio ($B = 0.1$).

242 The “global blockage” is the comparison of total swept area of turbines and the entire area of
243 channel cross-section, while “local blockage” is the fraction of the cross-sectional area of just
244 the elements that are occupied by turbines. These correspond to the definitions also used by
245 Nishino and Willden, 2013. For any given array, the local blockage is slightly higher than the
246 global blockage as the array does not extend to the full width of the channel.

247 The current position of the tidal bridge is not the most advantageous. As an individual array, the
248 bridge could deliver more power if it was installed at the southward location A3 nearby.
249 Furthermore, at the bridge position the power extraction would decrease if another array were to
250 be installed, either upstream or downstream.

251 The A3 array has the highest average power production when it is installed individually. This is
252 because the number of turbines that can be realistically installed in this array is higher than at
253 the proposed bridge position. Moreover, the array also exhibits less loss in the multi-fence
254 scheme.

255 5.3 Discussion

256 The increased average power for the realistic case compared to uniform $B = 0.1$ can be
257 explained using two approaches. The first is by comparing local blockage and global blockage.

As shown in Table 5, at the proposed bridge location (A2) the global blockage is 0.09, less than the blockage at uniform blockage scenario ($B = 0.1$). However, the local blockage of 0.14 is slightly higher than the uniform blockage ratio.

Table 5. Average Energy Extraction for Realistic Arrays with $D = 10\text{m}$ and $s = 10\text{m}$

Fence Length(m)	702	665	665	508	664		
Cross Section(m ²)	16,480	13,900	13,708	12,337	16,117		
Realistic Fence Length(m)	523	336	491	349	411		
Realistic Cross Section(m ²)	12,915	9,115	12,114	9,640	11,670		
Num. of Turbines (units)	25	16	23	17	19		
Total Turbine Area(m ²)	1,963	1,256	1,806	1,335	1,492		
Local Blockage	0.15	0.14	0.15	0.14	0.13		
Global Blockage	0.12	0.09	0.13	0.11	0.09		
	A1	A2	A3	A4	A5	Total	
	MW	MW	MW	MW	MW	MW	α_4
A1A2A3A4A5	3.53	3.18	5.67	4.47	1.91	18.77	0.48
A1A2A3A4	3.72	3.35	5.98	4.73	-	17.77	0.48
A1A2	4.57	4.40	-	-	-	8.97	0.41
A2A3	-	4.05	6.95	-	-	11.00	0.42
A2A4	-	4.34	-	5.65	-	9.98	0.40
A2A5	-	4.78	-	-	2.73	7.51	0.39
A1	5.10	-	-	-	-	5.10	0.39
A2	-	5.00	-	-	-	5.00	0.37
A3	-	-	7.11	-	-	7.11	0.40
A4	-	-	-	5.74	-	5.74	0.38
A5	-	-	-	-	2.84	2.84	0.36

Nishino and Willden, 2013 showed that within the range of blockages considered here, for constant global blockage ratio the limit of power extraction increased as local blockage ratio increases. Although study employed actuator discs, the flow modelling used steady state 3D Reynold Average Navier-Stokes (RANS). Therefore, there are differences between their model and the Larantuka model as theirs model does not account for the inertia of the flow (see Bonar et al., 2019). However, their conclusion is also applicable for resources assessment with a 2D actuator disc model, the increase of power output can be explained.

Note though that not all results show the increasing trend. The A5 array produces an average power output that is significantly lower than the $B = 0.1$ case. A possible explanation is that this array is located at the end of the zone with the high kinetic energy (see Figure 7).

Secondly, the 2D DG-ADCIRC and LMADT might not model in detail the flow passing the edge of turbine fence. As the turbine arrays in the realistic case are partial arrays, the flow field at the array position involves an important by-pass flow. Figure 14 shows the flow field change in the region due to turbine installation at the proposed bridge position. The diverted flows in the neighbouring straits (Boleng and Alor) change, but the flow in the area of the turbine array also changes significantly.

The flow field changes at the proposed bridge site can be seen in Figure 15. The flow field in the elements without turbines increase while in the elements with turbines the flow decreases. We could assume that the flow in the by-pass area is accelerated. Since the flow in DG-ADCIRC is recorded at the nodes of the model, at the edges of the fence this acceleration will affect the modelled velocity.

6 Discussion and Conclusions

In conclusion, the tidal bridge that has been proposed in Larantuka Strait has approximate average energy resources of ~4.67 MW at low blockage and ~19.06 MW at high blockage ratio. These numbers are lower than the power output that has been predicted for this project. However, the maximum (as opposed to average) power available approaches the 18-23 MW quoted for the first stage and 90-115 MW for the subsequent stages.

It may, however, be misleading to use the maximum resource as a measure of the capacity. The maximum power only occurs for a short period fortnightly or monthly. Furthermore, a turbine developer aims for a high capacity factor (average power divided by rated power) if the turbines are to be cost effective. The capacity factor is related to any power capping strategy, where the turbine developer limits the peak power production to increase the capacity factor. In this area of mixed semi-diurnal and diurnal tides the desired capacity factor can be around 45%-55% (see Firdaus et al., 2017). Thus, the actual power that could be delivered in the proposed alignment of the tidal bridge is significantly lower than the currently quoted Figure

Table 6 shows the powers from each fence in a multi-fence scheme, expressed as a fraction of the power available if that fence were installed alone (the figures are derived from those in Tables 1, 2 and 5). As shown in Table 6, the more fences are deployed downstream-upstream of each other, the greater the reduction.

Table 6 shows if a first fence was built at the bridge site (A2) and the next array was built north of the bridge (at location A1), the tidal bridge would only lose a relatively small portion of power. If the next tidal array was built at the southern side (A3, A4 or A5), Table 6 shows that the further the distance between fences, the less the power reduction at the tidal bridge. Presumably, the bridge position is fixed due to construction and other project constraints. Table 6 suggests that the next recommended fences, if developed, should be north of the bridge or further away to the southward side.

Having high blockage ratio at Larantuka might have another consequence for the flow field change. Since this area is part of the complex global ocean current called the Indonesian Throughflow (ITF), occupying the channel occupation with a high blockage tidal fence might influence the global flow pattern in the region. Further study in this matter is necessary before construction is undertaken.

Since uniform blockage is unrealistic, resource assessments based on uniform turbine size and tip-to-tip spacing are also assessed in this study. The simulations with realistic blockage show the current proposed position of the tidal bridge is less advantageous than another location (A3) simulated in this study. Although the results show a higher output compared to the uniform blockage results, and some explanations have been postulated, the reasons are uncertain.

There are two possible explanations. Firstly, the increase could be because the local blockage ratio is higher than the uniform blockage ratio modelled. However, at the site with the lowest average flow velocity, the average resources in a realistic case are lower than the result of the uniform blockage, even though the local blockage is higher. Secondly, the methodology for including turbines in the shallow water model cannot capture all the physics of a partial array, and in particular the modelling of the by-pass flow may be inadequate.

328

Table 6. Fraction of average power from multiple array schemes

329

compared to individual turbine arrays

Scenario	A1	A2	A3	A4	A5
Uniform blockage (low blockage scenario, $B = 0.1$)					
A1A2A3A4A5	68%	75%	77%	79%	74%
A1A2A3A4	71%	78%	80%	82%	
A1A2	85%	95%			
A2A3		88%	91%		
A2A4		90%		93%	
A2A5		95%			94%
Uniform blockage (high blockage scenario, $B = 0.4$)					
A1A2A3A4A5	27%	33%	38%	38%	33%
A1A2A3A4	31%	39%	44%	45%	
A1A2	61%	77%			
A2A3		64%	73%		
A2A4		69%		80%	
A2A5		74%			70%
Realistic Case ($D = 10$ m, $s = 10$ m)					
A1A2A3A4A5	81%	82%	85%	82%	78%
A1A2A3A4	82%	84%	86%	84%	
A1A2	92%	96%			
A2A3		90%	94%		
A2A4		95%		95%	
A2A5		98%			95%

330

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References

- Adcock, T.A.A., Draper, S. and Nishino, T. (2015) Tidal power generation – a review of hydrodynamic modeling. *Proc. of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 0957650915570349.
- Adcock T.A.A., Draper S., Houlby G.T., Borthwick A.G.L., Serhadlioglu S. (2013) The available power from tidal stream turbines in the Pentland Firth. *Proc. of the Royal Society A* 469(2157):20130072
- Ajiwibowo, H., Lodiwa, K. S., Pratama, M. W., Wurjanto, A., (2017) Field measurement and numerical modeling of tidal current in Larantuka strait for renewable energy utilization. *Int. Jour. of GEOMATE, Nov., Vol.13, Issue 39, pp.124-131*
- Bonar, P.A.J., Chen, L., Schnabl, A.M., Venugopal, V., Borthwick, A.G.L., and Adcock, T.A.A. (2019) On the arrangement of tidal turbines in rough and oscillatory channel flow, *Journal of Fluid Mechanics* 865, pp 790-810.
- Chen, L., Bonar, P.A.J., Vogel, C.R., Adcock, T.A.A., (2019) A note on the tuning of tidal turbines in channels, *Jour. of Ocean Engineering and Marine Energy*, 5(1) 85-98.
- Firdaus, A.M, Houlby, G.T. and Adcock, T.A.A. (2019), Estimating Tidal Turbine Resource in Lombok Straits, Indonesia. *Proc. of 13th European Wave and Tidal Energy Conference, Naples, Italy 1 Sept – 6 Sept*
- Firdaus, A. and Houlby, G.T. (2018). Tidal Asymmetry and its Effect on Capacity Factor of Tidal Resource. *Oxford Tidal Energy Workshop*, March.
- Garrett, C. and Cummins, P. (2005). The power potential of tidal currents in channels, *Proc. Roy. Soc. A*, 461(2060): 2563-2572.
- Garrett, C. and Cummins, P. (2007). The efficiency of a turbine in a tidal channel, *Journal of Fluid Mechanics*, 588: 243-251.
- Gordon A.L., (2005) Oceanography of Indonesian Seas and their Throughflow, *Oceanography* 18(4)

361 Houlby, G.T., Draper, S., and Oldfield, M.L.G, (2008) Application of Linear Momentum Actuator
 362 Disc Theory to Open Channel Flow, Report OUEL/2289/08, Dept. of Engineering Science,
 363 University of Oxford, U.K.

364 Houlby, G.T. and Vogel, C.R. (2017) The power available to tidal turbines in an open channel
 365 flow, Proc. of the Institution of Civil Engineers, *Energy*, 170(1), 1, pp 12-21

366 Jan-Vos, R., Seinen, S. and Eijnden, E., (2017) Palmerah Tidal Bridge – *Technical Feasibility*
 367 Report, Tidal Bridge DV

368 Kubatko E.J., Westerink J.J., Dawson C., (2006) hp discontinuous Galerkin methods for
 369 advection dominated in shallow water flow. *Computer Methods and Applied Mechanics in*
 370 *Engineering*, 196, pp 437-451.

371 Nishino, T., and Willden, R.H.J. (2013). Two-scale dynamics of flow past a partial cross-stream
 372 array of tidal turbines, *Journal of Fluid Mechanics.*, 730, 220-244.

373 Orhan, K., Mayerle, R and Pandoe, W.W. (2015) Assessment of energy production potential
 374 from tidal stream currents in Indonesia. *Energy Procedia* 76, pp 7 – 16

375 Orhan, K., Mayerle, R., Narayanan, R. and Pandoe, W.W. (2016) Investigation of the energy
 376 potential from tidal stream currents in Indonesia. *Coastal Engineering Proceedings*, 1(35), p
 377 10

378 Ray, R.D., Egbert, G.D. and Erofeeva, S.Y. (2009) A Brief Overview of Tides in the
 379 Indonesian Seas. *Oceanography*. 18. 74-79. DOI: 10.5670/oceanog.2005.07.

380 Schoenberg, I.J. (1946). Contributions to the Problem of Approximation of Equidistant Data by
 381 Analytic Functions: Part A.—On the Problem of Smoothing or Graduation. A First Class of
 382 Analytic Approximation Formulae. *Q. of App. Math.* 4(2), pp 45–99.

383

384 **Figure 1.** The proposed bridge positions. Map from Google Earth and the proposed bridge
385 position based on Jan-Vos *et al.*, 2017

386 **Figure 2.** Model domain with mesh and bathymetry, the red square indicates the location of the
387 proposed tidal bridge

388 **Figure 3.** DG-ADCIRC mesh in the area of the turbines

389 **Figure 4.** Power extraction at the bridge for low blockage ratio ($B = 0.1$) and $\alpha_4 = 0.40$

390 **Figure 5.** Average power extraction at the tidal bridge for low blockage ratio ($B = 0.1$)

391 **Figure 6.** Average power extraction at the tidal bridge for high blockage ratio ($B = 0.4$)

392 **Figure 7.** Average kinetic power in Larantuka Strait, showing alternative array locations,
393 including the bridge location at A2

394 **Figure 8.** Flow field change for a turbine array deployed at the bridge location for low blockage
395 ratio ($B = 0.1$)

396 **Figure 9.** Flow field change a turbine array deployed at the bridge location for high blockage
397 ratio ($B = 0.4$)

398 **Figure 10.** The flow change in the region and the effect on ITF at high blockage ratio ($B = 0.4$)

399 **Figure 11.** Change in flow field distant from the tidal bridge site for high blockage ratio ($B = 0.4$)

400 **Figure 12.** Illustration of a realistic array at the tidal bridge position

401 **Figure 13.** Mesh for DG-ADCIRC model of realistic arrays

402 **Figure 14.** Flow field around the channel for realistic arrays of turbines with $D = 10\text{m}$ and
403 $s = 10\text{m}$. The array is installed at A2 (the proposed position for the tidal bridge)

404 **Figure 15.** Flow in Larantuka Strait for the realistic array with $D = 10\text{m}$ and $s = 10\text{m}$ at A2 (the
405 proposed bridge location)