Tidal turbine array design and energy yield assessment for Naru Strait, Japan

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***Abstract*—Preliminary results are presented from an assessment of phased tidal stream energy development in Naru Strait, Nagasaki Prefecture, Japan. Results from a validated 3D hydrodynamic model show that flow speeds exceed 3 m/s in depths ranging between 30 - 60 m within the strait. Tidal stream turbine energy yield is estimated across the strait using mid-depth ambient flow results from the model. Array scale blockage effects are limited by capping the practical array install capacity below levels shown to reduce turbine power generation in literature. Energy yield estimates are presented for a 45 MW array, built out in four phases. For each phase, rotor swept area and generator rated power are designed to maintain high capacity factor levels. Results show that the 45 MW array in Naru Strait generates an estimated yield of 119 GWh/year. This is equivalent to the average electricity demand of approximately 40,000 households in Japan.**

***Index Terms*—Tidal stream energy, Japan, Goto islands, Naru Strait, rotor diameter, rated power.**

I. Introduction

The New Energy Development Organization (NEDO) has estimated that Japan's tidal stream power install capacity potential is 22 GW, with an introductory install capacity potential of 2 GW [1]. In addition to the tidal stream energy resource, NEDO estimates that Japan's ocean current power potential is 205 GW, with an initial accessible install capacity potential of around 1 GW [2]. Figure 1a shows the location of tidal stream and ocean current sites in Japan that have been identified and studied. Locations A-R are tidal stream sites, and location S is an ocean current site that utilises the uni-directional Koroshio current that has been designated for testing by the Japanese Government (Headquarter for Ocean Policy).

A high density of tidal stream sites are located around the Goto islands off the west coast of Kyushu in Nagasaki Prefecture (Figure 1b). The Goto archipelago contains around 140 islands. The five largest islands (Fukue, Hisaka, Naru, Wakamatsu and Nakadori) are located in a chain that separates the Korea Strait to the north west and the Goto-Nada Sea to the south east. The narrow straits between each island are approximately 8 km long, 2 km wide and 50 m deep. The islands funnel flow through the straits, creating high flow speeds that have been reported to exceed 4 m/s in some locations [3]. The islands shelter the flow within the straits, limiting significant wave heights throughout the year. The Goto City Renewable Energy Promotion Department report that significant wave height remains below 1 m 89% of the time [4].

Japanese Government (Headquarter for Ocean Policy) has designated Tanoura Strait and Naru Strait as test sites for tidal stream turbines. The combination of high flow speeds, suitable depths and calm seas are favourable for the implementation of early stage tidal stream turbines. In addition to these favourable resource characteristics, there is relatively low shipping activity and the straits are in close proximity to relevant marine and manufacturing industries. The demonstration of tidal stream turbines in Japanese waters is the necessary next step in the path to commercial scale roll out at other sites in Japan such as those shown in Figure 1a. Some key features that demonstration projects can achieve in the critical path to wider scale build out include:

1) Accumulation of operational turbine performance data at Japan-specific sites to deliver de-risked investment for future cost of capital.
2) Monitoring of biofouling rates in Japan-specific waters.
3) Development of a local supply chain to deliver future build out in the Goto region and beyond.
4) Reduction in OPEX through ongoing learning of installing, operating and maintaining tidal stream turbine arrays in Japanese waters.

This paper presents a preliminary analysis of the tidal stream energy resource in Naru Strait. The resource is quantified using results from a validated 3D hydrodynamic model, which was first presented in [5]. Regions were identified within the strait that exhibit high flow speeds and sufficient depths. Early stage development was considered for regions with depths below 40 m. Later stage development was considered in deeper waters, allowing the swept area of turbines to be increased significantly in order to increase generated power when the turbines are operating below rated power. Energy yield was estimated for each phase in the array development.

The novelty of the work lies in our preliminary assessment of suitable turbine locations and tubrine design (rated power/speed and rotor diameter) based on the site-specific flow conditions in Naru Strait. This builds upon literature that investigates the suitability of deep (>40 m), modest flow sites for future tidal stream turbine array build out [6].

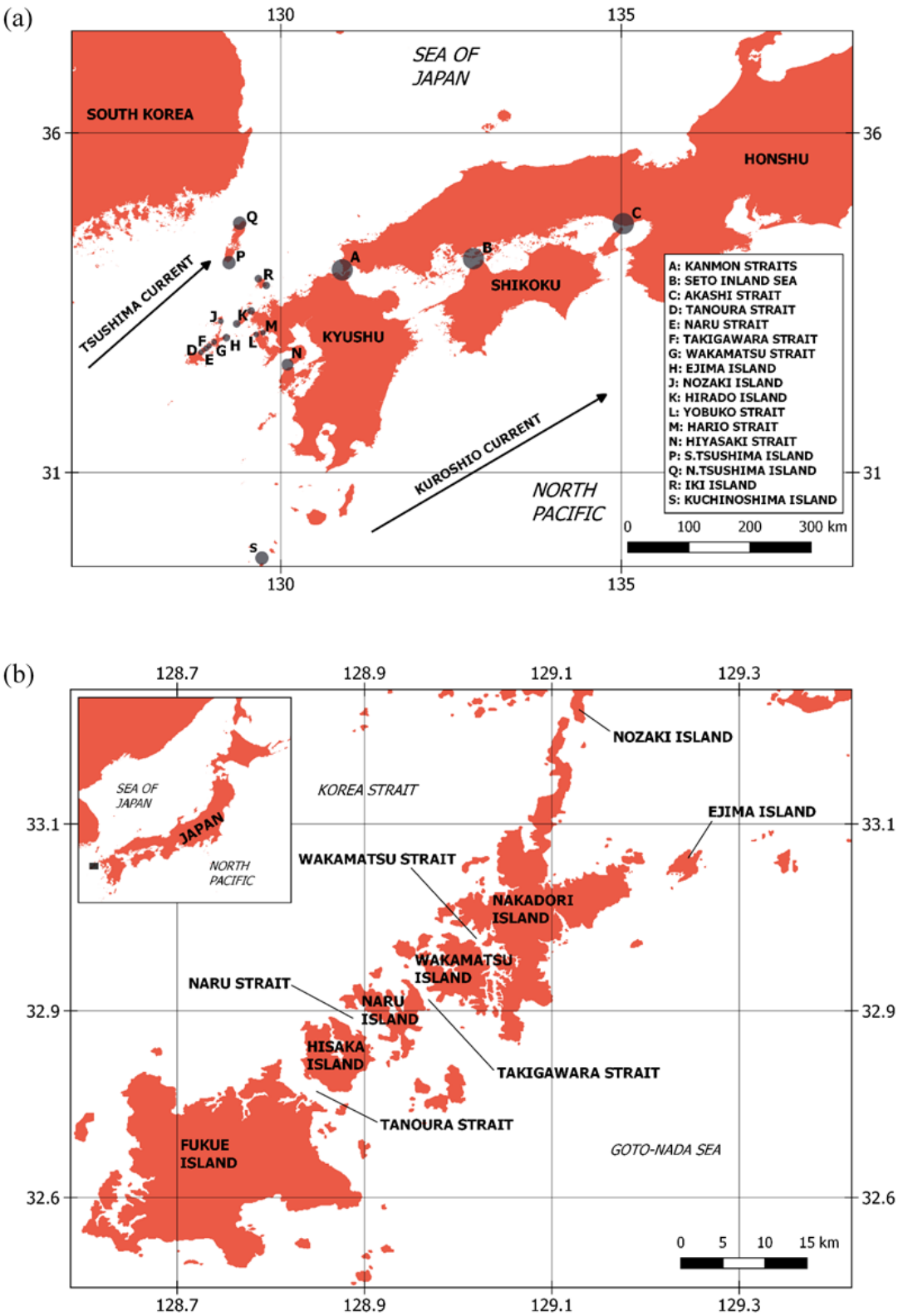

Fig. 1. (a) Location of tidal stream and ocean current resources in Japan (b) Location of the Goto Islands, with Tanoura, Naru, Takigawara and Wakamatsu Straits and Nozaki Island and Ehima Island in Nagasaki Prefecture, Japan.

II. Method

High resolution bathymetry data was obtained from Nagasaki Marine Industry Cluster Promotion Association. The dataset covers the majority of Naru Strait at a resolution of 1 m. In addition to this, 1,500 m resolution bathymetry data was obtained for the surrounding area from the Japan Oceanographic Data Center (JODC).

Mid-depth flow speeds within Naru Strait were obtained from a validated 3D hydrodynamic model that was first presented in [5]. The model was built to simulate tidal flows in the Goto region for a period of 2 weeks from 18th April 2013 to the 2nd May 2013. The model is forced by eight tidal constituents ($M_2, S_2, K_2, N_2, K_1, P_1, O_1$ and Q_1), with amplitudes and phases obtained from the NAO.909Jb regional tide model [7]. The model uses the same bathymetry supplied by the Hydrographic and Oceanographic Department, Japan Coast Guard, at a resolution of approximately 1,500 m. The model was validated by conducting harmonic analysis of surface elevations at a tide gauge station, and comparison between Acoustic Doppler Current Profiler (ADCP) data obtained in Tanoura and Naru Strait and the model results. Results from the model validation were deemed acceptable to conduct this preliminary study of Naru Strait. For further details of the model setup and validation results, the reader should refer to [5].

Turbine location and sizing were evaluated based upon depths and mid-depth flow speeds within the strait. Harmonic analysis was conducted to extrapolate the flow timeseries obtained from the hydrodynamic model to 1 year. High energy regions were identified by considering time averaged mid-depth flow speeds and available turbine power;

$$P_a = 0.5\rho U^3 A \tag{1}$$

where P_a is the available turbine power, ρ is the density of seawater, U is the onset mid-depth flow speed and A is the swept area of the turbine rotor. The rotor swept area is dictated by depth, where the minimum clearance between the sea bed and the bottom blade tip height is 5 m and the minimum clearance between the top blade tip height and the free surface at Lowest Astronomical Tide (LAT) is 8 m.

Regions within Naru Strait were allocated for early or late stage development based on depths and flow speeds. Early stage development utilises tidal stream turbines with physical dimensions most similar to those currently in operation. Later stage development utilises larger rotor diameters. This reflects the time that is needed to develop larger rotors and the necassarry modifications to installation processes as a result of increased rotor diameter. The generator sizes considered here are already common place in the tidal industry. The optimal turbine swept area and rated power capacity within each region has been investigated in order maintian high capacity factor levels.

Consideration for the practical limit to install capacity was considered using results from [8], which quantifies the energy yield of arrays within Naru Strait, and the reduction in time averaged power generation per turbine when installed capacity is increased. This is discussed in section III-*C*.

III. Results

A. Array allocation

The spatial distribution of depth (LAT), time averaged flow speed and time averaged available turbine power were used to assign suitable regions for tidal stream turbine development within Naru Strait (Figure 2).

Figure 2a shows the bathymetry within Naru Strait relative to LAT. Depths range between 20 - 60 m within Naru Strait. In this preliminary study we consider regions where depth exceeds 30 m in order to house turbines with rated power exceeding 1 MW.

Figure 2b shows the time averaged mid-depth flow speed within Naru Strait, obtained from the validated hydrodynamic model in (Yamaguchi, 2014). This is another metric used to identify suitable regions for development. In the narrowest section of the strait time averaged mid-depth flow speeds reach 1.56 m/s. In this study we consider regions where time averaged mid-depth flow speed exceeds 1 m/s for tidal energy development in order to maintain high capacity factor levels.

Figure 2c shows the distribution of time averaged available turbine power over Naru Strait. This is an important metric for Naru Strait as it considers both flow speeds and depths in order to identify suitable regions for tidal stream turbine development. At modest flow sites such as Naru Strait, it is important to recognise the benefits deeper water flows can offer in housing larger rotor diameters. Increases in rotor diameter in deeper regions of the strait are considered in section III-*B*.

Figure 3 shows the overlap between the 30 m depth contour and 1 m/s time averaged mid-depth flow speed contours within Naru Strait. Blue, orange and yellow regions have depth ranges of 30 – 40 m, 40 – 50 m and 50 – 60 m respectively. All regions have time averaged mid-depth flow speeds that exceed 1 m/s. The blue, orange and yellow regions are referred to as regions A, B and C respectively from now on. In total, regions A, B and C cover an area of approximately 3.65 km^2.

Table I summarises the depth range, area and time averaged mid-depth flow speed within regions A, B and C. Regions A and B are relatively shallow, making them suitable for early stage development using foundation design and installation methods most similar to those already being used in the industry. Later stages of development would utilise the deeper waters in region C. This allows larger turbines to be installed to increase power generation when the turbines operate below rated power. This is discussed further in the following section, which considers suitable rotor swept area and rated power for turbines in regions A, B and C.

B. Turbine specification

The energy yield of turbines installed in Naru Strait is highly dependent on (a) the location of the turbine (i.e. the tidal energy resource and depth) and (b) the turbine specification (i.e. the turbine rated power and swept area). The maximum

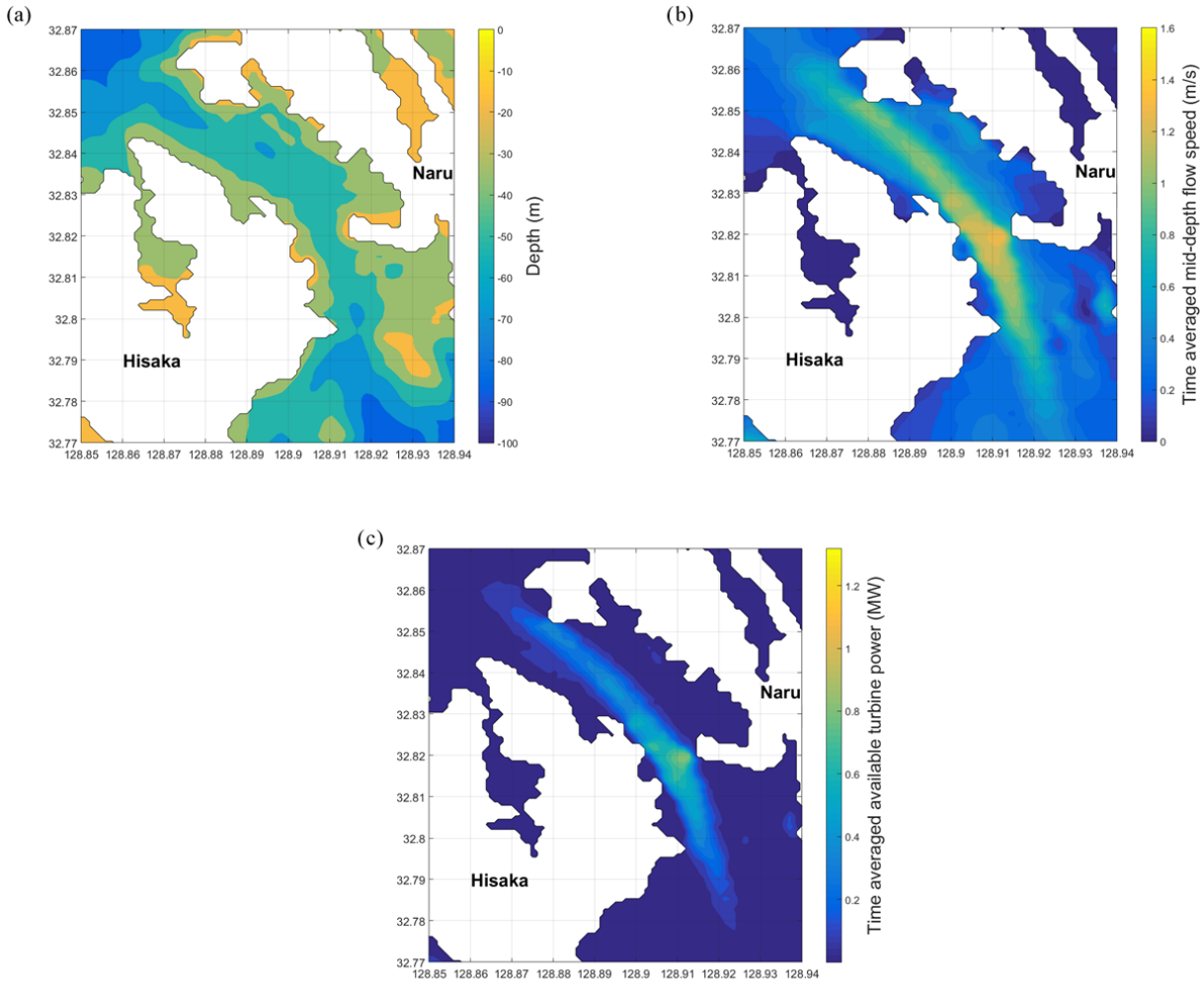

Fig. 2. (a) Depth (b) time averaged mid-depth flow speed and (c) time averaged available turbine power within Naru Strait.

allowable rotor diameter is constrained by depth. The rated power of the turbine must be selected based upon the rotor swept area and the tidal stream energy resource. Under-sizing the generator can lead to excess power shedding when the turbine is operating in flows above rated speed. Over-sizing the generator can increase the Levelised Cost of Energy (LCoE).

A simple analysis was conducted to establish the sensitivity of energy yield to turbine rated power at locations within regions A, B and C. Figure 4a shows the relationship between turbine rated power and time averaged power generation for isolated turbines located in regions A, B and C. Figure 4b shows the relationship between turbine rated power and the capacity factor of isolated turbines in regions A, B and C. In both plots the swept area of the turbines in region A, B and C are 18 m, 28 m and 38 m respectively to maximise generated power when the turbines are operating below rated power, whilst also maintaining acceptable clearance above and below the rotors.

In order to select an appropriate turbine rated power for each region, this study assumes a minimum capacity factor of around 0.3 must be achieved. Figure 4b shows that this is accomplished in regions A, B and C with a turbine rated power of 0.5 MW, 1.25 MW and 1.7 MW respectively. Based on these results we consider turbines with rated power of between 1 - 1.5 MW in regions B and C. Region A was discarded in this study because it covers a small area. A cap on the maximum turbine capacity in region C was implemented to maintain a relatively high capacity factor.

C. Practical install capacity limit in Naru Strait

Results in [8] quantify the impact of adding turbines to an array spanning the width of Naru Strait on energy yield. Two arrays are considered, one spanning the width of Naru Strait and the second spanning the width of Tanoura Strait. The estimated time averaged power from the Naru Strait array for three levels of development in [8] are summarised in Table II. Results show that the time averaged power per turbine quickly diminishes as the array capacity is increased, from 0.1 MW/turbine for 'low level' development

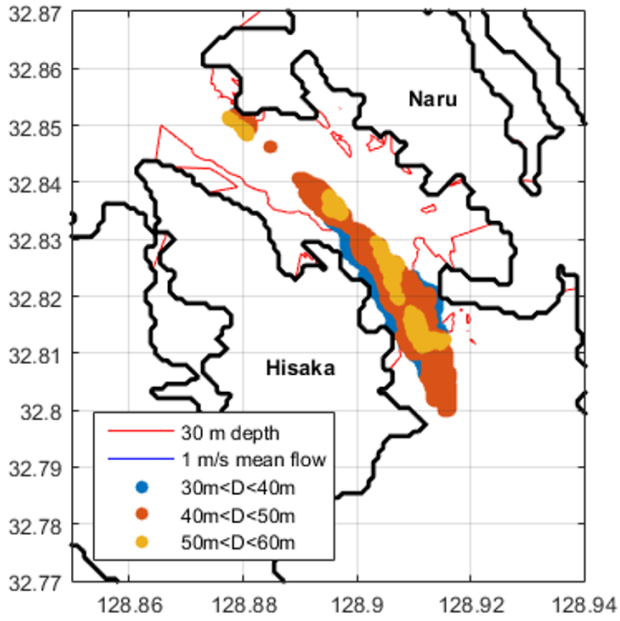

Fig. 3. Designated regions for tidal energy development in Naru Strait based on minimum depth and time averaged mid-depth flow speed criteria. Region A (blue), region B (orange) and region C (yellow).

TABLE I
SUMMARY OF THE AREA, DEPTH AND TIME AVERAGED, MID-DEPTH FLOW SPEED WITHIN DESIGNATED REGIONS OF NARU STRAIT.

Region	Depth	Area	Time averaged mid-depth flow speed
A (Blue)	30-40 m	0.15 km^2	1.16 m/s
B (Orange)	40-50 m	2.40 km2	1.20 m/s
C (Yellow)	50-60 m	1.10 km^2	1.10 m/s

TABLE II
SUMMARY OF ARRAY YIELD RESULTS IN NARU STRAIT FROM [8].

Level of development	Number turbines	Time averaged array power	Time averaged power/turbine
Low	42	4.20 MW	0.10 MW/turbine
Medium	88	6.35 MW	0.07 MW/turbine
High	190	8.36 MW	0.04 MW/turbine

to 0.04 MW/turbine for 'high level' development. Results in Table II assume that the capacity factor remains approximately the same amongst all turbines in both straits, which was confirmed from discussions with the lead author of [8].

In order to minimise array scale blockage effects for arrays in this paper, the practical array capacity was capped based on the preliminary results in [8]. The force exerted on the flow by an array of turbines is proportional to the total number of turbines, the onset flow speed squared, total array swept area and turbine coefficient of thrust;

$$F = n0.5\rho U^2 C_t A \tag{2}$$

where F is the force exerted on the flow by the array, n is the number of turbines in the array, ρ is the density of seawater, U is the onset flow speed, C_t is the turbine thrust coefficient and A is the swept area of a rotor. In [8] the modelled turbines have a rated speed of 3 m/s, a rotor diameter of 16 m and a rated capacity of 1.2 MW. The turbines considered in this paper have rated speeds of approximately 1.95 m/s, rotor diameters ranging between 25 - 38 m and rated power ranging between 1 - 1.5 MW.

Table III summarises some array properties for the medium level of development case in [8], and an array that exerts the same total force at rated speed using turbines with a lower rated speed. For the purposes of this preliminary array comparison study we assume all turbines are exposed to their rated speed (i.e. no turbine wake interaction) and all turbines have a constant thrust coefficient at rated speed of 0.85.

TABLE III
COMPARISON OF 'MEDIUM' DEVELOPMENT ARRAY FROM LITERATURE AND AN EQUIVALENT ARRAY USING A DIFFERENT TURBINE SPECIFICATION.

	Waldman *et al.* medium development	Coles *et al.*
Turbine rated speed	3.00 m/s	1.95 m/s
Total array swept area	17,693 m^2	41,877 m^2
Array capacity	105.6 MW	62.0 MW
Array force at rated speed	69.3 MN	69.3 MN

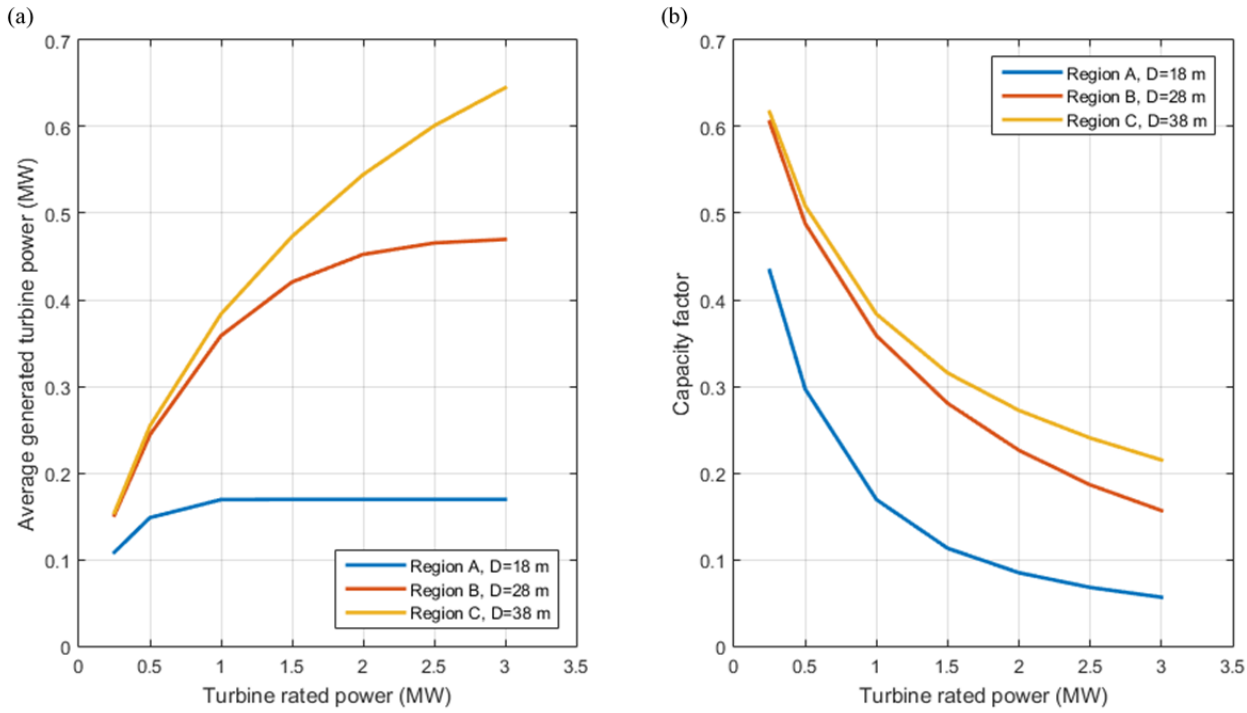

Fig. 4. Relationship between turbine rated power and (a) time averaged power generation (b) capacity factor for turbines located in regions A, B and C of Naru Strait.

The medium case array in [8] achieves a capacity factor of just 6%. This indicates that the array capacity of 105 MW is rarely reached, if at all. The turbines considered in this paper have a significantly larger swept area and a lower rated speed than those considered in [8]. As a result the array considered in this paper will reach its (lower) array capacity earlier in each tide as it ramps up to peak speed, which increases the capacity factor of the array significantly to around 30%. In a preliminary attempt to limit array scale blockage effects, the maximum array capacity considered in this paper is kept at 70% below the equivalent array capacity calculated from Equation 2 and presented in Table III. This gives a cap on the practical install capacity of around 45 MW, down from 62 MW in Table III. A detailed assessment of the array scale blockage effects on turbine power generation is underway to test this array capacity cap assumption, as outlined in section V.

D. Estimated energy yield

Table IV summarises the array characteristics and estimated annual energy yield of phased array build out within Naru Strait. Phase 1 would install a single 1 MW, 25 m diameter turbine in region B. Phase 2 would install an additional 5 x 1 MW turbines in region B. The Phase 2 turbines use the same rated power as Phase 1, but rotor diameter is increased to 28 m in order to increase generated power when the turbines are operating below rated power. Phase 3 would install 12 x 1.25 MW turbines with 28 m diameter rotor blades in region B. Finally Phase 4 would install 16 x 1.5 MW turbines with 38 m rotor diameter in region C. The total installed array capacity of Phases 1-4 combined is 45 MW.

Capacity factor and energy yield estimates in Table IV assume 95% turbine availability, 10% electrical losses and an average coefficient of power between cut in speed and rated power of 0.45 (when calculated to the generator tails). The estimated annual energy yield of Phases 1-4 combined is 119 GWh. This is equivalent to the electricity demand of approximately 40,000 households (based on an average domestic electricity demand in Japan of 3,000 kWh/year [9]). This preliminary analysis does not consider an optimal turbine/turbine micro-siting solution, which may increase array yield significantly [11].

The LCoE of Phase 1 will be relatively high. No economies of scale can be applied to either the cost of the turbine or offshore works. Nevertheless Phase 1 is critical to build up operational hours to raise finance for Phase 2 in Naru Strait. Future technology developments and economies of scale will enable rapid cost reductions. Such Technology developments include:

- Interconnected turbines via a sub-sea hub to minimise the number of cables and onshore drilling operations.
- Reduction in balance of plant for grid connection by feeding multiple turbines into each power converter.
- Monopile foundations to reduce the mass of steal required by around 90% on gravity-based substructures.
- Increased rotor diameter to increase power generation at below rated speed at deeper sites.
- Increased voltage from turbines to shore to reduce electri-

TABLE IV
SUMMARY OF ARRAY DESIGN AND ENERGY YIELD RESULTS FOR PHASED TIDAL STREAM ARRAY DEVELOPMENT IN NARU STRAIT.

	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**	**Total**
Array properties					
Region	B	B	B	C	
Number of turbines	1	5	12	16	34
Turbine power rating	1 MW	1 MW	1.25 MW	1.5 MW	
Rotor diameter	25 m	28 m	28 m	38 m	
Install capacity	1 MW	5 MW	15 MW	24 MW	45 MW
Array performance					
Capacity factor	0.34	0.32	0.3	0.3	0.3
Annual energy yield	3 GWh	14 GWh	39 GWh	63 GWh	119 GWh

cal losses and facilitate the transmission of turbine power from further offshore.

An updated assessment that includes a breakdown of LCoE for phased development in Naru Strait is in preparation [10].

IV. CONCLUSIONS

Preliminary results from an array development assessment in Naru Strait are presented. The key findings are:

- Energy yield was estimated for phased tidal turbine array development in Naru Strait. Array scale blockage effects were minimised by capping the total install capacity at 45 MW.
- We consider build out of the 45 MW array in 4 phases. Results show that by designing turbine rotor swept area and rated power for the tidal stream energy resource and depths specific to each phase, capacity factor can be maintained above 0.3 (where capacity factor includes electrical losses of 10% and turbine availability of 95%).
- The estimated annual energy yield of the 45 MW array is 119 GWh, which is equivalent to the average demand of approximately 40,000 households in Japan.
- This preliminary analysis does not consider an optimal turbine/turbine micro-siting solution, which may increase array yield significantly [11].

V. FUTURE WORK

Work is ongoing to:

- Improve the resolution of hydrodynamic model simulations using high resolution bathymetry provided by the Nagasaki Marine Industry Cluster Promotion Association. This work is being conducted using Thetis, a flow solver for simulating coastal flows implemented using the Firedrake finite element Partial Differential Equation (PDE) solver framework [12].
- Optimise the micro-siting of turbines within Naru Strait using Thetis. Additional spatial constraints will be considered based on geo-technical surveys of Naru Strait, which dictates foundation type and installation method. Outputs from this work will be used to update the energy yield results presented in this paper.
- Build LCoE models to asses cost competitiveness of array development in Naru Strait against competing technologies such as offshore wind.
- Replicate the method for tidal stream turbine array development to Tanoura Strait and Takigawara Strait, also located in the Goto region in Nagasaki Prefecture (see Figure 1b).

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