Floating Clean Multi-energy Systems Towards Driving Blue Economic Growth

Srikanth Narasimalu

Abstract The blue economy is the recent initiative among Indian Ocean realm association (IORA) countries, ASEAN and Caribbean Islands focusing towards sustainable use of ocean resources for economic growth, improvised livelihoods and jobs and preserving ocean ecosystem health. High-density population resides in coastal and islandic regions of these countries and with climate change, rising sea level is seen an imminent danger to the coastal community in the low-lying area. To counter the rising sea level, countries are looking for technologies to support the displaced coastal population by embarking on floating homes and floating cities in their Blue Growth strategy to support living space and amenities needs. Since these floating homes and cities are powered through fossil fuel there is a need to preserve the Coastal marine ecology from the emissions. This paper discusses about powering the floating homes through ocean based floating clean energy systems as a cost-effective energy system that can be manufactured, assembled and maintained in the onshore and easily towed and deployed at a specific ocean site and assure energy security and resilience even during natural disasters. In addition, the paper discusses the idea of hybrid renewable powered energy systems to exploit the multiple available energy sources at the specific site viz., tidal, ocean thermal, wave, solar and wind that may vary in different proportion of availability to increase overall energy generation density from the ocean site. To illustrate, a case study of floating tidal system is discussed that was designed and deployed in Singapore towards tropical shallow water conditions through systematic resource assessment, device design through simulation and field based assessment.

Keywords Tidal energy · Wave energy · Smart grid · Renewable energy · Floating structure

S. Narasimalu (✉)
Energy Research Institute @ Nanyang Technological University,
Singapore 637141, Singapore
e-mail: nsrikanth@ntu.edu.sg

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1 Introduction

High-density population resides in coastal regions of different countries. As noted by the International Panel on Climate Change [1], climate change will have many negative effects, increased intensity of storms, floods and droughts; rising sea levels and loss of biodiversity. Sea level rise (SLR) poses a particular threat to countries with heavy concentrations of population and economic activity in coastal regions [2]. Geographic Information System (GIS) based study shows hundreds of millions of population may be affected in more than 84 developing countries in the inundation zones demarcated as 1–5 m of SLR. In order to counter the implications of SLR for population location and infrastructure planning, governments can resort to floating homes and floating cities design concepts to meet the short term and long term coastal regional needs.

In parallel, coastal countries in the Indian Ocean Realm Association, Caribbean Islands, ASEAN region, etc. are focusing to exploit their marine resources through a Blue Economy Growth strategy to utilize their ocean resources towards job growth, energy resilience and economic growth. This paper proposes that the government can resort to Floating homes and Floating cities to meet the short term and long term coastal regional needs in their Blue Economy Growth Strategy to include the implications of SLR for coastal population location and infrastructure planning.

To make this floating homes a reality, the energy needs towards electricity and water even in a remote coastal location should be supported by a credible energy production and supply system. Presently floating homes are supported with fossil based energy systems such as diesel generators, which affects the carbon foot print and marine ecology of the ocean site. Accordingly, clean energy based marine energy systems is seen as a promising energy source to power the various marine industries and operations towards economic growth and help create job creation and increase the energy availability in the coastal region.

Ocean has various energy sources such as tidal energy, ocean currents, salinity gradient, ocean thermal energy gradient, wave energy. Today the corresponding energy generation technologies for deriving electrical power is developing into commercial solution at different pace within various industrial firms and designs are being tested for their technology maturity, performance and reliability in test sites such as European marine energy center (EMEC) in Orkney Islands and Force test site in Halifax (Canada).

Today, land based solar energy systems through integration of smart grids have become a credible clean energy source in terms of ensuring robustness against intermittencies in the regular energy mix of remote inland region and urban cities. In similar lines tidal instream flow currents are highly predictable in ocean conditions and can work well with other energy systems such as floating solar photovoltaic systems, floating wind and floating wave energy systems through smart grid systems that are empowered with machine learning based energy forecasting and load scheduling technology to operate as a credible clean energy supply system. Today, with proper hydrodynamic modeling, these energy systems can be integrated into floating structures and can be designed towards specific design life to structurally support the various energy systems and present as a floating renewable energy platform.

However, in coastal settings due to limited land area for deployment, the present paper proposes the concept of floating renewable energy systems that can wisely utilize the available tidal energy resources, photovoltaic energy, wave and wind energy at a specific site to increase the overall energy foot print at the specific site. For example, in Singapore coastal waters the solar energy can provide ~168 GWh/yr/km^2, Tidal can provide ~166 GWh/yr/km^2 while Wind will provide ~9 GWh/yr/km^2. The concept of the floating energy platform can be achieved through sizing the specific energy systems such as photovoltaic systems, tidal turbines, wind turbines, wave energy systems in tune to the energy resource assessment at a site and structurally integrate on a large floating structure as well as electrically integrating them through a smart hybrid AC–DC nano-grid technology and enhanced with complimentary machine learning based energy forecasting principles and load scheduling techniques to ensure the overall floating hybrid renewable energy system as a clean energy supply system which is trustable in terms of certainty and reliability in power production towards the essential needs such as electricity, water, air conditioning, etc. Accordingly, this paper systematically explains the various steps that includes the resource assessment principles of a coastal site and tailoring the energy systems in accordance to the energy availability in the specific site to maximize the energy production from the available ocean site footprint with minimal skilled manpower and infrastructure and minimal levelized cost of energy.

2 Ocean Based Renewable Energy Systems

Systematic ocean energy resource assessment [3] shows oceans possess various energy sources that exhibit a total energy capacity of:

- Ocean thermal energy gradient (OTEC) amounts to 10,000 TWh/year.
- Wave energy amounts 80,000 TWh/year.
- Tidal range (barrage) amounts to more than 300 TWh/Year.
- Tidal/marine current amounts to more than 800 TWh/year.
- Salinity gradient amounts to 2000 TWh/Yr.
- Offshore wind amount to more than 192,000 TWh/year.

Energy availability varies with geographic location due to earth curvature, spin, water depth, Coriolis forces, uneven solar radiation, and salinity concentration variation. Figure 1 shows the renewable energy resource availability in Southeast Asia.

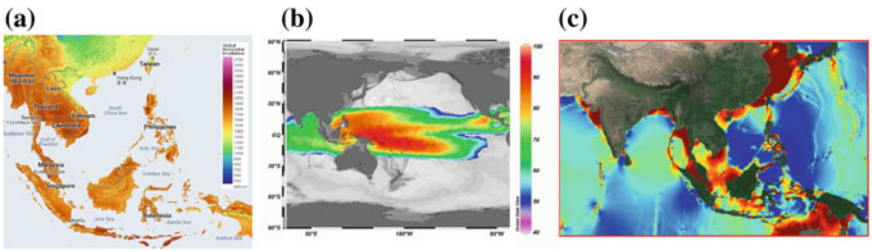

Fig. 1 Renewable energy resource availability, **a** solar energy, **b** Ocean thermal energy gradient, **c** tidal energy

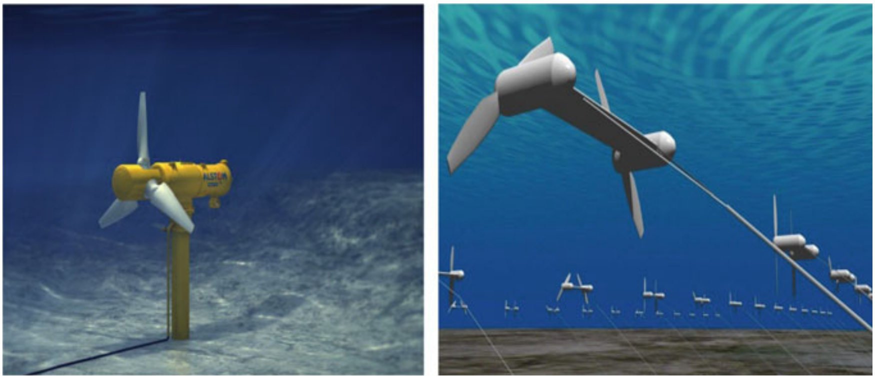

Fig. 2 Seabed mounted tidal turbine and semi-buoyant tidal turbine designs

2.1 *Tidal Energy System*

Tidal In-Stream Energy (TISE), a type of ocean energy which refers to the potential presence in tidal currents or flow, is a reliable clean energy resource option coastal region's energy needs [3]. TISE is more reliable (because it is periodic, thus highly predictable, since the resource follows the astronomical/earth-sun-moon rhythm), weather-resilient (unlike solar energy which may be disrupted by cloud cover) and is unaffected by climate-change (unlike wind energy). Tidal In-Stream Energy extraction technologies (devices, installations) do not require land area but make use of otherwise dormant underwater sea space (existing installations are seabed-mounted and does not conflict with shipping and navigation) as shown in Fig. 2.

2.2 *Wind Energy System*

Ocean surface experience higher wind speeds than over land more than five times as much energy as wind turbines over land. This presents an enticing opportunity

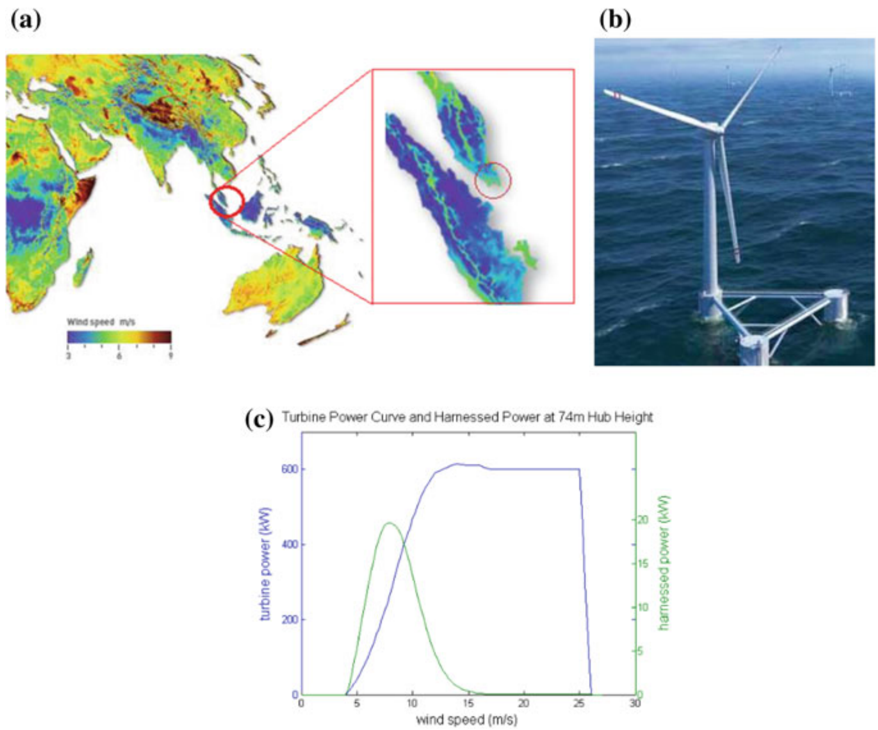

Fig. 3 **a** Typical wind energy flow in Southeast Asia, **b** floating wind turbine, **c** wind velocity Weibull distribution (green) and the power curve of typical wind turbine (blue)

for generating renewable energy through wind turbines through offshore support structures and floating structures. In Southeast Asia, wind speeds are relatively low compared to Europe. In Singapore, the wind speeds range around 6 m/sec at a hub height of 50 m as shown in Fig. 3 [4].

A floating wind turbine, an offshore wind turbine mounted on a floating structure, allows the turbine to generate electricity in deep water depths where fixed-foundation turbines are not feasible. Floating wind farms have the potential to significantly increase the sea area available for offshore wind farms. Sea surface experiences least turbulence and reach stronger and more consistent winds. Hence, commercial installations are towards large wind turbine structures to exploit increasing returns to geometric scaling. Floating wind farm in Hywind Scotland, developed by Statoil and commissioned in October 2017 is a good case study to show the robustness of commercial floating wind turbine which has 5 floating turbines with a total capacity of 30 MW [5].

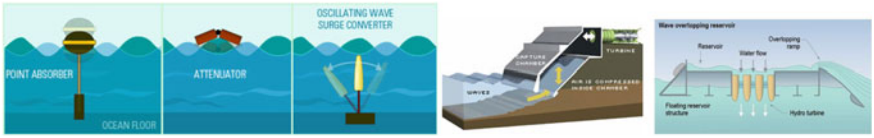

Fig. 4 Typical wave energy converters towards larger wave heights

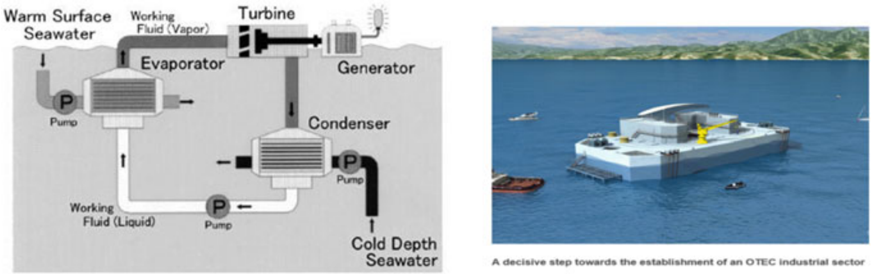

Fig. 5 OTEC working principle and floating DCNS system towards desalination support

2.3 *Wave Energy System*

A variety of wave energy converter designs have evolved (Fig. 4) and have been tested in European waters. These have been specifically designed towards larger wave heights (>1 m) [3].

However in the tropical belt experience low wave heights (<1 m) and hence in a recent study, the author had demonstrated that a roller based wave energy converter that can be integrated to guide rollers in pontoons can operate and produce electrical energy at a wave height of below 1 m wave height.

2.4 *Ocean Thermal Energy Conversion*

Southeast Asia has significant deep water regions that possess a thermal gradient of up to 20 °C within a depth of 1.5 km ocean depth from the ocean top surface, in places such as Philippines, Malaysia and Indonesia. This thermal gradient can help in boiling low boiling point liquids, as shown in Fig. 5, such as Ammonia to run a turbine and generate useful power [3].

Figure 6a shows with cumulative production the cost of energy of the different energy harvesting technologies have been reducing and the solutions are maturing at various rates (see Fig. 6b) for these different energy sources. To minimize the capital cost and operating cost, the design can integrate to exploit the common parts among the various systems and present as a hybrid energy system to maximize the energy

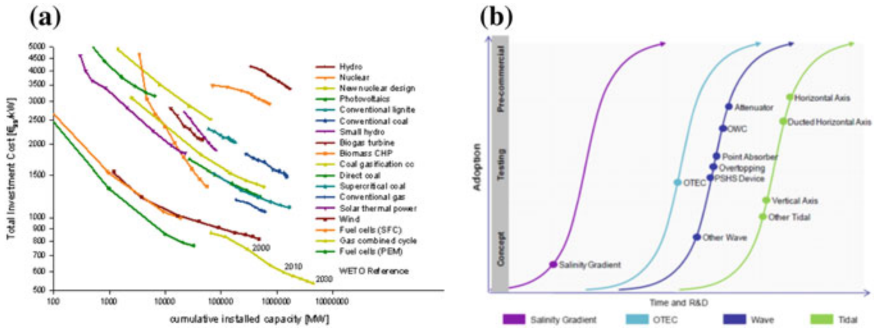

Fig. 6 **a** Total investment cost reduction with cumulative production (also called learning curve), **b** present day technology maturity curves of the renewable energy systems

Table 1 A comparison of different energy sources in an ocean site with respect to LCOE, footprint, predictability, carbon abatement and technology readiness level

Technology	LCOE (USD/kWh)	Footprint (sq m/MW)	Predictability	Carbon abatement	Technology readiness level (TRL)
Fossil fuel	~0.1	–	High	No	High
Wind	~0.15	~6000	Low	Yes	High
Tidal	~0.30	~2500	High	Yes	High
Wave	~0.4	~ 4000	Low	Yes	Medium
OTEC	~0.4	~5000	High	Yes	Medium

foot print and maximize the energy availability at a minimal levelized cost of energy (LCOE) (Table 1).

3 Case Study: Floating Hybrid Tidal Energy System

To elucidate the concept of floating renewable system a case study of floating tidal turbine is discussed in this section. Conventionally, tidal turbines are seabed mounted as shown in Fig. 2 which demands costly erection and deployment and in terms of maintenance procedure due to need of skilled divers' requirements and the necessary permissions as well as need of costly equipment for handling infrastructures such as special cranes and special vessels in the ocean site. In this present study, a systematic approach was made to develop a floating tidal turbine that enables the turbine to be deployed from a floating platform below the water surface and thereby experience high flow speeds as well enable to be lifted as necessary to provide cost effective maintenance. Owing to the towability of the floating platform, the floating renewable system can be dry-docked in the port for long duration repair

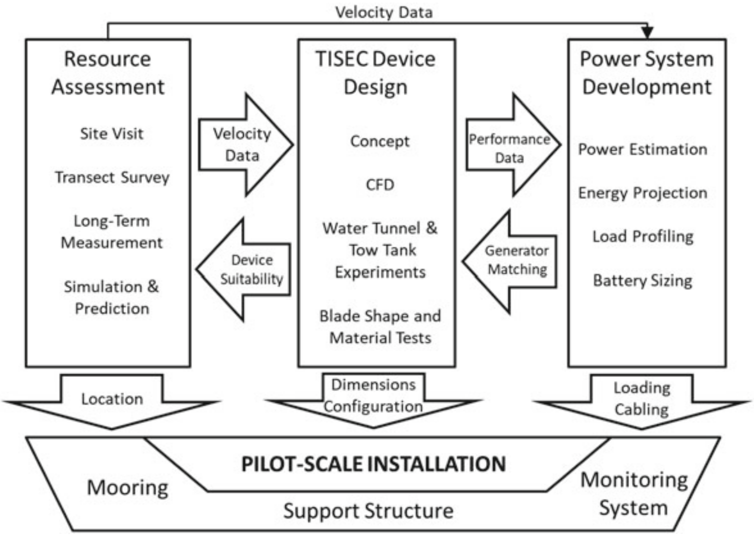

Fig. 7 Various steps in sizing floating tidal turbine towards coastal site

and maintenance. The design and development approach in this study adopted the following steps, as detailed in Fig. 7:

(1) Resource assessment of the ocean site of available tidal and wave energy resource was performed using both simulation and field based sensor deployment.
(2) The right dimensions of the turbine was selected towards optimum energy harvesting to achieve increased annual energy yield, capacity factor, availability factor and lower levelized cost of energy (COE).
(3) Genetic algorithm based hydrofoil selection helped to achieve towards higher lift and minimal drag forces and minimal cavitation factor, flap-wise and edge-wise structural rigidity of blades and hydrofoil robustness towards biofouling surface roughness.
(4) CFD based studies helped to confirm turbine's energy harvesting performance, thrust forces, wake performance and in hydro-acoustics evaluation.
(5) Based on the simulation results the dimensions were finalized and a scaled turbine was developed and was tested in open sea condition.
(6) The floating barge was designed as per naval architecture principles and Hydro-dynamics studies were conducted on the floating tidal turbine support system based on the site data.
(7) Fabrication of the Floating tidal turbine was conducted in Singapore Yards.
(8) The turbine was tested under simulated towing test condition to mimic tidal flow conditions and the stability of the floating barge and the dynamic stresses were experimentally measured and were compared against simulation predictions.

3.1 Resource Assessment in Ocean Site

Tropical waters have energy resources which includes tidal energy, wave energy and wind energy. Hence in the forth coming paragraph, a macro assessment methodology is shared using simulation based technique. Once upon citing the best energy sites micro energy resource assessment can be made by deploying sensor systems to check and calibrate the simulation model. Using the tidal flow velocities, wave height and wind speed the energy availability can be evaluated and thereby the energy system (such as tidal turbine, wave energy system as well as the floating PV system) can be sized for maximum performance. Further the wind, wave and tidal forces are useful for the structural dynamics of the floating structures and designing the mooring systems.

3.2 Tidal Modeling and Assessment in Ocean Site Energy

In the evaluation of tidal power resources cataloguing of appropriate sites and estimation of achievable energy are greatly important [6–9]. Performing tidal energy resource measurements is costly and hence simulation methods are popular to do macro and micro level simulations to provide accurate energy availability. Models are being developed to identify the locations with high flow velocities and later analyzing those areas for the average power density. In this way, sites are being identified for optimizing the tidal turbine design and size to suit the site for optimum energy harvesting before selecting and installing tidal turbine systems. However, the correctness of these models is a function of the accuracy and the resolution of the input data required for these models. Further, the certainty also depends on the hydrodynamic phenomenon being examined by the various models to simulate the ocean flow. Like certain models does 3-dimensional simulation [6] while other does a 2-dimensional depth-averaged simulation [7, 8]. Still, these models serve the purpose of distinguishing the potential sites for tidal energy extraction which can be later studied for specific sites through micro-level siting studies based on field level sensor deployment.

3.2.1 Macro Level Tidal Energy Modeling Methodology

In the present study, a two dimensional depth averaged model was developed which included a full region of Singapore mainland (Fig. 8) and nearby areas basically the computations have been performed in almost whole of Singapore so that the influence of most of the flow characteristics could be apprehended which influences the flow in the Region. The coastlines and the island boundaries have been extracted with 1-minute arc resolution to create the mainland and islands boundaries. The bathymetry of the area under consideration is obtained with 30-second arc resolution dataset and

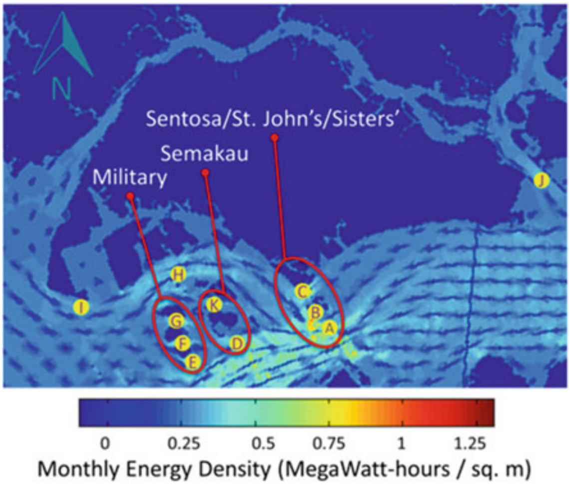

Fig. 8 Tidal instream flow in Singapore waters

the highest values of the depth of the region after interpolation is around 100 m. After generating the domain, the two dimensional depth averaged mesh model is developed using unstructured meshing technique to incorporate the complex coastline features of arbitrary shapes. The model is ensured to capture the seabed characteristics to create the drag force accurately and influence the velocity field. Each node of the model was specified with a certain value of friction coefficient which was predicted in accordance with quadratic shear stress law and the ocean boundaries were forced with tidal constituents of up to eight constants [9].

The tides propagations in the region was solved by ADCIRC which provides temporal and spatially varying velocity scalar and vector field in the region. Further, the vector plots enable to locate the regions which have maximum flow velocities. The simulation was performed for a 30 days time period of the month with a time step of 5 s and a ramp of 5 days. All the results have been shown for full simulation length of 30 days.

Velocity time series shows the transient variation of the scalar velocity at a point in the region of simulation. The velocity time series for a point in Singapore as shown in Fig. 9 has a maximum value of around 1.4 m/s with the friction coefficient of 0.009. The repetitive pattern of the velocity shows the influence of the tidal constant having a time-period of 15 days. Velocity time series was obtained by calculating resulting velocity from u, v components of the velocity field.

Surface elevation basically refers to the tidal heights because of all tidal constituents' interference which was used for modelling the tides. With the tidal constituents as a given boundary condition, for the selected site Fig. 10 shows the surface elevation can range from −1.5 to +1.5 m i.e. a range of 3 m.

The above flow velocity provide estimates of tidal turbine rotor power density by computing the power density per unknit frontal area. Thus the Fig. 11 shows

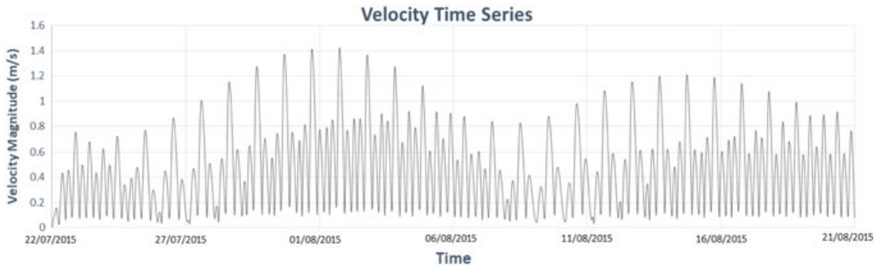

Fig. 9 Velocity time series

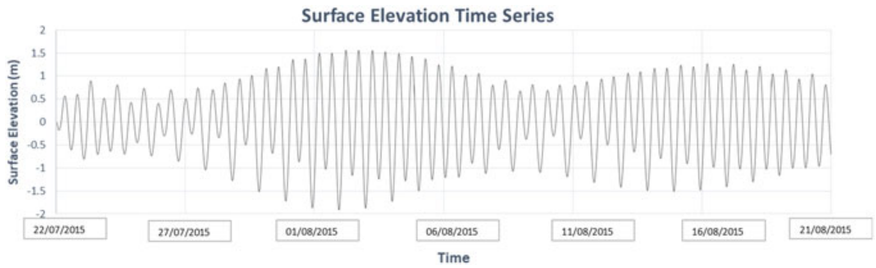

Fig. 10 Surface elevation

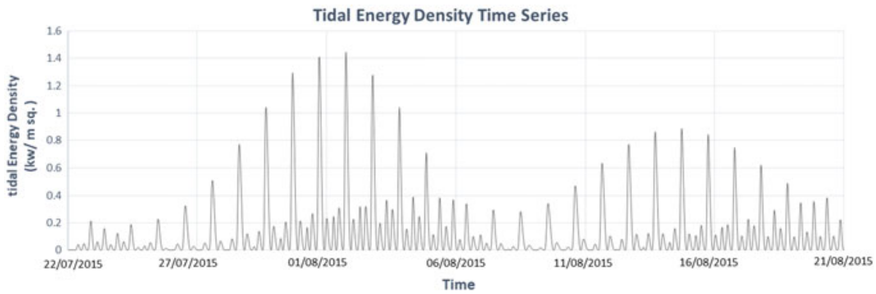

Fig. 11 Average power density

flow condition equates to a maximum annual power density (APD) of approximately 1.5 kW/m^2.

Further analyzing the plots of velocity time series, it can be concluded that the flow velocities at the specific site reach up to 1.4 m/s based on the numerical simulation estimation that the tidal energy will be a viable energy source. The tidal stream amounts to a maximum average power density of approximately 1.5 kW/m^2 of tidal energy density.

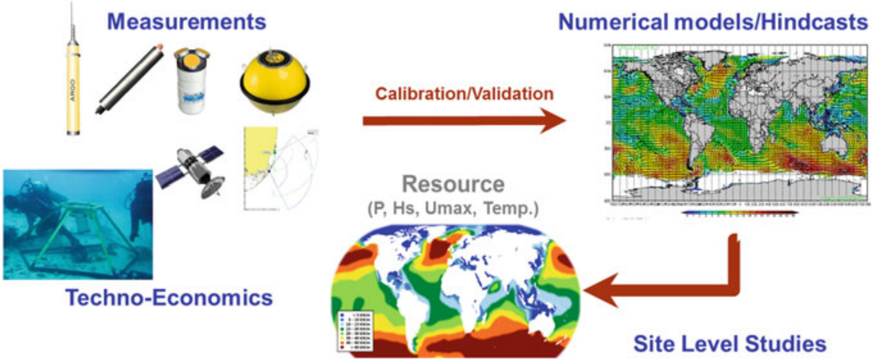

Fig. 12 Energy resource assessment in an Ocean site

3.2.2 Micro-Siting of Tidal Energy Deployment

Based on the macro level citing, high energy sites are identified towards a micro level citing to predict the energy potential distribution which shows the magnitude and the high energy potential locations towards the tidal turbine deployment. The prediction is based on combining the ocean depth information (seabed bathymetry and coastal bathymetry information) and the tidal current measurements as shown in Fig. 12 using simulation methods helps to predict flows and estimate the energy density plots of the site. In order to reduce the cost, the right sizing of the turbines has to be performed in tune to the sites tidal resource potential variation on an annual basis. For example, Fig. 13 shows the energy density maps that are generated and are presented for four sites in the Philippines, namely: Matnog-San Bernardino Strait, Verde Island Passage, Cebu-Santander Strait, and Davao Samal-Talicud Channel. Various estimates are made include annual energy yield, capacity factor, relative levelized cost of energy and availability factor to estimate different turbine operation in the ocean site. Figure 13 shows the results of the 4 sites that clearly identifies the best deployment locations of the optimum tidal turbine and its flow velocity distribution at that location.

4 Floating Tidal Turbine Development

In order to develop a low cost floating tidal turbine system towards remote coastal conditions, the present study focused on the following tasks:

- Tuning the hydrofoil towards low tidal flow conditions for Southeast Asian waters.
- Low inertial blade development with anti-seaweed and biofouling resistive functional coatings.

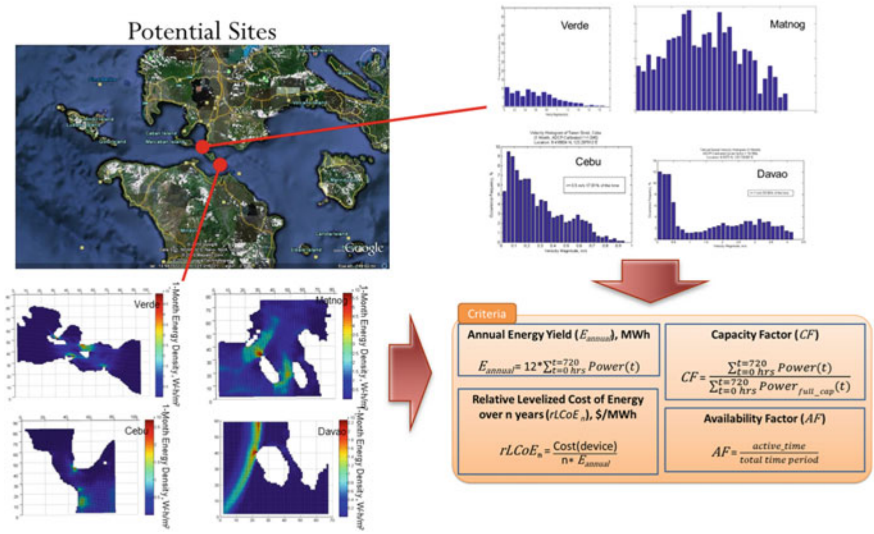

Fig. 13 Tidal energy modeling of specific sites and evaluating the site-turbine matching

- Testing of the turbine system through performance studies and further validation in field conditions.
- To differ from traditional seabed mounted tidal turbines, the present study focused to develop and demonstrate a novel tidal turbine integrated barge with a unique 'A' frame that was developed based on the naval architectural principles that is easily towable and deployable to any coastal location to minimize commissioning and decommissioning time and minimize overhaul and maintenance operations (O&M).

4.1 Hydrofoil Optimization of the Tidal Turbine Blade

Analogous to the wind turbine blade, a hydrofoil shape plays a major role in capturing tidal in-stream energy from the available tide's hydrokinetic flow. Significant efforts have been found in designing new airfoils for wind turbine application especially for megawatt class of wind turbines [10]. In a support for the development of small HAWT's, SG60XX airfoils are generally used [10]. However, it is from the operating conditions that hydrofoils for tidal hydrokinetic turbines the structural loads and the performance requirements differ significantly from the wind turbine airfoils and traditional aviation airfoils. Bigger challenge in designing marine current rotor is to avoid cavitation which causes lift to decrease and drag to increase. Cavitation inception can be predicted using cavitation parameter [11]. As a matter of fact, hydrokinetic turbines are plagued with soiling effects due to erosion and coating

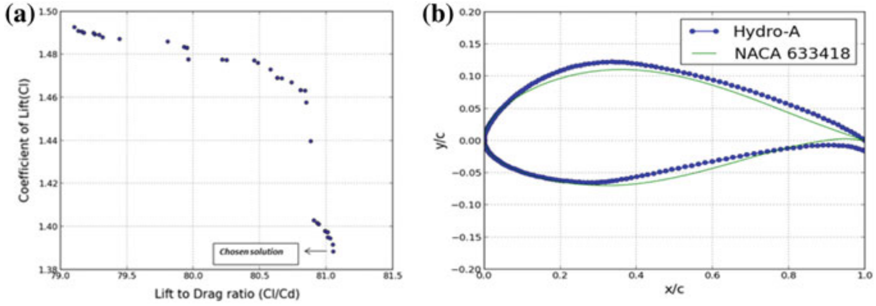

Fig. 14 **a** Pareto solution obtained from NSGA-II, **b** geometric shape comparison between optimized (Hydro-A) and baseline hydrofoil (NACA 633418)

spallation. These effects harms hydrofoil performance which includes reduction in lift and the lift curve slope, progressive aerodynamic stall with higher Reynolds number and surge in pressure drag due to premature transition on the boundary layer. In blade level, this poor performance leads to reduction in energy capture by virtue of drop in aerodynamic efficiency. Furthermore, thrust loads acting on the hydrokinetic blades are higher due to the density of water which is approximately 800 times larger than that of air. Therefore the designer should consider the structural requirements in designing hydrofoils for marine current application.

In the earlier study [11], the authors developed an elitism preserved Non-Dominated Sorting Genetic Algorithm (NSGA-II) can be used to design a hydrofoil by considering specific hydrodynamic and structural requirements. For example, when a NACA 633418 hydrofoil taken as the baseline geometry to start the process can be fit through a four Bezier curves to generate each hydrofoil in the geometry module. Accordingly in the present study, a hydrofoil was optimized for the tip region of a 3 m diameter axial flow horizontal axis hydrokinetic rotor operating at a tip speed ration (TSR) of 4.5. Based on the rotor specifications, optimization were performed at Reynolds number 1.8e6 and at a 6° angle of attack. Newly generated hydrofoil (called Hydro-A) exhibited a maximum thickness of 18.6% of chord and exhibits better performance than baseline airfoil in both free and fixed transition condition with less sensitivity towards biofouling induced surface roughness condition.

In multi-objective genetic algorithm, set of optimal solutions were obtained in a single simulation run which is called Pareto optimal solution as shown in the Pareto plot (see Fig. 14a) which shows optimal solution after 200 aerofoil design generation. Maximization problem is considered in this study and each dot in the Pareto plot represents an optimized hydrofoil obtained for a given design specification. In analogous to wind turbine, tip portion of the hydrokinetic machine contributes more towards the power production. Therefore from the Pareto plot, the hydrofoil that has high lift to drag ratio (termed C_l/C_d ratio which in this study was found to be $C_l/C_d = 81.05$) and with high lift coefficient ($C_l = 1.39$) was chosen as the optimized hydrofoil design solution (named as Hydro-A).

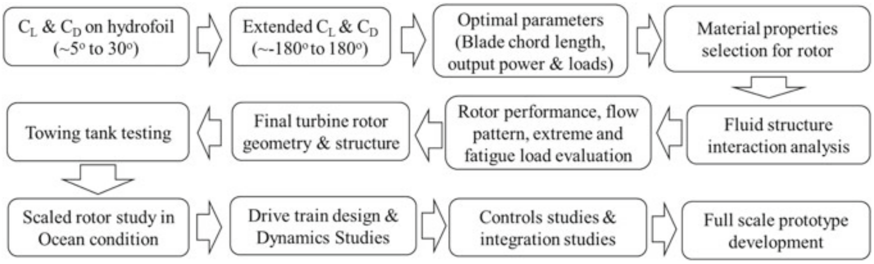

Fig. 15 Tidal turbine blade design methodology

As expected, flat back Hydro-A exhibits higher C_{lmax} both in free and forced transition condition that shows better lift performance at design condition when compared to the NACA 633418 (Fig. 14b). Drag characteristics evaluated in forced transition condition were also investigated. Hydro-A has a C_{lmax} value of 1.79 and corresponding C_d value of 0.051 at around 14 degree angle of attack in forced transition condition. Furthermore, in both free and forced transition condition, Hydro-A shows better post stall characteristics which avoids abrupt stall behavior. Due to the significant increase in C_L, lift to drag ratio value is increased to 81.05 at design condition which is 16% greater than the baseline value. Soiling and roughness effects are the major concern in the development of hydrokinetic turbine and it leads to performance degradation and increases maintenance cost. To mitigate soiling and roughness effects, design of flat back hydrofoil is employed in this study and optimization performed in the forced transition condition. As a result, the optimized hydrofoil Hydra-A exhibits less sensitive towards the roughness condition. Hydro-A exhibited high performance even for the rotors having other Reynolds number at the tip with less prone to cavitation. However as suggested in reference [11] the present study utilized twist modification at tip and usage of fibre reinforced composite which helped to reduce cavitation inception on the suction surface. Figure 15 showed the systematic procedure of the overall turbine blade and rotor development towards the full turbine development.

4.2 *Analysis of Turbine Rotor*

In order to obtain the optimal turbine power output, the BEM method is used to predict the hydrokinetic turbine performance and loads including rotor speed, torque, power, and thrust at the different current speeds [12, 13]. This analytical method is based on the aerodynamic theory, is easy to understand, and has high efficiency to analyses the turbine behaviour. It is the most widely used theory in practical wind or hydrokinetic turbine design currently. The computing procedure is described in the design methodology outlined in Fig. 15. The occurrence of cavitation is avoided theoretically in this processing by considering the local flow speed and water depth.

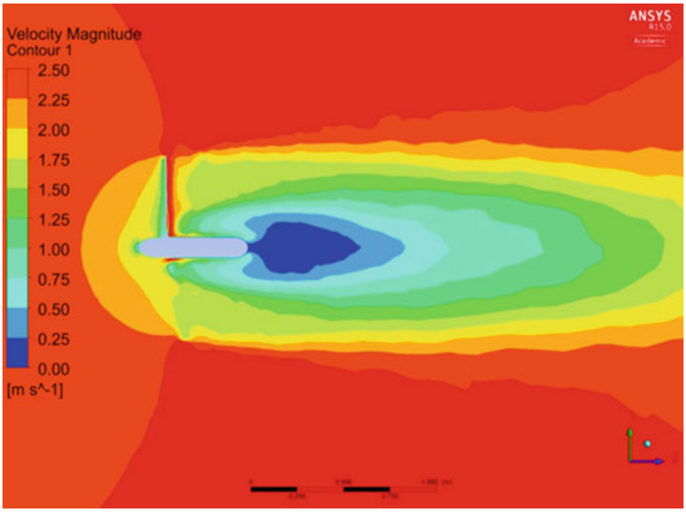

Fig. 16 Velocity-contour around tidal turbine and wave formation behind turbine

Novel blade designs have been analysed with different rake angle, pitch angle and load attenuation features to achieve good energy harvest characteristics and lower blade deflections. Detailed computation fluid dynamics was employed to evaluate the fluid induced torque, thrust force and the wake structure behind the wind turbine (see Fig. 16) and minimal hydro-acoustic noise.

4.3 Tow Tank Studies

Tidal Turbines capture the kinetic energy from hydrokinetic flow and convert it into useful mechanical power. The useful power generated at the turbine is given by

$$P = 0.5\rho A V^3 C_p \tag{1}$$

where P is power produced in Watts, A is the area swept by the rotor in m^2, ρ is the density of sea water in kg/m^3, V is the velocity of incoming flow in m/s, and C_P is the power coefficient which is the ratio of power extracted by the turbine to that contained in the tidal flow.

Towing tank testing is the experimental stage to validate the power coefficient of small scale device study and can mimics real field conditions in inflow direction (Fig. 17a). However it lacks cross-flow behaviour which occurs in field (see Fig. 17b). The initial towing tank studies help to obtain the turbine performance measurement (Fig. 18) which includes the power coefficient characteristics of the rotor and measure the different loads acting on the blades/rotor and to check the vibration from any

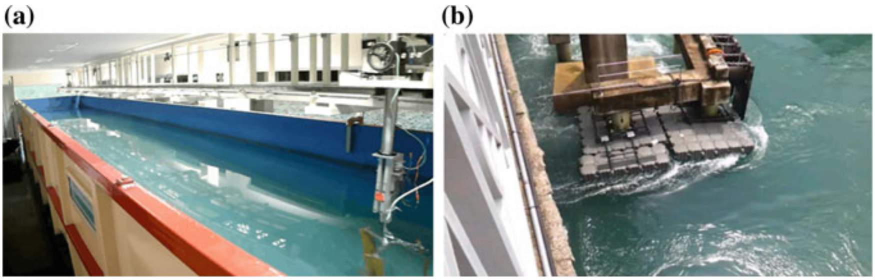

Fig. 17 **a** Typical towing tank to mimic different flow conditions on tidal turbine model in lab condition, **b** actual test bedding site where turbine is mounted on floating barge and tested

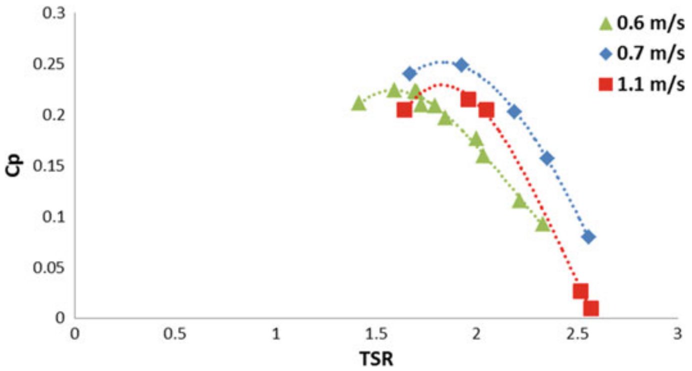

Fig. 18 Typical blade design's performance coefficient (Cp) versus tip speed ratio (TSR)

unbalanced loads. The experimental data is also used to validate the analytical and numerical results on the turbine performance and wake field investigation. This "Lab to Field" approach helps to directly allow the accurate prediction for the behaviour of the scaled up turbine once it is deployed into the sea as shown in Fig. 17b.

4.4 Tidal Turbine Development and Deployment

The initial prototype of the tidal turbine was designed towards a 1 m diameter towards a three bladed horizontal axis tidal turbine configuration. The geometry also includes a hub of about 0.1 m diameter and the nacelle part which is around 0.45 m long. Figure 19 displays the tidal turbine model used for the current study.

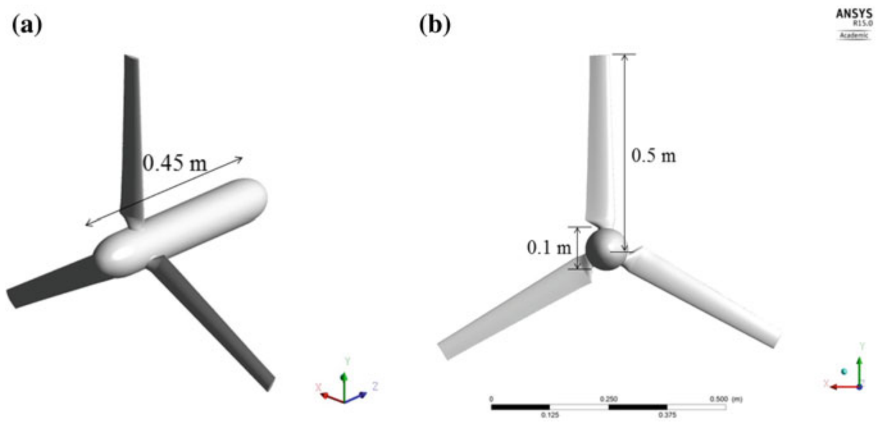

Fig. 19 **a** Isometric view of the turbine, **b** front view of the turbine

Fig. 20 Testing of balanced blade with rotor assembly

4.5 *Blade Manufacturing Method*

In this study, a novel manufacturing method for producing blades with moldless method was attempted and achieved to reduce the cost significantly. The blades were achieved using a novel core made by 3D printing process and further enhanced through carbon fiber layup to provide extra load bearing on the skin surface (Fig. 20). The blades were structurally tested for thrust loads (the predominant loading direction for the blade) in the lab using dead weight and further checked for structural damage. Results showed the design prototype can withstand the required loading level with a safety factor of 3.

4.6 Control System Design of Tidal Turbine

The working principle of tidal energy conversion system (TECS) is to use the potential and kinetic energy of the ocean waves caused by the celestial lunar gravitation to drive the turbine that is coupled with a generator to produce electricity. However, due to the physical structure of the generator, the power output is closely related with water speed, direction, load amount, etc., which show highly non-linear characteristics. The water speed and direction of the tidal stream are closely related to the lunar cycle, which can be considered as deterministic factor. However, there are non-deterministic factors such as sea habitat migration, seaweed entanglement, bio-foiling, etc. that can make the power output sub-optimal. In order to extract the maximum potential of tidal power in terms of electricity, the maximum power point (MPP) needs to be monitored and tracked in real time. In the present study, the state-of-the-art MPP tracking (MPPT) of TECS such as optimal tip speed ratio (TSR) method, optimum relation based (ORB) method, and perturb and observe (P&O) method was utilized to control the tidal turbine system [14]. Based on the reviewed methods, the principles, advantages and limitations of the methods can be summarized to show the performance of MPPT based on P&O in TECS with simulated results.

The Turbine was assembled in the Lab for detailed alignment check and friction & noise study was performed by obtaining the frequency response characteristics. Further it was tested to mimic the real field condition through motor actuation (Fig. 21). The electric motor was driven at variable speed to emulate the different speeds of the turbine. A gearbox is necessary to multiply the torque of the electromotor (max torque 7.3 Nm) 4 $\times$ times so the PM-generator was put under nominal load. The generated AC-power (variable voltage) was put through the rectifier bridge to get a variable DC-power to the MPPT battery charger. The charger reduced & stabilized the DC-voltage to 24Vdc, while increasing the (battery charge) amperage. Since Power-in is equal to power-out and thereby the losses were found to be within 2% due to power converter. The batteries are charged as per selected pre-programmed set-point schedule.

4.7 Prototype Tidal Turbine Testing at Sentosa Tidal Site

The turbine design was elegant which could be easily assembled on a floating barge and was tested for a significant period at the Sentosa test site in Singapore. The parts shifted were assembled and slide on a guide way design mounted on the floating platform into the water towards testing for performance in the water for a period of one year (see Fig. 22).

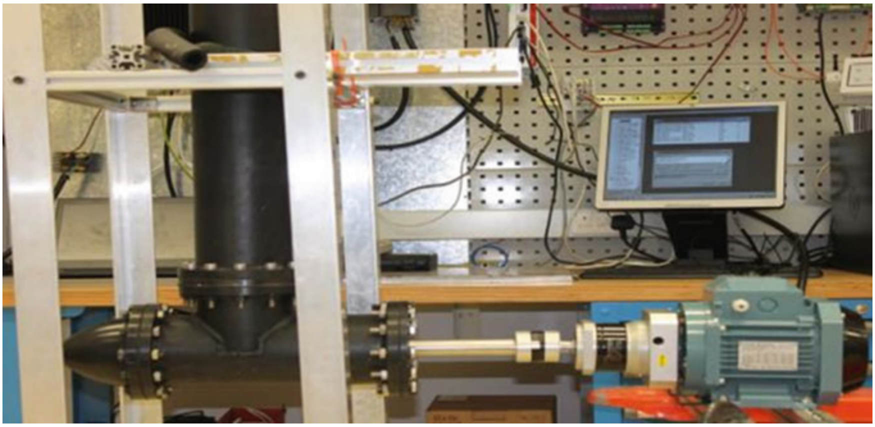

Fig. 21 Lab test of drivetrain system

(a) (b)

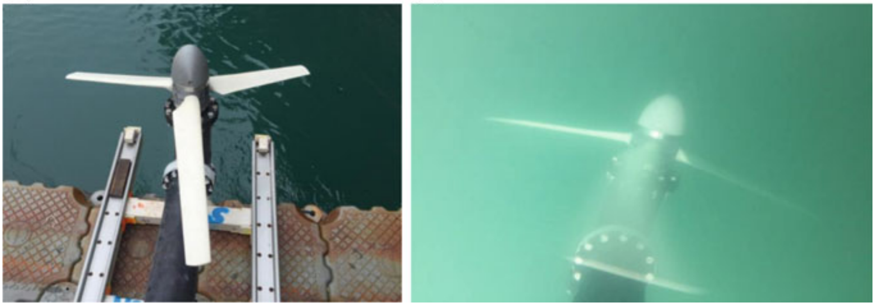

Fig. 22 **a** Tidal turbine ready for deployment, **b** successful deployment in Sentosa waters

4.8 Prediction of Stability of Floating Tidal Turbine Platform Under Towing Conditions

Tow tests were carried out as part of the development process to simulate and validate the behavior of the floating platform under expected operating conditions before deployment. The development of the dynamic model of the floating platform is based on the results of one such tow test that was carried out prior to deployment of the platform.

The dynamics simulation method was used to evaluate the stability of the floating tidal turbine platform. All forces are represented by coefficients, and the final loadings on each object is calculated using the Morison's approach. With the exception of the hull, the model of the floating platform was built within the software using regular geometric objects. The hull was imported as a custom object from a 3D modelling software. The turbine is represented by a disk, to which a drag coefficient equal to

Fig. 23 Illustration of tow setup in simulation model [7] and actual field test

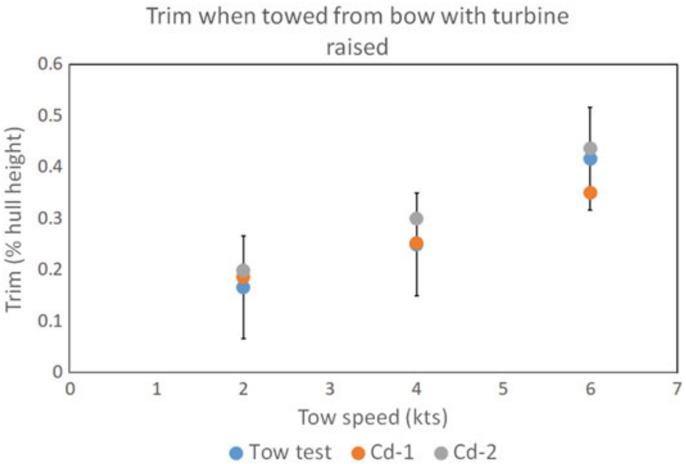

Fig. 24 Trim of model platform compared to tow test results for turbine-raised condition

the thrust coefficient of the actual turbine is applied. The features above the water line are ignored as the wind speeds were found to not be significant in this study. To simulate towing, one end of the tow line was fixed in space, with the other end of line being fixed to the floating platform. The water was then given a velocity to simulate the towing of the floating platform. This is illustrated in Fig. 23.

It is seen that the CG position of approximately 53% of the hull length from the stern produces the best match against the actual platform. Figure 24 shows the results under two drag coefficients tested, Cd-1 and Cd-2. Cd-2 is approximately 60% higher than Cd-1. Both drag coefficients are seen to produce good agreement with the results from the tow test. Cd-1 produced better agreement at tow speeds of 2 and 4 knots, while the Cd-2 produced better agreement at 6 knots.

The model can also be used to determine the maximum allowable wave height and period during towing operations. The model with the turbine raised was tested with 0.25 and 0.5 m wave heights and for wave periods of up to 15 s for flow speeds of 4 and 6 knots. This corresponds to the annual mean significant wave height and the 99% significant wave height found in Singapore. The model was also tested with

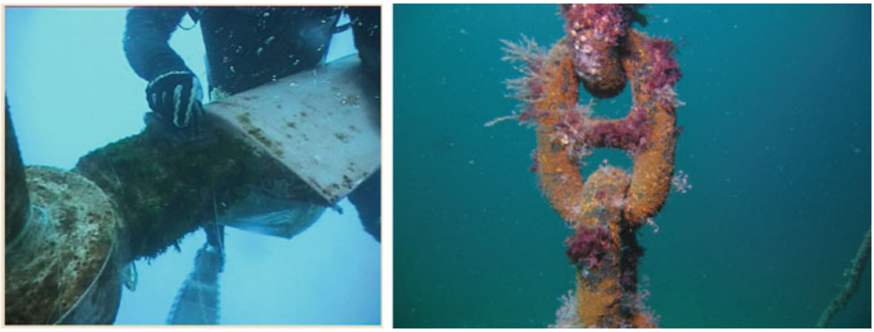

Fig. 25 Typical bio-fouling and corrosion in tropical waters

waves in the longitudinal and transverse direction with respect to the model. The 2nd order Stokes wave model was used. The minimum allowable wave period of each wave height was determined with the requirement that significant portions of the hull is not lifted out of the water at any time. The results show that the minimum allowable wave period is generally shorter in the transverse direction than in the longitudinal direction. This is because the platform is shorter in the transverse direction, leading to a shorter minimum allowable wavelength and hence smaller minimum allowable wave period. The minimum wave period is marginally shorter with slower flow speeds. The reason is likely because the shallower trim of the platform at lower flow speeds allows for higher additional pitching movements of the platform due to the wave action. The effect is expected to be more pronounced with higher tow speeds and larger wave heights.

4.9 Environmental Protection

Biofouling and corrosion are the key environmental challenges in tropical waters that can impart the operational efficiency of the tidal turbine (see Fig. 25). Accordingly, a systematic study of marine safe biofouling coating was studied using a dynamic test rig that tested the multi-functional coating in the turbid waters under the turbines and floating barges' operational velocities [15].

4.10 Fully Fabricated Floating Tidal Energy System

Tidal flow models help determine the best flow locations as explained in earlier Sect. 3.2, For example in the southern islands of Singapore, the flow velocity are good as shown in Fig. 8 which is suitable for such floating tidal turbine deployment. Acoustic Doppler Current Profilometers (ADCP) can be deployed to verify the pre-

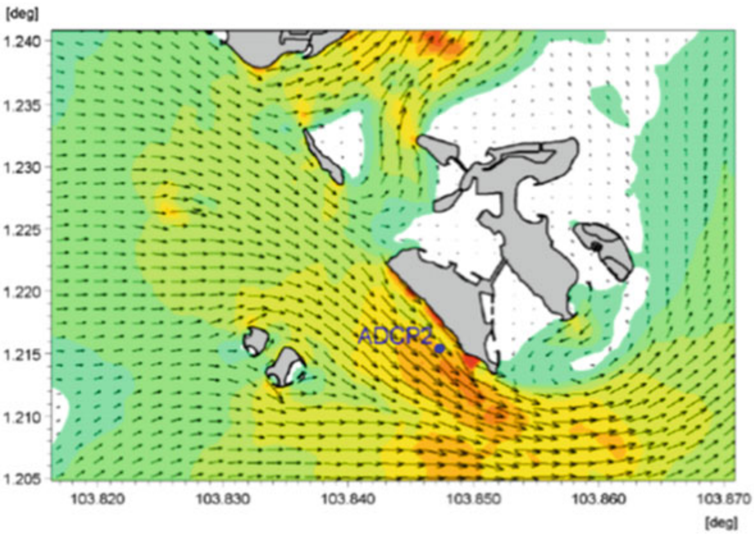

Fig. 26 Tidal flow around Southern Singapore island waters

dicted flow velocities. Using transect analysis the best flow velocity variations can be determined to finalized the optimum tidal rotor diameter. Using the micro-siting principles explained in Sect. 3.2.1, a detailed tidal flow study (see Fig. 26) was performed to identify the best location to deploy the floating tidal system and estimate the rotor size for best energy availability, capacity factor, relative levelized cost of energy and availability factor as explained in Fig. 13.

In the present study, the final floating tidal power platform is of a catamaran design and employed commercial tidal turbine with a rotor diameter of 4 m integrated to a generator that can provide a rated power of 62 kW. The reason being, as seen in Eq. (1) the power production is proportional to the rotor area and hence in low tidal flow conditions the design option is to use larger rotor diameter to compensate for the low velocity. However, in tropical coastal like Singapore waters the water depths are averagely up to 50 m and hence rotor diameters should be carefully sized based on high and low tides and estimates of regions with uniform flow velocities. In the present study the detailed tidal energy assessment was performed for Southern Singapore and the tidal energy density was found to be good in places near St. Johns island, Seringat, etc. as shown in Fig. 8.

Today the capital cost of the commercial small-scale tidal turbine is around 2800 USD/KW and is experiencing a steady cost reduction due to the industry's learning curve of up to 15% per year, as there is knowledge spillover from similar industry such as offshore wind & ship propeller industries.

Conventional ocean energy systems are subject to biofouling and corrosion that demands for regular maintenance. Performing maintenance in the ocean sites is costly than at dry dock conditions. Hence new generation systems are preferred to

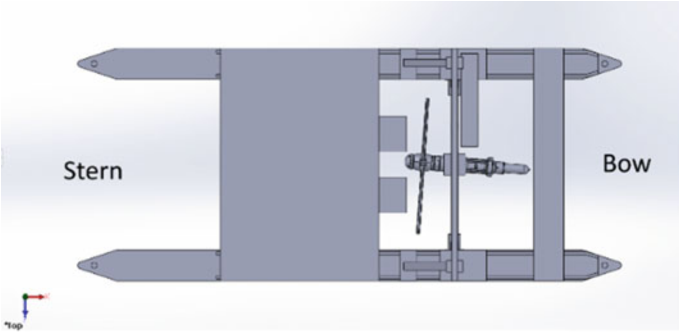

Fig. 27 Planform of floating tidal power platform

Fig. 28 Fully fabricated tidal energy system in Singapore

be floating systems so that it could be towed to any ocean site location and deployed with mooring supports. The mooring systems were designed towards minimal sway and pitching and yawing degrees of freedom [16]. The turbine was designed to be mounted on an A-frame, and the whole structure is capable to be lifted into and out of the water for maintenance using an electrical actuator such as winch and pulleys. Draft markings were painted at the bow and stern of the platform at intervals of 0.1 m, allowing the draft of the platform to be read. The planform of the platform is shown in Fig. 27. Figure 28 shows the fully fabricated floating barge system achieved in Singapore yards and was deployed for 6 months in Sentosa coastal waters to evaluate the stability performance and environment protection.

5 Floating Tidal Energy Concept

The above floating tidal energy system can be enhanced further for high energy harvesting capability per unit foot print by integrating a variety of matured renewable system such as floating solar, vertical axis wind turbine [17–19], wave energy converters [20, 21], ocean thermal gradient energy system [3], salinity gradient based energy system [3], e.t.c., as shown in Fig. 29, based on the ocean site's energy resource availability studies. For example, in sites such as Philippines, Indonesia

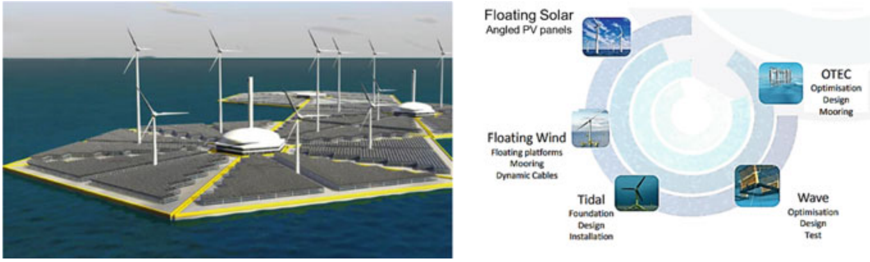

Fig. 29 Typical floating hybrid renewable system that integrates various renewable energy systems

and Malaysia there are sites with water depth beyond 1 km that offers ocean thermal energy gradient, tidal currents and wind loads which can be uniquely combined to offer high energy foot print in the floating renewable system. This concept helps to minimize the electrical and structural infrastructure to provide economic reduction in the capital cost and maximize energy availability. Further by deducing the static and dynamic forces in the specific ocean site on the proposed floating structure, the design life, stability and reliability of the floating renewable system and reliability can be evaluated by analyzing against fatigue and extreme loads from wind and wave energy as well as the environmental factors (like corrosion and biofouling) in the chosen site [16].

To evaluate the floating renewable energy system under natural disasters such as typhoons, hurricanes, and tsunamis detailed atmospheric boundary layer interfaced floating studies are being pursued. In reference [4, 22, 23] the tropical wind conditions from radiosonde sensors and LIDAR's are being studied and incorporated through a combination of DHI's MIKE software and WRF models [24].

5.1 Micro-Grid Design

The smart micro-grid is capable to combine multiple AC and DC type energy sources and store in multiple energy storage devices which includes, batteries, flywheel and compressed air energy storage. Each energy storage technology differs in its storage capacity and its charging and discharging speed and latency in reacting to external load and charging conditions. Through the smart grid architecture, the various renewable energy can be combined on the floating platform and controlled individually and at system level through artificial intelligence supported control systems.

To demonstrate this concept a smart nano-level grid study was conducted in Tuas Singapore to study the grid architecture of combining multiple AC and DC energy sources towards AC loads of a workers quarters (Fig. 30). The solar PV and wind turbine were directly connected to the 48 V DC bus via DC–DC converters. This demonstration of the nano-grid solution utilized wind and solar hybrid energy generation due to their AC and DC energy characteristics and was combined with Fuel

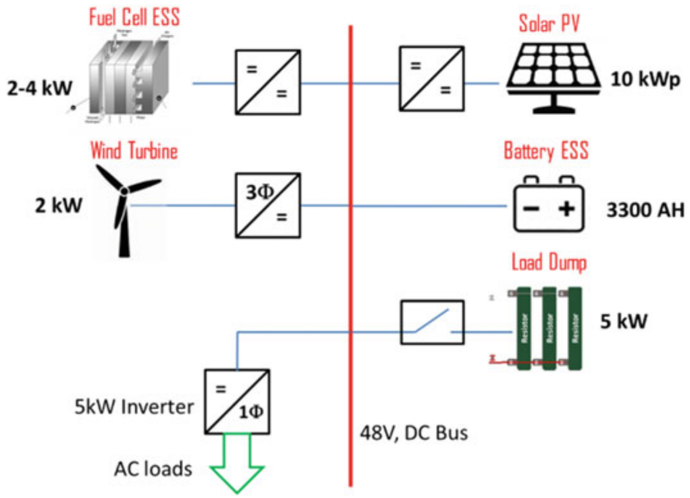

Fig. 30 Smart Nano grid architecture studied in Tuas Singapore towards combining AC and DC energy sources and support AC electrical loads

Cell storage and Battery based energy storage system (BESS). The fuel cell system was of 3–5 kW with one high pressure electrolyser, along with a hydrogen storage. The energy storage systems (Fuel cell and battery) were connected to the DC bus via bi-directional converters as electricity was flowing in and out of the energy storage systems. A load dump was incorporated into the power system to provide to burn out excess energy and as a means to protect battery against overcharging. The electrical loads (single phase) were connected to the DC–AC inverter. Upon commissioning the system was setup to power local loads of the temporary worker quarters such as street lights, fridge and water heater. Further the project focused in demonstrating novel inverters and a nano-grid controller. A supervisory control system was incorporated in the project to the power system along with the energy storage system [14].

To enhance the certainty and reliability of power production machine learning based energy Forecasting methods was utilized [16, 25–27]. The author and other team members have utilized a variety of machine learning techniques to predict wind, wave and tidal energy sources and have found its capability to predict the sharp ramp in energy variations and the intermittencies [16, 25–27]. The capability to forecast helps to implement a feed forward control schema to the individual energy generation system.

Recently a survey was done in Southeast Asia to understand the energy availability in remote coastal and island region and how ocean based renewable energy sources can support the livelihood of the people [28, 29]. The survey focused also to understand the barriers to renewable energy adoption in these remote sites, which included the techno-economic challenges, the lack of understanding in terms of renewable energy resources available in southeast Asian remote coastal locations, lack of skilled personal, environmental interactions such as doubts in terms of underwater noise from ocean energy systems on the nearby fish farms and other sensitive marine industries [28]. In reference [29] it was clearly shown that Ocean based renewable sources are capable to power remote islands and coastal locations. Presently efforts are in progress to study the environmental impacts of the floating renewable system on the marine ecology to ensure there is minimal impact on the marine mammals and fishes.

The present study has shown that the systematic development of the floating hybrid renewable energy system can exploit the presence of various renewable energy sources in a given ocean site. This can be achieved through the advancements in smart grid science to combine various relevant ocean energy systems towards an ocean site and powered through novel controls that are supported with machine learning methods to overcome the inherent intermittencies of renewable energy sources to assure quality power with high certainty.

6 Conclusion

Blue economic growth is seen as a promising strategy to utilize the ocean resources towards economic growth without exploiting the ecology through setting up various marine industries including deep sea fishing, seabed mining, maritime transport, desalination. Development of floating homes and cities will be a key industry in this Blue Economy and Growth strategy as it addresses the imminent need for solutions towards sea level rise effects on inundation zones' coastal dwelling. In any such remote coastal location, multiple energy sources exists viz., solar, tidal and wave energy sources which can displace the use of fossil fuel and can ensure the pristine marine ecology through effective use of renewables. Remote coastal site has challenges of less available skilled people and hence the idea of floating renewables with modular design helps easy means to bring the system to main land for dry-dock conditions and achieve necessary repair and maintenance at least cost and necessary quality.

In this paper the concept of hybrid energy system is proposed that could be housed in a floating platform system and integrated with smart grid and energy forecasting and energy storage methods to become a smart power system in a marine condition. This will ensure credible power supply to marine industrial use and floating homes in any remote coastal sites with high energy availability and support essential human needs such as electrical, water, air conditioning and other energy requirements towards marine operations. The floating power plant will ensure necessary energy resilience and electricity and water security towards a floating home or a floating cities through a uniquely combination of all available energy resources at an ocean site.

This paper also shared how the field based seabed and coastal bathymetry surveys could be uniquely combined with tidal current & wave measurements through simulation to perform energy resource assessment, and assess structural integrity through hydrodynamics, fluid-structure interaction studies of these floating energy systems and load studies under real ocean conditions. In addition, through detailed resource mapping and device performance studies the best site locations can be identified for the ocean device deployment to achieve optimum levelized cost of energy, maximum availability and maximum capacity factor. Thus this paper has elucidated that the hybrid floating energy system can be a viable power plant towards tropical coastal and island regions to support remote floating homes' energy needs through clean energy solutions with greater certainty and power quality.

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