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System Performance Characteristics of Darrieus Turbine with Tilted Blades in Current and Wave Conditions

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Abstract

Indonesia has abundant sources of renewable energy from ocean currents and waves, or a mixture of currents and waves at certain times to be used as an energy source for power plants. So at the Indonesian Hydrodynamics Laboratory, a study has been carried out to determine the performance of the Darrieus-type vertical axis turbine model to utilize the energy of ocean currents and waves. But the Darrieus Turbine with the turbine blades positioned perpendicular to the turbine axis cannot rotate if there is only wave force. Then several turbine models were made with the placement of the blades in an inclined position, to produce optimal rotor rotation in current conditions or a mixture of currents and waves. This paper describes the testing of 3 turbine models by varying the angle of inclination of the turbine blades (45°, 60°, and 75°), but still having the same turbine rotor area and giving different input currents and wave periods to produce the best efficiency and rotation in absorb current energy or a mixture of current and wave energy. The test results show that the 3 models of slanted blade turbines can absorb both wave and current energy, but turbines with 75° blade inclination produce the best performance compared to the others when exposed to currents and waves.

1. Introduction

Indonesia is an archipelagic country with abundant marine energy sources to be used as power plants as green energy in one of Indonesia's net zero emission (NZE) efforts until 2050 [1]. So that Indonesia has a very large need for ocean current power generation technology to be utilized immediately due to a government policy committed to achieving the NZE which must be implemented in Indonesia. However, Ocean Renewable Energy (ORE) is a relatively new and underutilized source of renewable energy that has a lot of potential to reduce carbon emissions from burning fossil fuels and help with global climate change [2]. Even the Center for Data and Information Technology for Energy and Mineral Resources (CDI-ESDM) states that until 2022 there will be no electricity generation from currents or ocean waves in Indonesia [3].

But the study of the conversion of renewable energy from the ocean has progressed rapidly. Among them is energy conversion technology for circulation/movement of sea water. There are two types of seawater movement. The first is the motion of ocean currents caused by the tides due to the interaction of gravitational forces between the earth, the moon and the sun. The second is sea waves, where the water surface experiences ups and downs caused by wind blowing on the sea surface due to weather changes. Technological developments to capture the two types of seawater movement run separately, where the technologies are different [4]. Where the capture of the two energies requires different technology and research. For example, to capture the movement of energy from waves, a wave turbine is used by changing the wave motion which always moves back and forth in two directions in one wave period, which lasts in seconds. The turbines used are usually well turbines of the oscillating water column type, both on the beach and floating in the middle of the sea, floating turbines of the heave rider or wave rider type, or pendulum type turbines [4,5], and to capture energy from ocean currents using a device in the form of vertical turbines [6,7] and horizontal turbines [8] which are installed by means of being driven or moored at sea. However, there is also research similar to this research, only the specimen model is different, namely regarding the Hybrid Wave and Current Energy Converter (HWCEC) design, which is used to extract energy from ocean waves and currents simultaneously by combining the absorber point and horizontal turbine axis into a single unit [9].

But the weakness of this tidal turbine (vertical axis type Darrieus turbine) is that it cannot rotate due to wave forces because the position of the turbine rotor is perpendicular to the turbine axis [10]. In several cases, previous research has shown that using straight blades, the Darrieus Turbine (90°) can absorb the energy of ocean currents well, but the turbine cannot rotate if there is only wave energy because the turbine blades cannot absorb pure ocean wave energy [10,11]. Based on this problem, a change in the angle of the vertical type turbine blade is made in an inclined position which can produce optimal rotor rotation and can rotate in the presence of only wave energy or the presence of a mixture of current and sea wave energy. The Indonesian Hydrodynamics Laboratory's study of the wave current rotor design has also been installed under the Suramadu Bridge in the Madura Strait which shows that the wave period affects the rotation of the turbine and it is hoped that the tilted blade vertical axis Darrieus turbine can also be used in various straits in Indonesia which have weak ocean currents but usually the sea is choppy [12].

This paper discusses a vertical axis Darrieus type turbine with angled blades of 45°, 60°, and 75° which are designed to increase the ability to absorb kinetic energy of ocean currents and simultaneously absorb potential energy of waves by testing methods in Indonesian Hydrodynamics laboratory water tanks. The 3 fixed tilt blade turbine models have the same turbine rotor area and are given different input currents and wave periods. Furthermore, measurement of rotation, torque, and power generated. Giving water currents between 0.5-1 m/s and water wave heights of 0.15 meters with variations in wave periods ranging from 1.2-2.5 seconds. The concept proposed in this study is based on the basic operating principle of a helical blade turbine. However, it is simplified by using a tilted blade turbine to capture wave and current energy. The direct turbine blade forms an angle from the upper arm position to the lower arm position and has a certain angle. The Darrieus turbine in theory seeks to spread the hydrodynamic load evenly at every point. On the other hand, angled blades have the advantage of a simpler shape, making them easier to manufacture. With the use of a vertical Darrieus turbine with angled blades, it is possible to absorb both of these energies.

The difference between this research and research [10] is about the design related to the construction of a turbine model using a combination of Wells Rotor and Darrieus Turbine to absorb mixed or single ocean currents and waves, where in that model there are six turbine blades in horizontal position (Wells rotor type) and three Darrieus turbine blades to rotate the main shaft in a vertical position and the rotation of the turbine rotor is connected to a gearbox to a generator so that electricity can be generated, and the difference between this study and research on patents [13] is that the design of the turbine is held by three upper radial arms placed on the rotor, and the vertical turbine blades are connected by radial arms so that the rotor can rotate when exposed to waves. And there is also a difference in previous research on patents [14] which shows the design of a combination of tilted blade Darrieus turbines and wells turbines where in that model there are three turbine blades in a horizontal position (Wells turbine type) and three inclined blades Darrieus turbines to rotate the main shaft to reduce turbine projection area. Several experimental studies have improved the ability of vertical axis turbines to self-start by incorporating wells, Darrieus, or Savonius type turbines [10,15,16]. However, this research only uses the vertical axis Darrieus turbine by providing variations of wave and current periods to be able to drive the turbine because the Darrieus turbine has a performance coefficient that is good enough to be able to rotate with angle angle modifications. While the difference between the turbine model in this study and the research above is in the design which only has 3 vertical Darrieus turbine blades where the blades are set at an angle of 45°, 60°, and 75° and in the research system using a laboratory scale testing system. Vertical axis turbines whose blades are tilted can harvest energy taken from water waves when the force is equal to or exceeds the mass load of the turbine so that the turbine can start rotating itself with good rotational ability in the shortest wave time needed to produce energy [17].

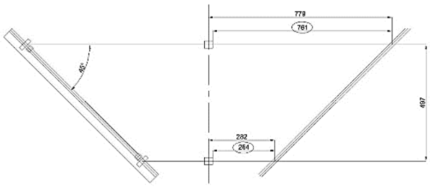
With the background previously mentioned, this study aims to analyze the ability of 3 vertical axis Darrieus type turbine models which are designed to see the ability to absorb the kinetic energy of ocean currents as well as absorb potential wave energy properly, and to obtain one turbine model that produces efficiency and the best rotation and produce the greatest power. The test results show that a turbine with a rotor angle of 75° produces the best performance in absorbing current energy and wave energy. And the benefit of this research is that research can be further developed and further utilized on small islands in Indonesia which have straits with current and wave energy for independent sources of electrical energy, because in the small Indonesian Archipelago there is not necessarily only current or ocean waves alone can have energy for both, and can also be used as a way to realize a green economy with sustainable energy sources and to increase the development of national renewable energy by 37.8% in 2050 and this plan also specifically designs the stages of power plant development marine renewable energy in various small Indonesian archipelago areas that have good wave and current energy potential [18].

2. Model Test Method

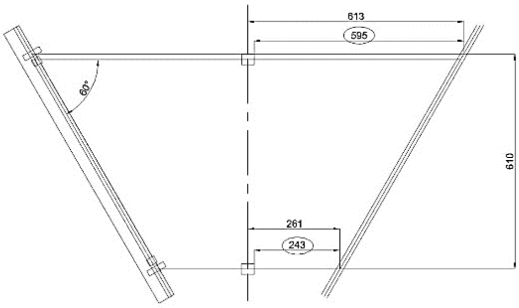
Section 2 describes the experimental method, including the turbine model, test setup, calibration, and gauge validation. The turbine model is made of 3 pieces with 3 differences in the installation of blade angles, namely angles of 45°, 60°, and 75°, which absorb wave energy and energy of ocean currents. Furthermore, the installation of the 3 models was placed in the model tank test at MOB with the model installation method using belay on a sub carriage so that the fixed model does not move even though it is exposed to waves and currents. However, the turbine rotor will absorb the current and wave forces to rotate properly.

2.1. Turbine Models

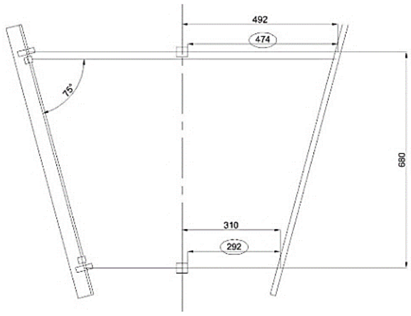
The turbine model was selected based on reference [10]. Using turbine blades of the NACA 0021 type which were initially installed symmetrically vertically, because they could not rotate when given a wave of water, a change was made to the installation of turbine blades with angles of 45°, 60° and 75°. The design of the model is in accordance with Figure 2(a), 2(b), 2(c), by changing the Darrieus turbine blade from a straight blade to an angled blade to be able to absorb wave energy in addition to absorbing ocean current energy.



(a)



(b)



(c)

Figure 1. Schematic design of vertical axis Darrieus turbine model with (a) 45° blade angle, (b) 60° blade angle, and (C) 75° blade angle.

So in this study a schematic model was made according to Figures 1(a), 1(b), 1(c), and the finished results of the model were as shown in Figures 2(a), 2(b), 2(c), with changing the blades from the straight blades of the Darrieus turbine to blades angled at 45°, 60°, and 75° to better accept wave energy in addition to the energy of ocean currents. Table 1. describes the blade angle due to the difference between the top and bottom diameters when installed with three different turbine angle variations but with a fixed area. For blade installation with an angle of 45° in Figure 2(a) there will be a difference in the top diameter of 1824 mm and a bottom diameter of 438 mm, for installation of a blade with an angle of 60° in Figure 2(b) there will be a difference in the top diameter of 1413 mm with a bottom diameter of 433 mm , and mounting the blade at an angle of 75° in Figure 2(c) will have a difference in the top diameter of 1081 mm and the bottom diameter of 573 mm. Although in the 3 pictures of the model it can be seen that there are differences in the diameter of the lower turbine arm and the diameter of the upper turbine arm, the area of the 3 variations of the turbine model remains the same.

Table 1. Specification of the model turbine

Parameters	**Specifications**		
Angle Blade	45°	60°	75°
Number of blades (N1)	3	3	3
Chord length (C)	83 mm	83 mm	83 mm
Blade span (S)	980 mm	980 mm	980 mm
Foil type NACA	0021	0021	0021
Area (A)	784000 mm	784000 mm	784000 mm
Turbine diameter (D1) Up	1824 mm	1413 mm	1081 mm
Turbine diameter (D2) Down	438 mm	433 mm	573 mm
Number of arms (N2)	6	6	6
Shaft diameter (d)	50 mm	50 mm	50 mm

(a)

(b)

(c)

Figure 2. Vertical axis Darrieus turbine model with (a) 45° blade angle, (b) 60° blade angle, (C) 75° blade angle.

In Figure 2(a), 2(b), 2(c), you can see 3 turbine models whose assembly process uses a nut and bolt knock down system which is useful in the disassembly process in testing in the test pool and in the maintenance process, where to connect the 3 blades with a radial arm using a bolt system on each side of the blade with a radial arm up and down, the Radial arm is made of ½' diameter galvanized pipe, and at each end it is connected with AS SS40 steel with a diameter of 40 mm by machining and welding processes and finishing with painting . The radial arm is divided into two, namely 3 pieces at the top to support the upper 3 blades of the Darrieus turbine and 3 pieces at the bottom to support the 3 blades of the lower Darrieus turbine. And each upper and lower radial arm that supports the blade is connected to the turbine shaft using a bolt system with a hub. The hub is the fulcrum of the radial arm which connects to the turbine shaft. The hub is made of 2 Teflon materials, including the upper hub which is used as a support for the 3 upper radial arms of the turbine, while the lower part is used as a support for the lower radial arm of the turbine. while the turbine shaft to be able to rotate properly, the lower and upper parts of the shaft are given bearings which are supported by iron plates of the turbine housing so as to reduce the frictional resistance force. The upper shaft bearing uses 2 types of ball bearings with an inner diameter of 50 mm and an outer diameter of 70 mm and for the lower shaft it uses a Conical Roller Bearing with an inner diameter of 50 mm and an outer diameter of 70 mm. Hollow steel pipe type turbine shaft, made of 50 diameter pipe with a total length of 1400 mm. With the process of machining and finishing with painting. Home Construction of the turbine support frame which is used to support three vertical axis Darrieus turbine models, made of 40 x 40 x 4 steel ST 41 elbow profiles with joints through a welding process, and for finishing equipment made of iron is done by painting to resist the corrosion process [19] and also makes it easier in the process of treating the mechanical part, because the turbine model will be submerged in water.

2.2. Test setup

Turbine testing was carried out in the Maneuvering Ocean and Engineering Basin (MOB) wave test tank with dimensions of 60 x 35 x 2.5 meters for length, width, and depth, respectively. The test pond has wave generator equipment to generate regular waves (regular waves) and wave absorbers to dampen reflected waves. Figure 3. The MOB wave test tank at the Indonesian Hydrodynamics Laboratory (IHL) was used for testing 3 vertical axes of Darrieus turbine models with tilted turbine blades. Drawings of the MOB facility include a wave generator, carriage, and sub-carriage with the characteristics listed in Table 2. To achieve consistent wave height and period and to avoid reflected waves, the Darrieus Turbine is installed in Figure 4. under the sub-carriage, facing perpendicularly at a distance of 5 m to the wave generator.

Table 2. Specification of the MOB wave tank

Parameters	Specifications
Deep part	60 x 35 m, maximum water depth 2.5 m
Shallow part	45 x 35 m, maximum depth 1.25 m
Main Carriage	Maximum Accelaration 0.8 m/sec Maximum Speed 2.00 m/sec
Sub Carriage	Maximum Accelaration 0.8 m/sec Maximum Speed 2.00 m/sec
Wave Generator Capacity	Regular and irregular waves Wave period 0.5 - 3 sec Wave height up to 0.3 m (significant)
Wave Maker	Single wave board type consists of 72 pieces Electric motor driven Simultaneously control of electric motor and frequency by computer

Figure 3. MOB facilities: water tank with wave generator, carriages, and sub carriages.

Figure 4. Turbine model settings in the sub-carriage at the MOB facility.

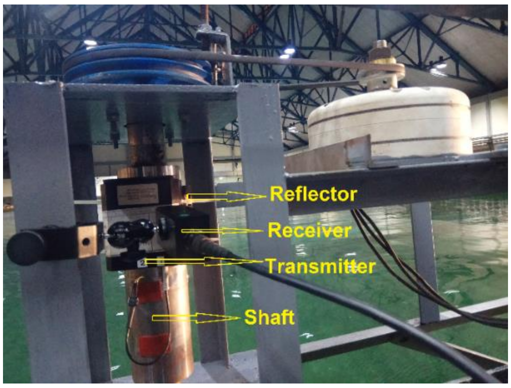


Figure 5. Installation of measuring devices on turbine shafts at sub-carriage MOB facilities.

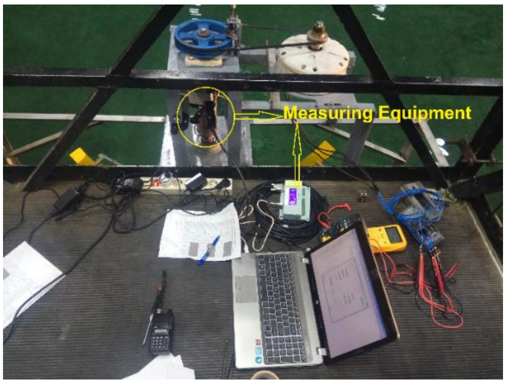


Figure 6. Installation of measuring equipment power shaft datum series 430-compact on computer

Figure 5 displays the installation of a strain gauge and a rotation reflector (rpm) to measure the torque and output power of the Darrieus turbine shaft. A revolving Darrieus turbine shaft is subjected to measurement using the power shaft apparatus in Figure 6. The equipment system uses a strain gauge sensor element to measure the shaft's torsional torque. The transmitter, which doubles as a strain gauge amplifier, transmits the strain gauges' output voltage to the receiver. The receiver serves as a shaft rotational speed sensor as well. The Data User Interface (DUI) tool processes torque and rotational speed data from the receiver to produce the power value. Torque, rotational speed, and power values can be shown and recorded using the DUI, or these three parameters can be sent to a computer for display and recording.

2.3. Calibration and validation of measuring equipment

In generating waves, the wave generator in the MOB test tank is set in such a way by moving the flap wave maker in various variations of frequency and stroke length so that the desired wave spectrum is obtained, namely with a wave height of 0.15 meters and a wave period of 1.2 – 2.8 seconds for testing 3 models Darrieus vertical axis turbine with tilted blade angle. The wave generator is monitored using a wave height sensor and equipment in the MOB facility to support this experiment. The power shaft meter is another measurement tool used in this study to calculate the turbine's rpm, torque, and output power. Calibration data is included to guarantee the functionality of each sensor and its parts [17]. Because this study aims to analyze torque, power production, and turbine shaft rotation, the measured data includes turbine rotation and wave formation in the wave test tank. Other research [15,20] further measured torque or power output to account for performance effects.

The equipment for measuring torque, rotation, and power shafts uses the 430 series datum, which displays on a computer, as shown in Figure 6. The specifications are shown in Table 3. The power shaft meter is a hardware package and includes the DUI Config Software power shaft datum 430-series compact on the turbine. DUI Config Software is used on the computer to input the voltage calibration factor generated by the strain gauge into the torque values of DUI Instruments and to display and store torque, rotational speed, and power data sent from DUI instruments.

Figure 7 shows a measurement view of the power shaft meter, where turbine speed, torque, and power output are three variables displayed on a computer screen. It is possible to simultaneously monitor all of the collected data. The numbers are then averaged once the data has been retrieved steadily. The strain gauge sensor may be calibrated to measure the output and torque of the turbine. The tachometer and strain gauge simulator are used as calibrators. With a Full-Scale Torque of 1000 Nm and Full-Scale Strain of 0.105847802 mV/V, Figure 8. illustrates calibration data for the strain gauge on the Darrieus turbine shaft. It can be observed that raising the torque (Nm) will significantly increase the output signal in the strain gauge mV/V with linear. The rpm meter, combined with the shaft meter sensor, monitors turbine rotation.

Figure 7. An example of a measurement display from a Power shaft meter

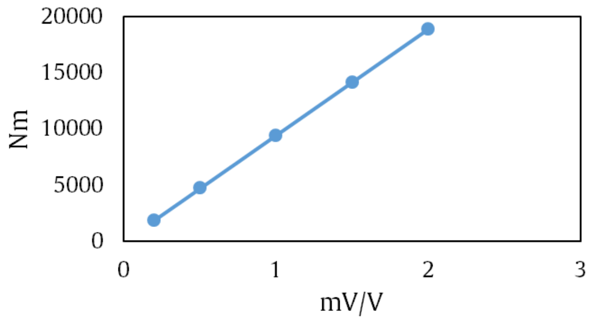


Figure 8. Calibrate the value of strain gage (torque) with input from the strain gauge simulator

Shaft OD	88	mm
Shaft ID	42	mm
Max Expected Torque	1,000	Nm
Tool Steel	ST37	
Youngs Modulus	2.00E+11	
Poisson Ratio	0.285	
Gauge Factor	2.09	
OD	0.088 M	
ID	0.042 M	
T*16000*GF*(1+PR)*OD	3.78E+06	
T*16000*GF*(1+PR)*ID	1.80E+06	
((OD^4)-(ID^4))*π*YM	3.57E+07	
Calibration Value	0.106	mV/V

Figure 9. Determining the calibration factor for the torque value on the turbine shaft.

In Figure 9, the turbine shaft calibration value from the voltage generated by the strain gauge to the torque value is 2.09. The cell calibration value is filled with a value according to the diameter of the turbine shaft whose torque is measured, the estimated maximum torque, and the strain gauge measurement factor value used. The basic theory to calculate the value of Torque (T) in Nm and Shaft speed (ω mech) in radians/second is :

$$\text{"Pmech} = T * \omega \ \text{mech"} \quad (1)$$

3. Results and Discussion

3.1. Experiment 3 Variation of the ability of a tilt blade turbine with water currents

Experimental studies of 3 oblique blade Darrieus turbine models with a tensile test using a carriage to imply the presence of water flow were carried out in the MOB test pond, one of the Indonesian Hydrodynamics Laboratories, Surabaya. This study aims to determine the effect of rotation, torque, and output power of the Darrieus turbine shaft on changes in the angle of the turbine blades by providing several variations of current flow velocity. By going through the turbine's tensile test with the carriage. The testing process for three variations of the 45°, 60°, and 75° Turbine models is carried out one by one by giving a current of 0.5 – 0.9 m/s; the overall test setting system is the same. Namely, the turbine model is inserted into the pool water until the upper turbine blade limit is submerged.

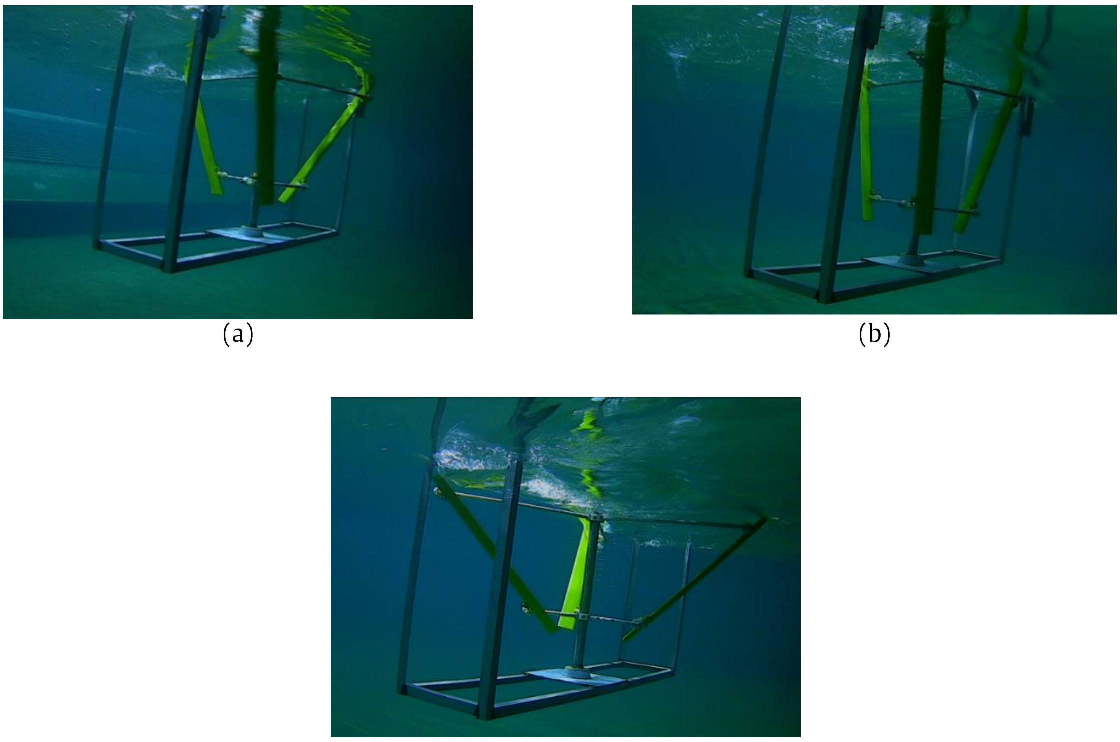

(a) (b) (c)

Figure 10. Testing the Darrieus turbine model with water currents with (a) a vertical axis blade angle of 60°, (b) vertical axis blade angle of 75°, (c) vertical axis blade angle of 45°

In Figure 10. This is a Darrieus turbine test with (a). a blade angle of 60°, (b). with a blade angle of 75°, and (c). a 45° blade angle. The video was recorded using an underwater camera with variations in water currents between 0.5-0.9 m/s and a depth of 2 meters. In this experiment, changing the conditions of the three turbine blade angle variations from 45° to 60° and from 60° to 75° was only carried out by replacing the three radial arms of the upper turbine and the three radial arms of the lower turbine. Model replacement with different angles is carried out after the completion of testing with current in one variation of the tilt turbine blade model testing has all been completed. In the test results with the current on the turbine blades tilted 45°, 60°, and 75° in Table 3. with current variations of 0.5 m/s, 0.7 m/s, 0.9 m/s, 1m/s have produced rotation, torque, and the output power of the turbine shaft where the increase in current will increase overall rotation and torque and turbine power.

Table 3. Test results for 3 models of blade angle Darrieus turbines with variations in water current

Turbine blade position	Carriage speed / current (m/s)	Rotation speed (rpm)	Torque (Nm)	Power (Watt)
Blade angle 45°	0	0	0	0
	0.5	12	4.521	5.681
	0.7	16	6.027	10.099
	0.9	28	10.548	30.928
	1	34	12.808	45.603
Blade angle 60°	0	0	0	0
	0.5	32	12.055	40.396
	0.7	43	16.198	72.941
	0.9	52	19.589	106.670
	1	57	21.472	128.169
Blade angle 75°	0	0	0	0
	0.5	50	18.835	98.622
	0.7	81	30.513	258.824
	0.9	128	48.219	646.329
	1	138	51.986	751.263

However, when viewed in detail through Table 3 and Figure 11. Regarding the relationship between the current and rotation of the 3 turbine models, it can be seen that an increase in current speed will further increase the turbine rotation, especially a turbine with an angle of 75° of the inclined blade, which has the highest rotation of 2 other turbine models. Research [16] showed that there were tests of a vertical Darrieus turbine and a hybrid turbine which linearly produced more rotation as the speed of the water flow increased, only in study was the Darrieus Turbine, given water currents ranging from 0.3 m/s to 0.7 m/s. Where is in this study, the beginning of the provision of water flow to rotate the Darrieus turbine at a speed of 0.5 to 1 m/s. However, this study [15] shows that there is a perception equation with this research about increasing turbine rotation along with increasing current speed by showing an increase in rotation of 3 turbines even though starting at a current speed of 0.5 m/s and being able to increase turbine rotation as the current increases can be seen in Figure 11.

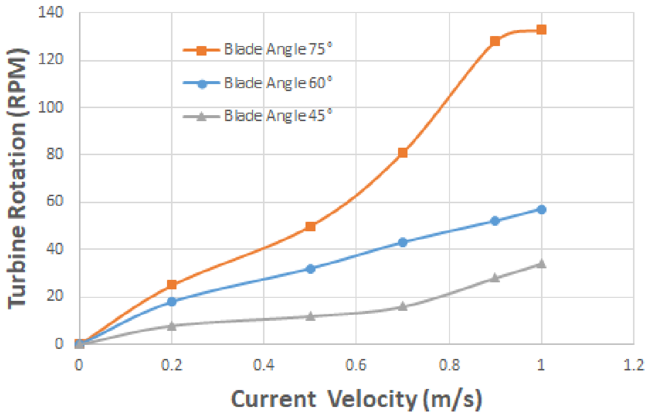


Figure 11. Correlation of current velocity with rotation turbine

To show the correlation between the tip speed ratio (TSR) of the turbine and the increase in the water currents seen in Figure 12. The TSR is the ratio between the tip speed of the rotor and the actual current speed (V).

$$TSR = (\omega * R)/V \quad (2)$$

With:

$$\omega = 2\pi\ n/60 \quad (3)$$

TSR has an intense connection with efficiency by optimizing the blade design. A higher TSR will increase vibration, generating noise and requiring a tougher blade to cope with the high centrifugal force. The TSR at a certain current speed is tried to be as high as possible because the turbine can produce more power due to the greater rotation of the shaft. However, this requires a more robust turbine system design so that it is not damaged in Figures 12 and 13. can see a similar trend of increasing TSR with increasing current speed (m/s) and turbine rotation (RPM), only in 2 turbines with blade angles of 60° and 75° there a decrease in TSR after the current speed was more than 0.9 m/s, but it can be concluded that the highest TSR is in a turbine with a blade angle of 75°. However, there is a decrease in TSR above 1 m/s, the decrease in TSR is not significant compared to other turbines.

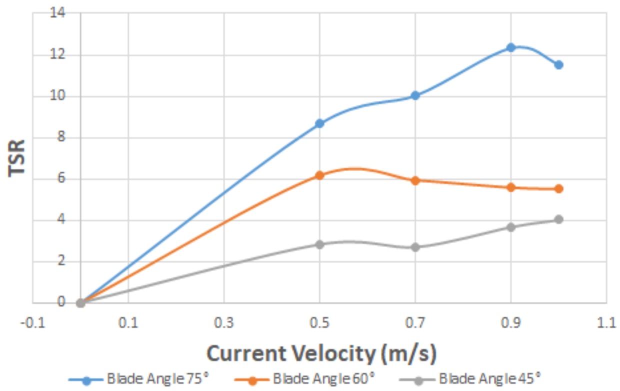


Figure 12. Correlation of current velocity with TSR turbine

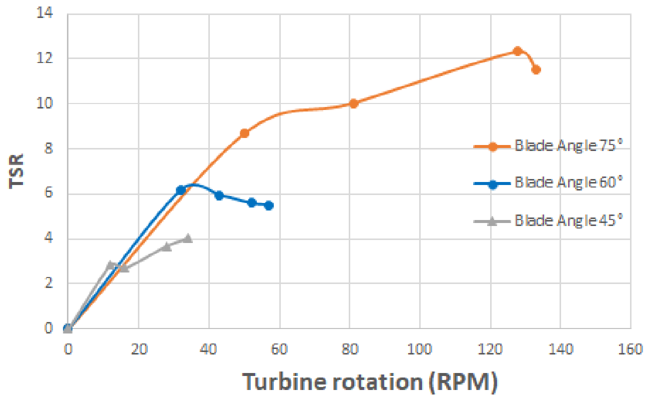
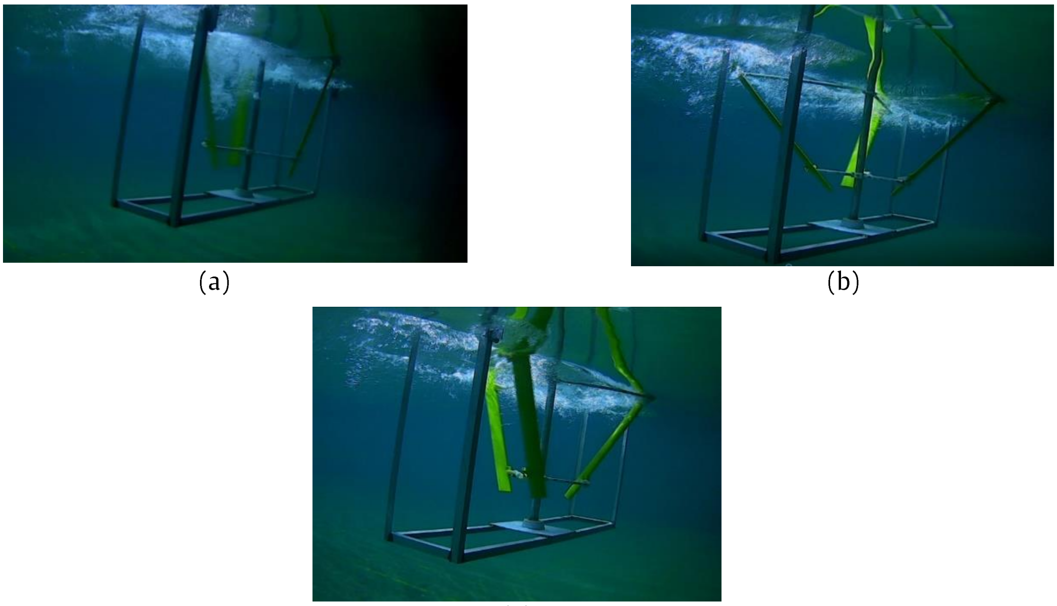


Figure 13. Correlation of turbine rotation with TSR turbine

3.2. Experiment 3 Darrieus turbine with tilted blade variations using Current and Wave

Next is the experiment of 3 inclined-blade Darrieus turbines with a tensile test using a carriage to imply the presence of water flow and the generation of regular waves. This was also carried out in the MOB test pond. This study aims to determine the change in the angle of the turbine blades to the rotation, torque, and output power of the Darrieus turbine shaft by providing several variations of current with the addition of waves. The testing process for three variations of the Turbine model 45°, 60°, and 75° is carried out one by one, the same as the test, by giving current only, with the overall test setting system being the same; namely, the turbine model is inserted into the pool water, only at 15 cm around the turbine blade not submerged in water.



(a) (b) (c)

Figure 14. Testing the Darrieus turbine model with water currents and wave with (a) vertical axis blade angle of 75°, (b) vertical axis blade angle of 45°, (c) vertical axis blade angle of 60°

Figure 14. shows the vertical axis of Darrieus turbine testing with: (a). blade angle 75°, and (b). blade angle of 45°, and (c). blade angle 75°. Documentation using an underwater video camera with a wave height generation variation of 0.15 m and a period variation of 1.2 - 2.5 seconds. In this experiment, the replacement of the test model of the three turbine blade angle variations from 45° to 60° and from 60° to 75° was only carried out by replacing the three radial arms of the upper turbine and the three radial arms of the lower turbine. The replacement of the turbine model in the test will be adjusted after each completion of one test variation of the inclined turbine blade model.

Table 4. Response of the vertical axis Darrieus turbine model to variations in wave and current periods with (a) 45° blade angle, (b) 60° blade angle, and (c) 75° blade angle.

Turbine testing	Carriage speed / current (m/s)	Wave period with wave high 0.15 m	Rotation speed (rpm)	Torque (Nm)	Power (Watt)
Blade angle 45°	0.5	1.2	12	2.4	3
		1.5	22	4.4	10
		1.8	23	5.2	14
		2	25	4.6	11
		2.3	29	4.0	8
		2.5	32	3.6	7
	0.7	1.2	15	3.0	5
		1.5	23	4.6	11
		1.8	32	6.4	21
		2	37	7.4	29
		2.3	29	5.8	18
		2.5	25	5.0	13
	0.9	1.2	32	6.4	21
		1.5	40	8.0	34
		1.8	48	9.6	48
		2	42	8.4	37
		2.3	38	7.6	30
		2.5	35	7.0	26

(a)

Turbine testing	Carriage speed / current (m/s)	Wave period with wave high 0.15 m	Rotation speed (rpm)	Torque (Nm)	Power (Watt)
Blade angle 60°	0.5	1.2	18	3.6	7
		1.5	24	4.8	12
		1.8	30	6.0	19
		2	50	10.0	52
		2.3	44	8.8	41
		2.5	40	8.0	34
	0.7	1.2	49	9.8	50
		1.5	60	12.0	75
		1.8	68	13.6	97
		2	62	12.4	81
		2.3	56	11.2	66
		2.5	50	10.0	52
	0.9	1.2	60	12.0	75
		1.5	73	14.6	112
		1.8	80	16.0	134
		2	74	14.8	115
		2.3	67	13.4	94
		2.5	58	11.6	70

(b)

Turbine testing	Carriage speed / current (m/s)	Wave period with wave high 0.15 m	Rotation speed (rpm)	Torque (Nm)	Power (Watt)
Blade angle 75°	0.5	1.2	44	8.8	41
		1.5	56	11.2	66
		1.8	67	13.4	94
		2	62	12.4	81
		2.3	56	11.2	66
		2.5	50	10.0	52
	0.7	1.2	45	9.0	42
		1.5	73	14.6	112
		1.8	81	16.2	137
		2	78	15.6	127
		2.3	74	14.8	115
		2.5	70	14.0	103
	0.9	1.2	75	15.0	118
		1.5	92	18.4	177
		1.8	122	24.4	312
		2	118	23.6	292
		2.3	110	22.0	253
		2.5	108	19.4	220

(c)

On the results of turbine testing with currents and waves on turbine blades tilted 45° (Table 4a), 60° (Table 4b), and 75° (Table 4c) with current variations of 0.5 m/s, 0.7 m/s, 0.9 m/s , 1 m/s and a wave height generation variation of 0.15 m and a period variation of 1.2 – 2.5 seconds has resulted in rotation, torque and output power of the turbine shaft which is greater than the result by simply providing current. Increasing the current and wave period will increase the rotation, torque and power of the 3 turbine models, but in Tables 4a, 4b, and 4c, there is a tendency to decrease the turbine rotation when the wave period rises above 1.8 Seconds so that the turbine power becomes smaller. However, turbines with 75° blades tend to spin higher than the other two turbine models, resulting in increased torque and better turbine power.

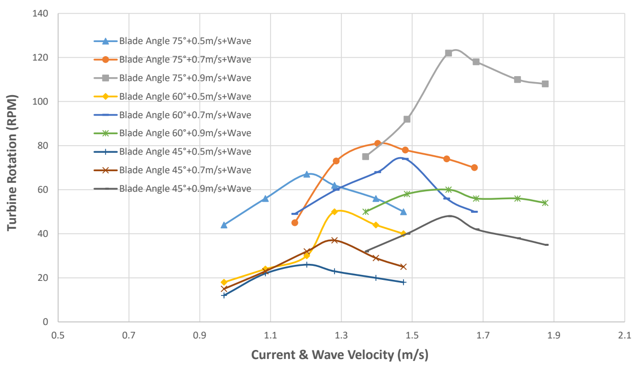


Figure 15. Correlation of current and wave velocity with rotation turbine

In Figure 15, overall it can be seen that an increase in current and wave period will increase the rotation of the 3 turbine models, and the turbine model with a blade angle of 75° has a greater increase in rotation than the other two turbine models. But the most important thing here is that the increase in turbine rotation will be in line with the increase in current and wave period (see Table 4(a), 4(b), 4(c)), so that with an increase in current plus a wave period it will produce a turbine rotation with blades greater than in the presence of current alone (see Table 3). But there is a decreasing trend of turbine rotation after increasing the rotation of each turbine if the speed of the water wave is above 1.8 seconds even though the current speed varies. An example is if 3 turbines are given a current with a speed of 0.5-0.9 m/s with added waves with a period of 1.2-1.8 seconds then there will be an increase in rotation for each turbine, but if 3 turbines are given a current with a speed of 0.5-0.9 m/s with an addition giving a wave with a period above 1.8 seconds, there will be a decrease in the rotation of each turbine (see Table 4).

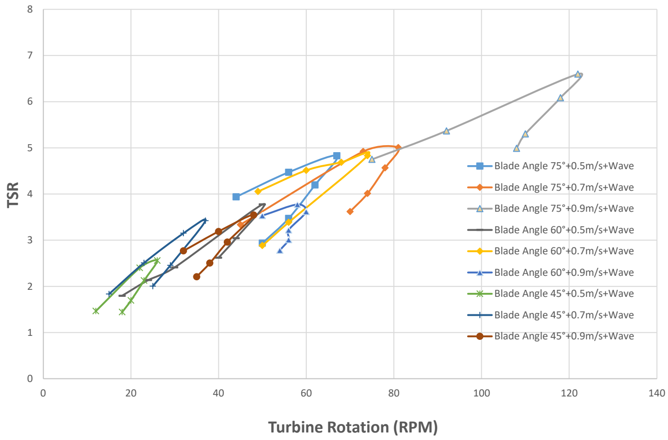


Figure 16. Correlation of turbine rotation with TSR turbine

In Figure 16, overall the rotation of the 3 turbine models will increase the TSR for each model but at certain times the turbine rotation will decrease which will also reduce the TSR value for each turbine model. In addition, a larger TSR is still obtained in the turbine model with an angle of 75° compared to the other two turbine models. However, there is the same trend in the 3 turbine models, namely the increase and decrease in the TSR of the turbine along with the rise and fall of the turbine rotation (RPM), the rise and fall of the turbine rotation are due to changes in the wave period, the addition of the wave period from 1.2-1.8 seconds will cause an increase in turbine rotation but in additional wave period above 1.8 seconds will cause a decrease in turbine rotation (see Table 4). Only the decrease in TSR in each turbine model varies according to the decrease in turbine rotation as well. A large TSR occurs in the turbine model with a blade angle of 75°, but there will be a decrease in TSR after the turbine rotation is above 120 RPM given the current and wave speed of 1.6 m/s. So it can be concluded that the highest turbine TSR is owned by a turbine with a blade angle of 75° compared to the other 2 turbine models. In actual testing, the presence of a high TSR will cause a strong vibration even though it produces high power as studied by [21].

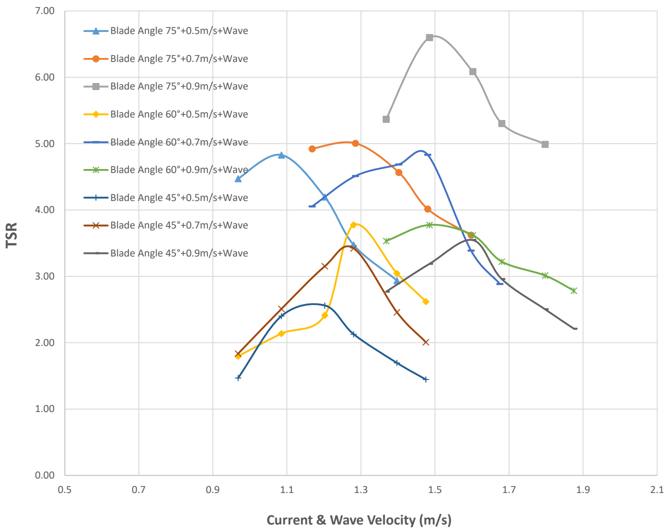


Figure 17. Correlation of current and wave velocity with TSR Turbine

In Figure 17. Overall, an increase in current and wave flow with an increasingly large period will increase the TSR of the turbine, and the turbine model with a blade angle of 75° has a greater TSR than the other two turbine models. However, there is the same trend, namely an increase or decrease in TSR in several turbine tests with an increase in current and wave speed (m/s). That the highest TSR is found in a turbine with an angle of 75°, even though there is a decrease in TSR above 1 m/s current flow, the value is still higher than the others.

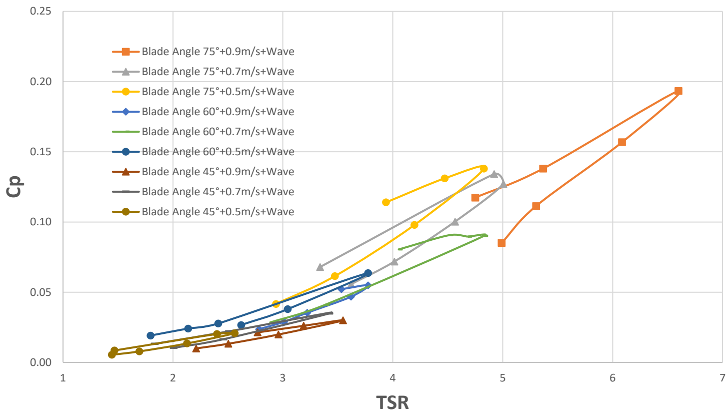


Figure 18. Correlation of Coefisien Power and TSR Turbine

Figure 18 is a graph of the relationship between the power coefficient (Cp) and TSR on the inclined blade Darrieus turbine (45°, 60°, and 75°). Turbines with a 75° blade angle have a Cp with the highest value of 0.19 at TSR 6.6, turbines with a 60° blade angle have the highest Cp value of 0.05 at a TSR 3.6, and turbines with a 45° blade angle have the lowest Cp value at 0.03 at TSR 3.5. The Cp of a 75° inclined blade turbine has increased from TSR 5.4 which has a value of 0.14, to a TSR 6.6 which has a value of 0.19, but the Cp value has begun to decrease with a TSR value below 6.1, Darrieus turbine with a blade angle of 75° has a higher power coefficient value than with 2 Darrieus turbines with an angle of 45° and 60°.

Further testing of turbines with blade angles of 45°, 60°, and 75° using currents and waves decreases the power coefficient at turbine rotation values and wave period values above 1.8 seconds so as to capture the phenomenon of decreased power coefficient that occurs in turbines with certain characteristics with The highest power CP is around 19%. While research [6] on numerical research models and experiments with a range of TSR values around 2-4 can capture the phenomenon of fluctuations in the value of the turbine power coefficient at certain TSR values. This is due to the impact of changes in the pitch angle of the turbine blades on the power coefficient and the number of blades used in the turbine, the more blades are in the downstream area, the additional force will be generated so that the resulting torque value is very large. very large, and this also affects the resulting power coefficient. The maximum power coefficient of the turbine is about 28.5% lower than the maximum power coefficient of the Darrieus turbine with the blade tilted at 75°. The greater the TSR value, the power coefficient value will also increase. However, the value of this power coefficient will increase to a certain TSR value until finally the value decreases with an increase in the wave period above 1.8 seconds.

This difference in the TSR range occurs because, in research [6], the variable that influences the TSR value is the value of ω (turbine rotation) with changes in the pitch angle of the turbine blades only with constant freestream velocity and turbine radius values in each simulation, whereas in this study Variables that affect the TSR value are current and wave speed which varies with the turbine area value being kept constant even with different blade angles.

In this study there were differences in the power coefficient values obtained from previous research [6], and the Cp max value in this study was higher than the Cp max study [6]. This difference can occur because the method used in this study is direct testing in test tanks, thus allowing the resulting data not to be in accordance with previous studies that used neater numerical models. However, the Cp max value of the Darrieus turbine with 75° inclined blades is lower than the Cp max of the four blade Darrieus turbine based on previous research, because other things that might cause this difference are differences in chord length and the type of turbine blade used so that the value of rotation and power produced can be different which causes Cp to also be different.

4. Conclusion

In this paper, 3 models of Darrieus turbines with tilted blades of 45°, 60°, and 75° have been tested using the experimental method in the wave and current test tank of the Indonesian Hydrodynamics Laboratory by providing water currents of varying speeds of 0.5 - 1 m/s and providing a mixture of currents and waves with a wave height of 0.15 m and a variation of the wave period between 1.2 - 2.8 seconds. Where it can be concluded by testing on 3 models of Darrieus turbines with angled blades shows that with the addition of current and wave flow for a certain period, good rotation, torque and turbine power performance will be obtained. Furthermore, it has been confirmed that changes in the vertical axis Darrieus turbine design with blade angles will increase the turbine rotation performance, which is directly proportional to the increase in turbine torque and power.

Testing 3 turbine models with the provision of water flow showed an increase in turbine rotation and power. Still, the best turbine rotation and power were in the Darrieus turbine with a 75° angle with a maximum rotation of 85 RPM and 189 Watt power, rather than a 60° angle turbine which was only able to get 57 RPM rotation and 85 Watts of power, especially with a 45° angled turbine which only has a maximum rotation of 34 RPM with 30 Watts of power. Testing 3 turbine models with the provision of water currents and waves showed an increase in rotation and power exceeding the test—testing of 3 turbine models with only water currents. Even though when given a wave height of 0.15m with a wave period above 1.8 there is a decrease in rotation and power in each turbine model, the turbine performance (rotation and power) is still better than testing with current alone. And according to the above study, the turbine with the best rotation and power is the Darrieus turbine with a blade angle of 75° with a current of 1 m/s, a wave height of 0.15m, and a wave period of 1.8 seconds to get a rotation of 122 RPM and a power of 312 Watts. The Darrieus turbine with a blade angle of 60° has a rotation of 80

RPM and a power of 134 Watt with a current of 1 m/s, a wave height of 0.15m, while the Darrieus turbine with a blade angle of 45° only has the best rotation at 48 RPM and a power of 48 Watt with current supply 1 m/s, wave height 0.15 m.

From testing 3 models of Darrieus turbines at angles of 45°, 60°, 75° by giving water current only or by giving water currents and waves, it shows that good rotation, torque and power performance of the turbine is obtained, especially the performance of the turbine with an angle of 75° which has the best power coefficient of 0.19 than the Darrieus turbine with an angle of 45° and 60°. So this paper suggests that the Darrieus turbine with an angle of 75° can be used as a wave current turbine that can be installed in coastal areas that have current and wave conditions. Only before that it should be studied more deeply about the problem of the strength of the turbine structure, especially the problem of piling and corrosion as part of the resistance to installation in coastal areas that have very damaging natural conditions which have not been conveyed in writing in this paper.

References

[1] W. G. Santika, T. Urmee, Y. Simsek, P. A. Bahri, and M. Anisuzzaman, "An assessment of energy policy impacts on achieving Sustainable Development Goal 7 in Indonesia," *Energy for Sustainable Development.*, vol. 59, pp. 33–48, 2020, doi: 10.1016/j.esd.2020.08.011

[2] M. Kabir, M. S. Chowdhury, N. Sultana, M. S. Jamal, and K. Techato, "Ocean renewable energy and its prospect for developing economies," *Renewable Energy and Sustainability*, pp. 263–298, Jan. 2022, doi: 10.1016/B978-0-323-88668-0.00007-3.

[3] E. S. Baruna and F. Indarwati, "Ministry Of Energy and Mineral Resources Republic of Indonesia," in *Handbook of Energy & Economic Statistics of Indonesia Final Edition*, 2022. [Online].

[4] Erwandi *et al.*, "Power plant for ocean currents and waves to convert the kinetic energy of ocean currents and or potential energy of ocean waves into Electrical Energy (Indonesian Language)," IDP000054295, 2018 [Online]. Available: https://pdki-indonesia.dgip.go.id/detail/P00201500496?type=patent&keyword=IDP000054295

[5] M. A. Hanif, F. Nadeem, R. Tariq, and U. Rashid, "Power generation by ocean energy," *Renew. Altern. Energy Resour.*, pp. 359–430, 2022, doi: 10.1016/B978-0-12-818150-8.00002-2.

[6] M. T. Nguyen, F. Balduzzi, and A. Goude, "Effect of pitch angle on power and hydrodynamics of a vertical axis turbine," *Ocean Engineering*, vol. 238, pp. 109335, 2021, doi: 10.1016/j.oceaneng.2021.109335.

[7] Y. Ma, C. Hu, and L. Li, "Hydrodynamics and wake flow analysis of a ⊓-type vertical axis twin-rotor tidal current turbine in surge motion," *Ocean Engineering*, vol. 224, no. March 2020, p. 108625, 2021, doi: 10.1016/j.oceaneng.2021.108625

[8] G. Shoukat, B. Gaurier, J. V. Facq, and G. S. Payne, "Experimental investigation of the influence of mast proximity on rotor loads for horizontal axis tidal turbines," *Renewable Energy*, vol. 200, no. August, pp. 983–995, 2022, doi: 10.1016/j.renene.2022.10.006.

[9] S. Chen *et al.*, "Design, dynamic modeling and wave basin verification of a Hybrid Wave–Current Energy Converter," *Applied Energy*, vol. 321, no. January, p. 119320, 2022, doi: 10.1016/j.apenergy.2022.119320.

[10] D. Rahuna, "Kajian Eksperimental Konversi Energi Gelombang dengan Menggunakan Kombinasi Wells Rotor dan Turbin Darrieus," *Wave: Jurnal Ilmiah Teknologi Maritim*, vol. 10, no. 1, pp. 31–38, Jul. 2016, doi: 10.29122/jurnalwave.v10i1.2631.

[11] E. J. Soons, "Improving the Hydrodynamic Performance of a Combined Wells-Darrieus Rotor," 2007. [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid%3Af6531921-ee06-4a8c-88f9-95a31a262797

[12] Erwandi, D. Rahuna, and C. S. J. Mintarso, "The development of the IHL wave-current turbine to convert the ocean energy from both wave and current," *IOP Conference Series Material Science and Engineering*, vol. 588, no. 1, pp. 5–13, 2019, doi: 10.1088/1757-899X/588/1/012008.

[13] Scheijgrond, Peter, and Cornelis, "a Device for the Utilisation of Wave Energy and a Method," WO 2010/011133 Al, 2010 [Online]. Available: https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2010011133&_cid=P21-LGG92C-92057-1

[14] Scheijgrond *et al.*, "an Apparatus for Harvesting Energy from a Body of Water and a Method," WO 2010/062170 A1, 2010

[15] T. Iqbal, M . T . Iqbal "A Low Cut-In Speed Marine Current Turbine A Low Cut-In Speed Marine Current Turbine, Memorial University of Newfoundland, 2020, [Online]. Available: https://www.researchgate.net/publication/347441467

[16] G. Saini and R. P. Saini, "Comparative investigations for performance and self-starting characteristics of hybrid and single Darrieus hydrokinetic turbine," *Energy Reports*, vol. 6, pp. 96–100, 2020, doi: 10.1016/j.egyr.2019.11.047.

[17] D. Satrio, I. K. Aria, and P. Utama, "Experimental investigation into the improvement of self-starting capability of vertical-axis tidal current turbine," *Energy Reports*, vol. 7, pp. 4587–4594, 2021, doi: 10.1016/j.egyr.2021.07.027.

[18] Lemhannas RI, "Orasi Ilmiah HUT ke-57 Lemhannas RI 'GEO V,'" *Biro Humas Lemhannas RI.* Jakarta, pp. 1–27, 2022.

[19] S. Musabikha, I. K. A. P. Utama, and Mukhtasor, "State of the art in protection of erosion-corrosion on vertical axis tidal current turbine," *AIP Conference Proceedings.*, vol. 1964, no. November 2019, 2018, doi: 10.1063/1.5038329.

[20] D. H. Zeiner-gundersen, "A novel flexible foil vertical axis turbine for river , ocean , and tidal applications," *Applied Energy*, vol. 151, pp. 60–66, 2015, doi: 10.1016/j.apenergy.2015.04.005.

[21] M. Shiono, K. Suzuki, and S. Kiho, "Output Characteristics of Darrieus Water Turbine with Helical Blades for Tidal Current Generations," *Proc. Int. Offshore Polar Eng. Conf.*, vol. 12, pp. 859–864, 2002, [Online]. Available: https://www.academia.edu/14239924/Output_Characteristics_of_Darrieus_Water_Turbine_with_Helical_Blades_for_Tidal_Current_Generations