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Evaluation of Tidal Energy Potential Using a Two-Way Tidal Energy Model

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Abstract

Tidal energy is a renewable energy source that provides sustainable energy through the utilization of tidal differences, making it a very promising option. This study examines a more effective tidal energy reservoir model by building a 1:100 scale prototype in the laboratory with several predetermined variations, namely an earthen pond (100, 80, and 60 cm), and flow holes (1.5, 1, and 0.5 cm) with initial tidal height differences of 10 cm, 15 cm, and 20 cm. The model uses a 6-hour time period, which corresponds to a semidiurnal tidal model. The results showed that the highest energy output was 281.84 kWh, achieved with a 1.5 cm flow hole, 20 cm tidal height difference for the initial condition, and 80 cm pond width. For a 1 cm flow hole, the outputs were 1774.8 kWh and 1803.78 kWh for 15 cm and 20 cm tidal height difference for the initial condition with a pond width of 100 cm. Meanwhile, the 0.5 cm flow hole produces potential energy outputs of 2623.8 kWh and 2611.4 kWh for different tidal heights of 15 cm and 20 cm for the initial condition with a pond width of 100 cm. Better model performance can be connected to a mini generator to validate the energy generated from the designed prototype model.

Keywords: Renewable Energy; Tidal Energy; Prototype Model; Potential Energy.

1. Introduction

One of the world's biggest archipelagic nations is Indonesia. This is due to the 17,500 islands that make up Indonesia, which are 70% water and 30% land. Because of this, Indonesia benefits from having a sizable ocean region that may be used for the benefit of all. Indonesia has the potential to be a source of electrical energy because of its large oceanic area. Still, not many people are aware of Indonesia's potential as a new source of renewable energy from seawater. Electrical energy can be produced by certain oceanic energy, such as temperature and waves. The potential of new renewable energy to generate and produce electrical energy that can replace energy produced from fossil fuels has been observed and expanded even in industrialized countries [1, 2].

One renewable energy source that could significantly help Indonesia meet its energy needs is water. This includes hydroelectric power facilities, which use the height and speed of the water to harness the potential energy of the water and transform it into mechanical energy via turbines and electrical energy via generators [3]. The process of the sea level rising and falling on a regular basis due to the gravitational pull of celestial bodies, particularly the sun and moon, against the earth's water mass is known as tides. Tides are produced by gravitational attraction and centrifugal forces, and changes in a celestial body's center of rotation have a significant impact on how tides form [4]. One type of renewable energy source is tidal power plants, which use the energy of the tides in the ocean to generate electricity. The water power found in ocean tides, which are produced by the interaction of the earth's rotation and the moon's and sun's gravity, is utilized by the tidal power plant itself. Since tidal waves occur for roughly ten hours every day, tidal power plants have greater potential for usage as an endless supply of electricity [5].

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The main objective of the government's national energy policy is to accomplish these objectives. According to this policy, the use of petroleum must not exceed 20%, natural gas must not exceed 30%, coal must not exceed 33%, biofuels must not exceed 5%, geothermal energy must not exceed 5%, wind power must not exceed 5%, and liquefied coal must not exceed 5%. While liquefied coal rises to more than 2% and other innovative and renewable energy sources, such as biomass, nuclear, hydropower, solar, and wind power, reach more than 5% of the total [6, 7].

One of humanity's main concerns is the generation of energy sufficient to meet society's energy needs. The swift advancement of technology has led to a notable surge in energy consumption as well. But the most widely used energy source is still fossil fuels. Worldwide research is being done on renewable energy to lessen the pollution that traditional energy sources contribute to the environment, including carbon dioxide emissions. In the future, the share of renewable energy sources will progressively rise. For future energy systems to be sustainable and safeguard the environment, making the best use of renewable energy sources is essential. Tidal energy has a lot of potential as an ocean energy source because it is renewable. The potential energy of the water level produced by high and low tides and the kinetic energy carried by ocean currents are the two primary forms of tidal energy [8]. Natural resources abound in Indonesia that may be used by living creatures. Renewable energy is defined as non-fossil energy that is renewed and well-managed by humans. As a result, sources of renewable energy will be sustainable. Nuclear, geothermal, water, solar, wind, biomass, marine, and fuel cell energy can all be categorized as renewable energy [9]. One clear benefit of tidal energy over other renewable energy sources is its great predictability, which can be estimated well in advance due to the tides' reliance on the continuous cycles of the Earth, Moon, and Sun (see Figure 1) [10].

The sun and moon are the primary sources of tidal forces on Earth, as the tides are produced by the gravitational pull of terrestrial planets. Because of gravitational force, seawater's crustal rocks move up and down, transmitting the effects of tidal energy [11].

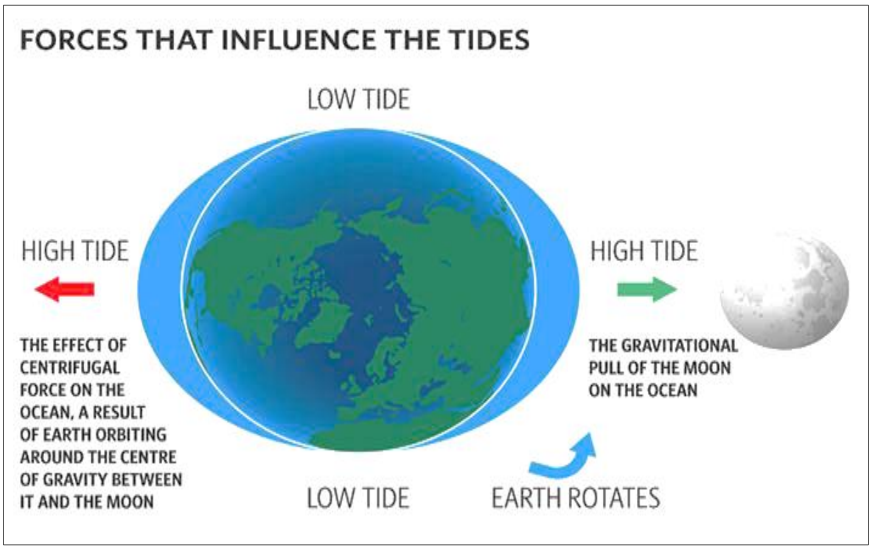


Figure 1. The Gravitational Attraction Tidal Bulge from Earth, Moon, and Sun

The influence of tides, a natural phenomenon that repeats every given amount of time, can be felt much upstream from the river's mouth. The force of attraction between celestial bodies, particularly the sun and moon, and the bulk of sea water on Earth causes variations in water levels, which is what causes tides. The lunar attractive force can have an up to 2.2-fold larger impact on Earth than that of the solar attractive force due to the moon's closer proximity to Earth than the sun [12].

Produced from naturally occurring resources, renewable energy is non-invasive to the environment, safer, and comes from the source. The ocean itself is capable of producing renewable energy, particularly in the Makassar Strait. Most significantly, Indonesia's primary energy source is fossil fuels. Oil, natural gas, coal, and wood will all eventually run out, just like fossil fuels themselves. An estimated 417.8 GW of renewable energy can be produced in Indonesia. However, its utilization is just about 2.5%, or 10.4 GW, which is very low [13].

When marine hydro-kinetic energy converters and tidal currents are installed in precommercial arrays. Developers employ turbulence models to create unsteady flows in order to simulate device performance because turbulence is known to affect fatigue loads and power generation. The majority of these models use a combination of theoretical presumptions and measurable characteristics to create a synthetic flow field. The majority that are now in use may not be very applicable in tidal environments because they are based on air flow conditions. model assumptions to turbulence (which are utilized in design software and advised by the tidal turbine specifications) [14].

Alternative energy sources for water pumping include gate water pumps, which draw water from the ground through vertical sump pumps installed in water towers known as caissons to completely stop water leakage. Utilizing is an alternate method of Tambahan to get Surut Tenaga. hydroplane uses the energy from the passing wave to generate a very large wave that resembles the surface of a whale and that rises and falls in response to the passing wave. To maximize efficiency, you can adjust the hydroplane's suction cup relative to the suction cup axis. This book discusses wave energy, including its generation, the principles of wave energy work, and wave energy functions that affect the environment [15]. At each site, there are potential basin Tidal Power Plant areas of 5×106 m^2, 7×106 m^2, 10×106 m^2, and 12×106 m^2. The highest tidal range in the Gulf of Kutch is found to be 8.88 m, 9.41 m, 7.97 m, 8.88 m, and 8.07 m at Okha, Sikka, Rozi, Kandla, and Navlakhi, in that order. At Daman, Hazira, Bhavnagar, Pipavav, and Diu in the Gulf of Khambhat, the greatest tidal ranges are 8.96, 13.14, 13.33, 13.41, and 11.56 m, respectively [16].

In the process of powering our daily life with renewable energy instead of fossil fuels, tidal energy has become a clean, dependable, predictable, and dependable energy source. Europe will have installed 27.9 MW of tidal stream technology by the end of 2020, having started in 2010. Almost four times as much as the rest of the globe, 10.1 MW of this is presently in operation, with 17.8 MW retired as projects successfully complete their testing programs. The EU Strategy on Offshore Renewable Energy, which the European Commission issued at the end of 2020, and which lays out a concrete goal for the deployment of 100 MW of ocean energy by 2025, increased support for its development [17]. Massive renewable energy reserves are found in oceans, with kinetic and potential energy being the most easily extracted forms. These reserves are created by many ocean processes, including tides and waves. According to reports, the total tidal energy potential was approximately 26,000 TWh/year, while the estimated global theoretical wave energy potential was approximately 29,500 TWh/year [18].

Tidal range schemes, which generate electricity on both the incoming (flood) and outgoing (ebb) tides, can convert energy over four distinct periods every lunar day. Cyclistically intermittent describes the tidal energy conversion process as periodic and predictable. The reservoir area, the tide height, and the turbine and sluice discharge capacity all affect the generating period, at least approximately. The duration of a barrage or lagoon changes significantly between the neap and spring tides, typically by 2-4 hours [19].

Schemes Tidal Power Plants are big and costly to build; as such, an evaluation of their costs is typically conducted under strict commercial confidentiality guidelines. A more transparent method that facilitates cost comparisons across schemes is necessary for a national delivery strategy; a model that assesses the capital cost of key components has been created [20]. The usage of tides as a renewable energy source tends to support the existing electricity sector. Therefore, this research aims to investigate a two-way system model for capturing tidal energy. Prototype models were designed in the laboratory for accurate scale implementation.

2. Literature Review

The power density and kind of turbine technology that are appropriate for application in the Molo Strait can be ascertained from the simulation findings. According to this paper, the two-way currents in the Molo Strait move differently during high and low tides. Furthermore, during the spring and neap tides of the Molo Strait, the highest mechanical power density at the potential point, coordinates (-8.625242°,119.805644°), is 5.47 kW/m^2 and 0.7 kW/m^2, 5.18 kW/m^2, respectively. When the kind and size of the turbine technology are established, these can be converted into mechanical power [21].

At coordinates 5°31'32.8 "LU 95°07'10.7 "BT" in the offshore area of Aceh Besar. The average sea current speed in this area is 0.37 m/s, whereas the maximum average wind speed is 4.9 m/s. Based on the modeling results, the hybrid plant with 5 wind turbines and 10 hydrokinetic turbines can generate 5,437,333 kWh of electricity annually. The hydrokinetic turbine only generates 17.6% of the total electricity production due to the sea current speed being too low for this electricity generation system to be optimal. This results in a high cost of energy generation price of Rp. 3,969/kWh when compared to the basic electricity tariff of PLN, which is Rp. 1325/kWh [22].

The process of tidal power involves using the same principle as hydroelectric power generation to create energy from the difference in the hydrostatic head brought about by rising and falling tides. While developments in micro-hydro technology may allow for the exploitation of new resources with shorter extraction times, it is commonly asserted that energy production requires a minimum 5-meter differential between low and high tides [23].

Tidal currents in the Flores Sea waters of the Labuan Bajo and Maumere case studies, the tidal current velocity pattern in the study area is that the water flows northward at high tide and southward at low tide. This relationship is influenced by tidal propagation from the Indian Ocean, water morphology, and meteorological conditions. The tidal currents in both places are a type of alternating current or countercurrent [24]. On the beach, the Portable Tidal Power Plant was tested at high tide (413 RPM), maximum voltage of 3.3 V, and maximum RPM of the sea. The maximum voltage and peak RPM measured on the estuary during the retreating sea level are 2.6 V and 284.4 RPM, respectively [25].

Other than wind, waves, and a vertical axis turbine with a Darrieus blade type with five, six, or seven blades, the potential for developing renewable energy is very suitable. The average tidal current speed of sea water in Bangkabelitung waters is 3-5 m/s, and the generator runs at an average speed of 102 rpm. When a 3-watt lamp load is used, the resultant voltage is 4.32 volts, and the current is 0.69 amperes [26].

The tidal turbine's performance was tested for each speed option, and the findings are as follows: 22.474; 9.136; 4,703; 2,642; 1,539; 0.900. The ANOVA method is used to process the data based on the test findings. The conclusion reached is that there is no difference in the test results for the speed variant when the value of $F(speed) = 2.219512 < Fcrit = 2.53355$, and there is a difference in the test results for the variance of results when the value of $F(test) = 25.59739 > Fcrit = 2.42052$ [27].

The third quarter of 2021 saw Indonesia's per capita power usage of 1109 kWh. Indonesia's per capita usage of electricity has been rising since 2015, according to the Ministry of Energy and Mineral Resources. The biggest rise, 6.8%, happened in 2017, while the smallest increase, 0.4%, happened in 2020. Future demand will rise as a result of government initiatives to hasten the usage of electric stoves and cars [28].

The magnitude of the resource, the basin, the tidal range's quantitative value, and other environmental conditions are all important considerations for tidal power plants. Water depths of 30 to 60 meters are necessary for the tidal energy system to provide enough electricity. Numerous scholars that have previously examined the resource assessment of tidal energy systems outline a multi-measure estimation of likely locations for these systems in Australia. The process of multi-parameter assessment of tidal energy systems involves evaluating various characteristics, including water depth, high and low tide values, and the optimal site for producing electricity using the tidal energy system [29].

Utilizing comparatively recent technology, renewable energy is energy that does not contribute to climate change because it often produces no greenhouse gases or pollutants. This is especially true in Indonesia. Despite being ecologically benign, renewable energy has a number of drawbacks, one of which is its intermittent nature, which makes it extremely challenging to fulfill peak energy demand because the energy source varies annually owing to seasonal variations. There are many different types of renewable energy, including hydroelectric, geothermal, wind, and solar power plants. Given the variety of technologies now in use, the Indonesian government needs to consider which one has the greatest promise for renewable energy. Given that Indonesia is a maritime nation with 3,257,357 m^2 of ocean, marine power generation has enormous potential for usage in Indonesia as a renewable energy source [30].

Many nations with significant tidal energy potential, including the UK, France, Russia, India, China, Korea, and Canada, have shown a particular interest in tidal energy. The scant results have produced mainly broad conclusions and occasionally resorted to using tidal data from a single place for large-scale regional simulations. With a possible 41.6 $GWh/km^2/y$, Vietnam has significant tidal energy potential in the southeast and along the Hai Phong-Quang Ninh coastal area [31].

Seawater is made up of 3.5% additional substances, including salts, dissolved gasses, organic materials, and other particles not dissolved in water, and 96.5% regular water. Every seawater has a unique salinity. The mineral salts found in rocks and soil on Earth are the cause of the salt found in seawater. Salt is carried by river water when it enters the sea. Salt that is present in rocks can also occur as a result of ocean waves crashing onto the shore. As a renewable energy source, seawater is used as an electrolyte in battery cells [32].

Among renewable energy sources, tidal energy generation has demonstrated some very noteworthy benefits. Because of the tidal producing forces produced by the linked Earth-Moon system, there is a potential for the generation of power from tides. It is imperative to enhance the efficiency of kinetic energy extraction from freely flowing water and optimize these tidal systems. The fundamental parameters for utilizing tidal turbine energy are a free flow velocity of two to three meters per second and a minimum depth of twenty to thirty meters for first testing with deeper water models (>40 m) [33].

The simplest generation system for tidal generation consists of a dam, known as a barrage, across an inlet. Sluices in the barrage allow the tidal basin to fill with the incoming tide and empty through the turbine system on the outgoing tide, also known as the ebb tide. There is a two-way system that generates electricity on both the incoming and outgoing tides) [34]. A Barrage Tidal System, such as the Prototype Tidal Power Plant, operates on the principle of building a dam through which, as the tide rises, water enters through a turbine gap, causing the turbine to rotate (Figures 2 and 3). Conversely, as the water recedes, water exits the dam through the same turbine gap, causing the turbine to rotate [35].

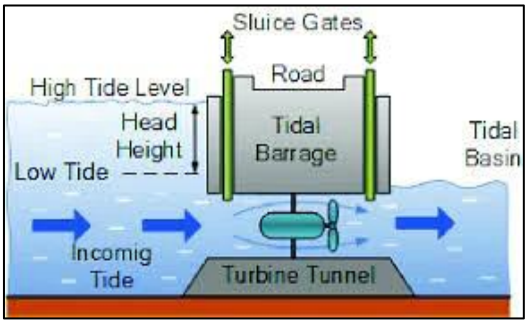


Figure 2. Barrage tidal system (incoming)

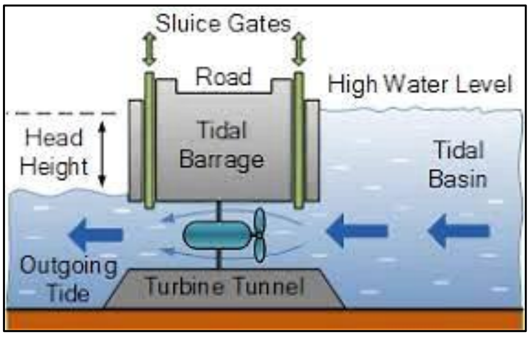


Figure 3. Barrage tidal system (outgoing)

Tidal energy is a kinetic energy that utilizes the difference in sea level height between high and low tide. The basis of the working principle for utilizing tides is the same as hydroelectric power plants found in reservoirs such as Jati Luhur & Cirata [36].

Since the tenth century, the rise and fall of the tides have been used to generate electricity through tidal mills, and tidal range schemes are still in use in a few places. The interaction between the solar and lunar components and the local geography determines the magnitude of the tidal movement at a specific site. The Bay of Fundy in Canada and the Severn Estuary in the United Kingdom have the biggest tidal ranges in the world, with spring tidal ranges of 16 and 14 meters, respectively (Figure 4). Tidal range schemes contain a volume of water in a space connected to the fluctuating external water level via engineering construction, and they employ the vertical change in elevation of the water surface at a suitable site to produce energy [37].

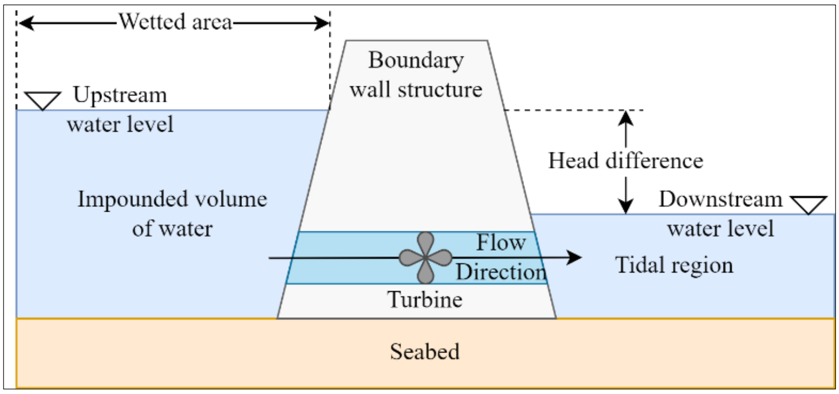


Figure 4. Tidal range scheme idealized structural cross section diagram

This method uses a dam with a penstock or water pipe that has pressure flowed by water flow to convert tidal energy into electrical energy. The process involves other factors as well. Specifically, the effective water fall height, or net head, is determined by the difference in height between the height of the sea surface and the height of the dam pool. There will be a filling and emptying process in the dam pool if there is a water flow between the sea and the dam. where tides will occur during this filling and draining procedure. When a turbine is installed with a penstock or pressurized pipe, the turbine's rotation or movement is caused by the emptying. When a turbine is equipped with a penstock or pressured pipe, the turbine's ability to rotate or move is caused by the filling and emptying those results in tides. The turbine will convert electrical energy as it rotates [38].

Using offshore turbines and tidal movements brought on by ocean currents, tidal power generation generates rotational power for the water-based turbines (Figure 5). Compared to wind turbines, these offshore turbines are more productive and efficient. Seawater has a density that is higher than that of air [39].

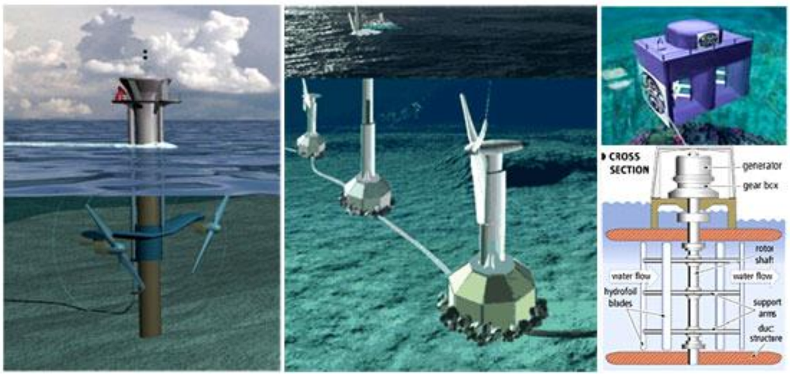


Figure 5. Offshore Turbine [39]

In the past, people on the coasts of North America and Europe harnessed tidal energy to power turbines. They ground wheat using the mechanical energy they had converted. This method did not start to be evolved into electrical energy until the 19th century. The Rance Tidal Power Station was the first large-scale tidal power station in the world. France constructed it, and it has been in use ever since 1966. The amount of tidal energy produced near the mouth of the Rance River in France is 240 megawatts. There is no energy produced in Annapolis, Canada, with a 16MW capacity. In contrast, the generated tidal energy in South Korea has a 254 MW capacity. The capacity of the sea and ocean to generate electricity is one of their lesser-known potential applications. Tidal power, wave energy, and ocean thermal energy are the three main categories of ocean energy potential that can be used to create electricity. The movement of seawater caused by tidal differences is the source of tidal energy. By taking advantage of the difference in water levels between high and low tide, tidal energy can be transformed into electrical power. The most widely used method of converting tidal energy is the construction of dams in estuaries or bays. Water pours into the dam during high tide until a particular point is reached, at which point it is kept. When the sea recedes, the water is returned to the sea via a water turbine, which generates electrical energy. In the 20th century, engineers created methods for harnessing tidal movement-the area that separates high tide from low tide-to produce energy in places where there is a substantial tidal range. Tidal energy is converted into electricity using specialized generators in all techniques [40, 41].

There have been many tidal power plants in the world, which are further explored in this study.

2.1. La Rance (France, 1966)

The La Rance power plant, situated in Brittany, France, was the first tidal barrage project to be constructed and put into service. With a 720 m embankment, a 22 km^2 basin, 24 10 MW bulb turbines, and six sluice gates, it has an installed capacity of 240 MW and produces about 480 GWh of electricity annually. Because the turbines are reversible, the facility operates on a two-way pumping and generation system (Figure 6). The site's tidal range resource spans 9 to 14 meters. Travel time between Dinard and St Malo has been reduced by several hours thanks to the barrage, which functions as a four-lane roadway in and of itself [41-43].

Figure 6. La Rance Tidal Power Plant, France

2.2. Sihwa Lake Tidal Power Station (South Korea, 2011)

With 254 MW of installed capacity, the Sihwa Lake tidal power plant in Gyeonggi Province is now the largest tidal barrage project in use. Because the plant only runs when there is a flood, it serves to keep the water level in the basin low and keeps the surrounding infrastructure from flooding (Figure 7). The basin's surface size is 42.4 km^2, and the average spring tide range is 7.8 m [42, 44].

Figure 7. Sihwa Lake Tidal Power Plant in South Korea

2.3. Jiangxia Experimental Tidal Power Plant (China, 1980)

The Jiangxia Experimental is situated in Zhejiang Province's Wenling County, where the mean tidal range is 5.08 meters and the maximum is 8.39 meters. The basin spans approximately 1.5 km² and is enclosed by a 670 m-long rockfill embankment made of clay core. In 1980, the plant began to run with a single 500 kW bidirectional bulb turbine (Figure 8). With six turbines and an installed capacity of 4.1 MW, the plant is presently the largest running tidal plant in China, having undergone three decades of expansion and technological upgrading [42, 45, 46].

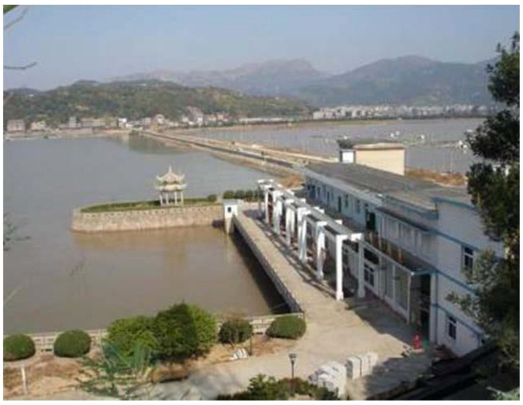


Figure 8. Jiangxia tidal Tidal Power Plant in Wenling, China

2.4. Kislaya Guba (Russia, 1968)

Kislaya Guba's 400 kW installed capacity was increased to 1.7 MW after it was constructed in 1968 (Figure 9). The impounded basin area is 1.1 km^2, the embankment is just 40 m broad, and the turbines are bulb type. It is the only tidal plant in the Arctic and may be found in a fjord in the Kola Peninsula, close to Murmansk, where the tidal amplitude is 2.5 m [42, 47].

Figure 9. Kislaya Guba Tidal Power Plant in Russia

2.5. Haishan Tidal Power Plant (China, 1975)

The only functional linked-basin tidal scheme in the world is the Haishan. Constructed in 1975, it remains the sole operational tidal plant in China, along with Jiangxia (Figure 10). It is situated in the Zhejiang Province's Yueqing Bay, where the tidal range is 4.87 meters. One benefit of this two-basin plant is its near-constant ability to produce energy. Pumping was added later to increase storage capacity and improve the stability of the power supply to the grid. The installed capacity is 150 kW [42, 46].

Figure 10. Haishan Tidal Power Plant in China

2.6. Annapolis Royal Generating Station (Canada, 1984–2019)

The second-highest tidal resource in the world is found in the Bay of Fundy, Nova Scotia, where the Annapolis Royal Generating Station was situated on the Annapolis River (Figure 11). It was equipped with a single 20 MW Straflo turbine that ran on ebb current. Due to the high fish mortality linked to turbine operation, the plant was shut down in 2019 [41, 42, 48].

Figure 11. Annapolis Royal Generating Tidal Power Plant in Canada

3. Methods

3.1. Prototype Model

The scaled prototype model for capturing tidal energy considered several parameters and variations. This research focused on three types of variations, namely changes in the width area of the tidal capture medium (land pond area), adjustments in the diameter of the flow holes from the sea to the land ponds, and dissimilarity in tidal height difference (Table 1 and Figures 12 to 14).

Table 1. Types of Prototype Model Variations

Variations	Dimension
Flow Hole Diameter	
Variation 1	Length 150 cm × Width 100 cm
Variation 2	Length 150 cm × Width 80 cm
Variation 3	Length 150 cm × Width 60 cm
Dia Flow Hole Diameter	
Variation 1	Diameter 1.5 cm
Variation 2	Diameter 1 cm
Variation 3	Diameter 0.5 cm
Initial Tidal Height Difference	
Variation 1	Height Difference 10 cm
Variation 2	Height Difference 15 cm
Variation 3	Height Difference 20 cm

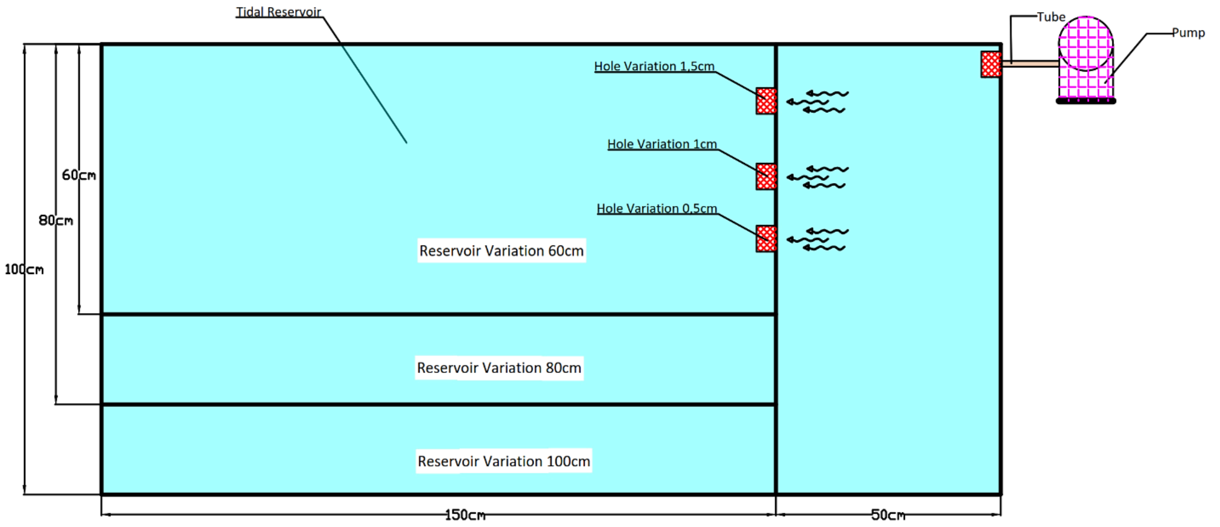


Figure 12. Top view of the 2D design of the tidal energy capture prototype model

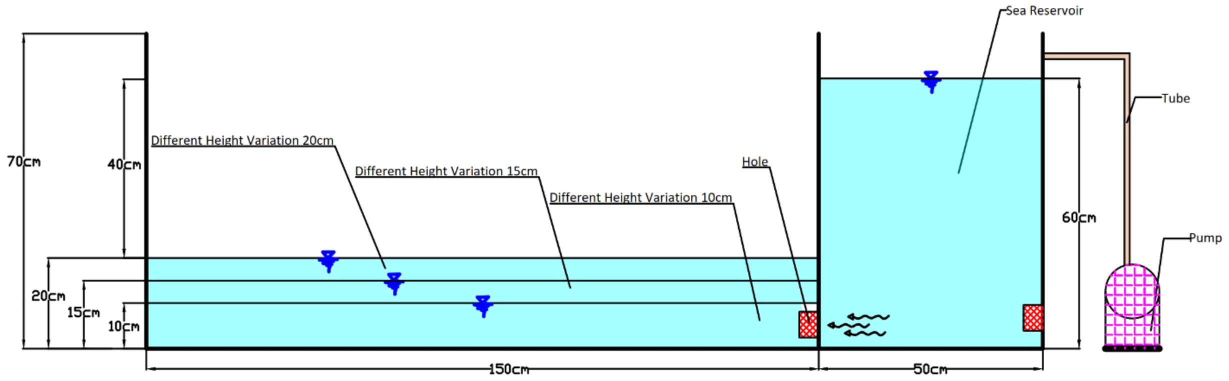


Figure 13. Longitudinal section of the 2D design of the tidal energy capture prototype model

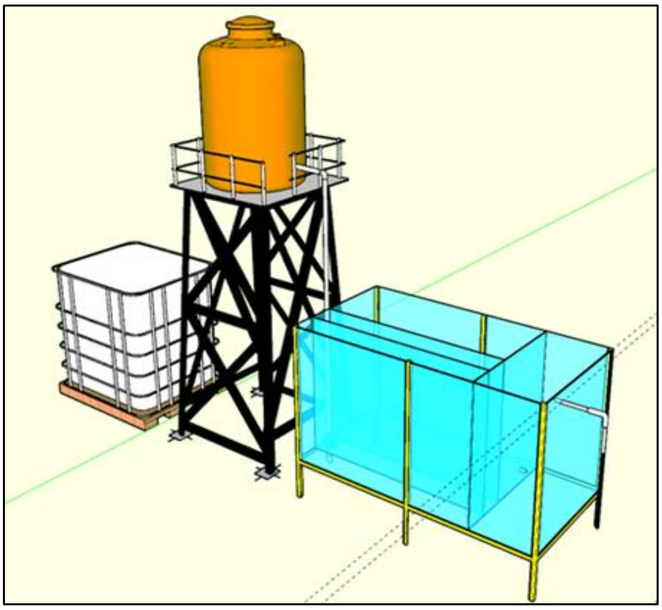


Figure 14. 3D design of the tidal energy capture prototype model

3.2. Time Tidal Model

The tidal model design used reflects the predominant semidiurnal tide found on most islands in the country. The tides pattern featured two high and low tides daily, with each complete cycle lasting approximately six hours. Therefore, the research adopted a time scale of six hours. The model was adjusted based on the planned height differences as follows (Table 2):

Table 2. Time Scale in the Model Research

Scale	Time
Scale 1:1	6 hours
Scale 1:10	6830.52 seconds ≈ 1 hour 53.84 minutes
Height difference 10 cm	5692.1 seconds ≈ 1 hour 34.87 minutes
Height difference 15 cm	5122.89 seconds ≈ 1 hour 25.38 minutes
Height difference 20 cm	4553.68 seconds ≈ 1 hour 15.89 minutes

3.3. Research Flow Framework

To see the research flow framework starting from the preparation stage to data analysis until completion, can be seen in Figures 15 and 16.

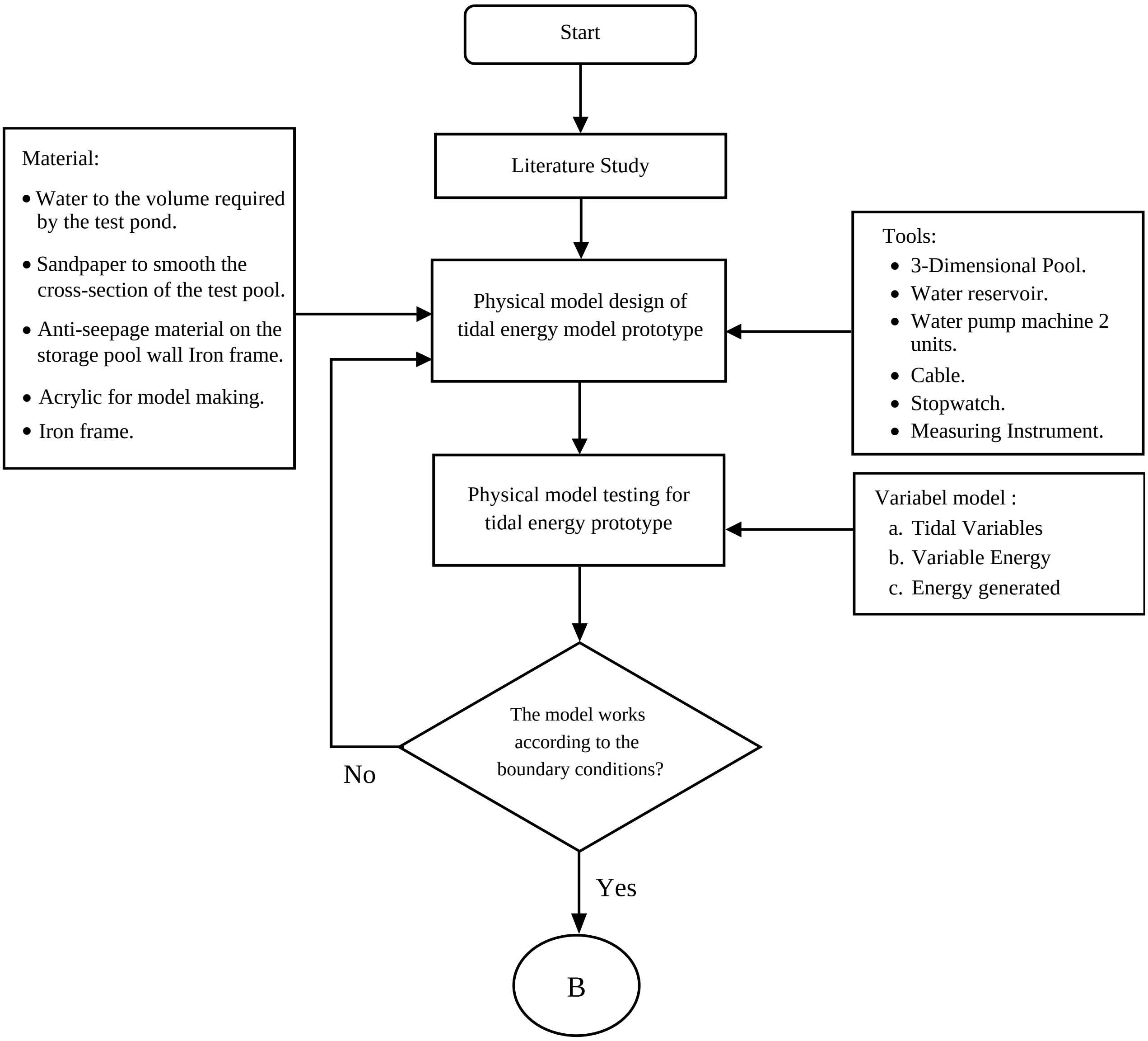


Figure 15. Flowchart of the study (A)

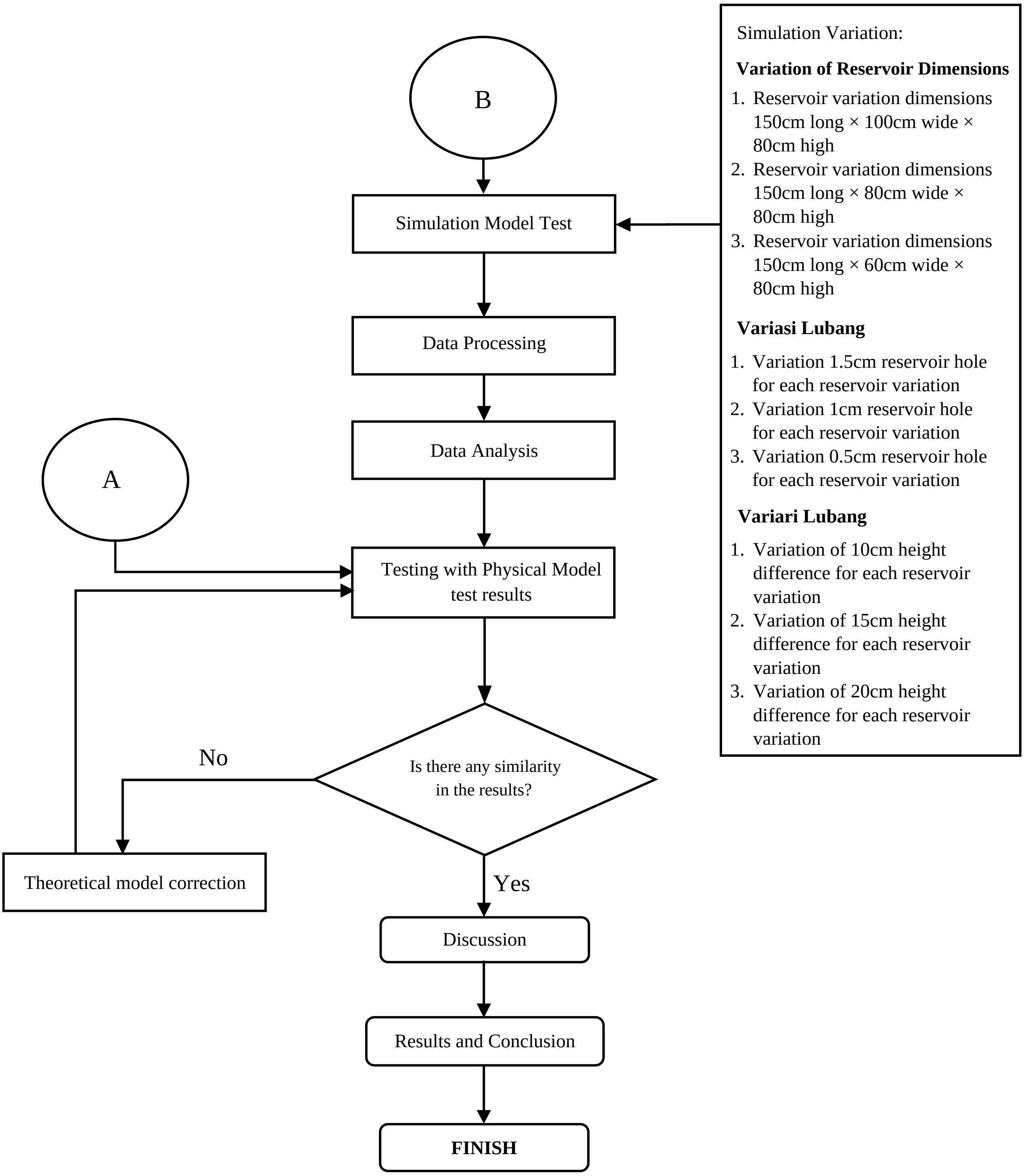


Figure 16. Flowchart of the study (B)

4. Results and Discussion

4.1. Research of Water Level in the Land Pond and Tidal Model Time

The research conducted on the water level in the pond, with adjustments to the predetermined time scale, aimed to determine the effectiveness of each variation. It also examined the water level in the pond over time, considering variations in height differences (10, 15, and 20 cm), hole diameter (1.5, 1, and 0.5 cm), and the width of the land pond (100, 80, and 60 cm). More detailed information is available in Table 3 and Figure 17.

Table 3 and Figure 17 show that several differences were obtained for each variation, specifically evident in the scenario with a 100 cm width and a flow hole diameter of 1.5 cm. In this setup, during high tide, the water level in the land pond reaches a peak of 53.1 cm at high tide, with a 10 cm height difference. For a 15 cm height difference, the peak height slightly decreased to 51.3 cm, while for a 20 cm height difference, it was increased to 51.6 cm.

Table 3. Relationship between the water level in the land pond and time with a hole diameter of 1.5 cm

Water Level in the Land Pond (cm) height difference 10 cm	Water Level in the Land Pond (cm) height difference 15 cm	Water Level in the Land Pond (cm) height difference 20 cm	Time (seconds) height difference 10 cm	Time (seconds) height difference 15 cm	Time (seconds) height difference 20 cm
0	0	0	0	0	0
5	5	5	563.08	499.8	414.85
10	10	10	499.92	466.99	401.78
15	15	15	521.67	504.82	420.79
20	20	20	530.11	507.31	439.53
25	25	25	530.84	493.76	453.46
30	30	30	538.92	508.24	453.53
35	35	35	539.34	491.93	467.77
40	40	40	532.75	519.16	458.19
45	45	45	543.29	505.61	466.13
50	50	50	537.08	515.49	476.86
53.1	51.3	51.6	355.1	109.78	100.79

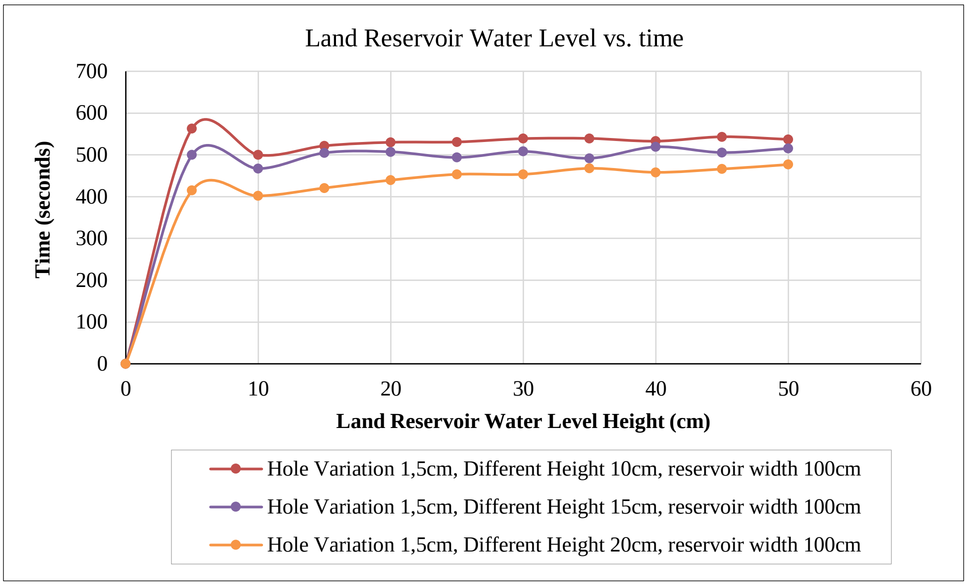


Figure 17. The relationship between water level in the land pond and time at a tidal height difference of 10 cm

Table 4 and Figure 18 showed significant differences among each variation, specifically in the case of a 100 cm width with a flow hole diameter of 1 cm. Under these conditions, during high tide, the water level in the land pond reached a peak of 39.2 cm, with a 10 cm height difference. As the height difference increases to 15 cm, the peak height slightly decreases to 38.5 cm and further decreases to 35.5 cm with a 20 cm height difference.

Table 4. Relationship between the water level in the land pond and time with a hole diameter of 1 cm

Water Level in the Land Pond (cm) height difference 10 cm	Water Level in the Land Pond (cm) height difference 15 cm	Water Level in the Land Pond (cm) height difference 20 cm	Time (seconds) height difference 10 cm	Time (seconds) height difference 15 cm	Time (seconds) height difference 20 cm
0	0	0	0	0	0
5	5	5	978.14	859.35	720.61
10	10	10	762.18	716.17	639.53
15	15	15	748.61	631.57	621
20	20	20	695.87	641.23	622.61
25	25	25	671.57	641.15	626.77
30	30	30	682.12	636.56	633.48
35	35	35	689.66	641.72	633.71
39.2	38.5	35.5	570.42	263.34	55.97

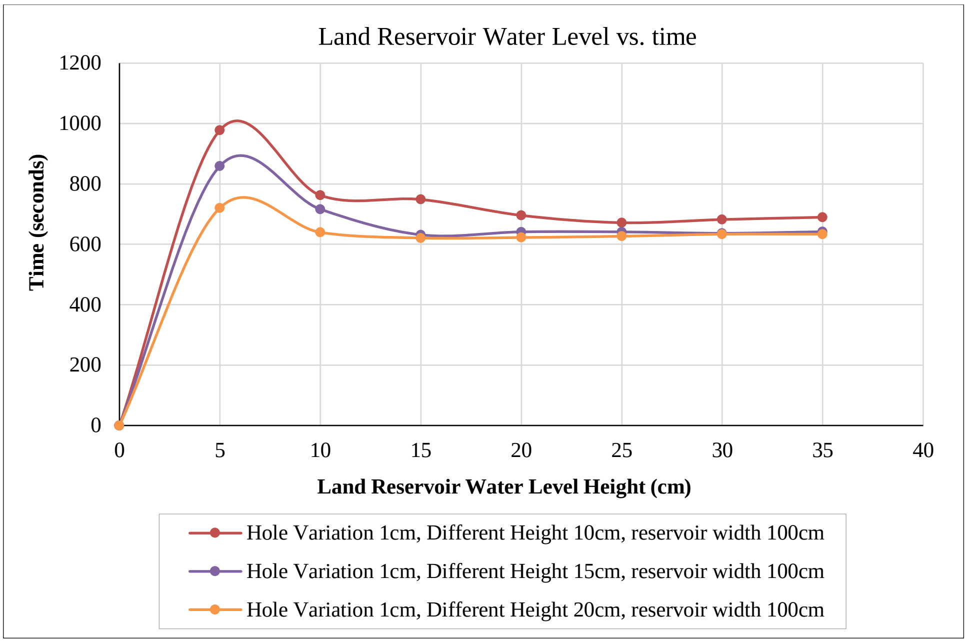


Figure 18. The relationship between water level in the land pond and time at a tidal height difference of 15 cm

The data summary for all variations in the land pond, with dimensions of 150 × 60 cm, including different flow hole diameters and heights, showed that this configuration had longer durations compared to the others. Further details are shown in Table 5 and Figure 19.

Table 5. Relationship between the water level in the land pond and time with a hole diameter of 0.5 cm

Water Level in the Land Pond (cm) height difference 10 cm	Water Level in the Land Pond (cm) height difference 15 cm	Water Level in the Land Pond (cm) height difference 20 cm	Time (seconds) height difference 10 cm	Time (seconds) height difference 15 cm	Time (seconds) height difference 20 cm
0	0	0	0	0	0
5	5	5	1893.18	1713.24	1489.31
10	10	10	1685.52	1317.68	1137.29
15	15	15	1101.12	1160.14	1080.48
19.6	19.5	19.2	1012.28	931.83	846.6

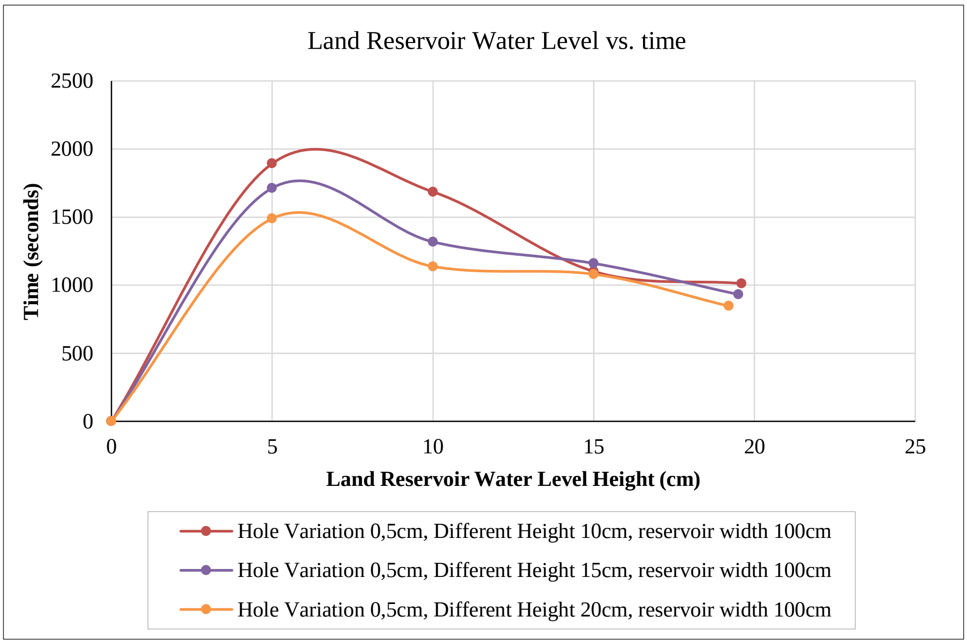


Figure 19. The relationship between water level in the land pond and time at a tidal height difference of 20 cm

Table 6 summarizes all the variations between water level in the land pond and time in the prototype model, from which it can be seen that the diameter of the flow hole and the area of the land pond greatly affect the time in this model. For more clarity between the relationship of each flow hole to time can be seen in Figures 20 to 22.

Table 6. Data summary of the relationship between water level in the land pond and time in the prototype model

Height Difference	Land Pond Length 150 × Width 100cm			Land Pond Length 150 × Width 80cm			Land Pond Length 150 × Width 60cm		
	Φ1.5 cm	Φ1 cm	Φ0.5 cm	Φ1.5 cm	Φ1 cm	Φ0.5 cm	Φ1.5 cm	Φ1 cm	Φ0.5 cm
10cm	53.1	39.2	19.6	53.9	43.5	16.5	57.4	50.8	27.5
15cm	51.3	38.5	19.5	56.2	42.1	19.4	56.7	48.9	25.2
20cm	51.6	35.5	19.2	53.2	42.3	16.5	56.5	47.5	25.2

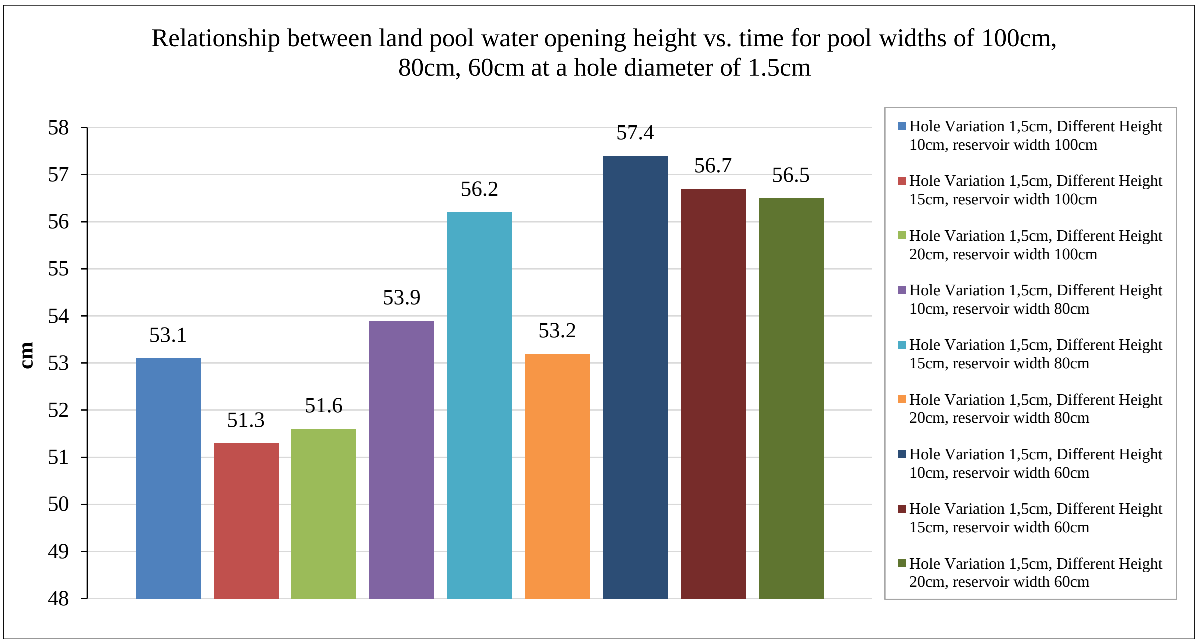


Figure 20. The relationship between water level in the land pond and time with a flow hole diameter of 1.5 cm for all variations

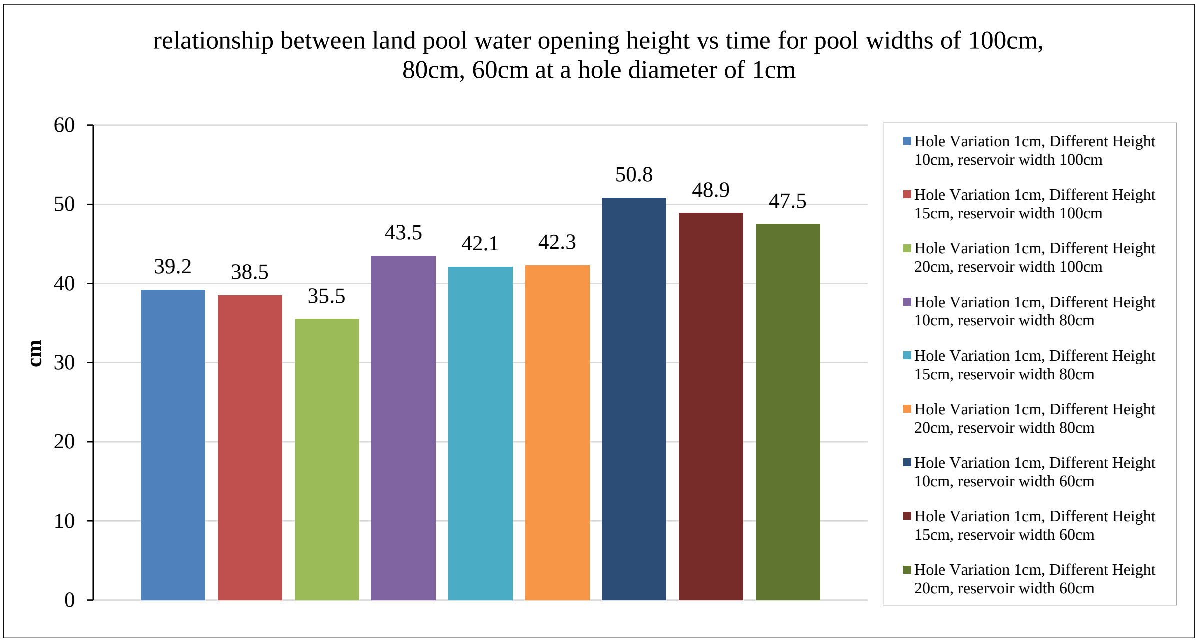


Figure 21. The relationship between water level in the land pond and time with a flow hole diameter of 1 cm for all variations

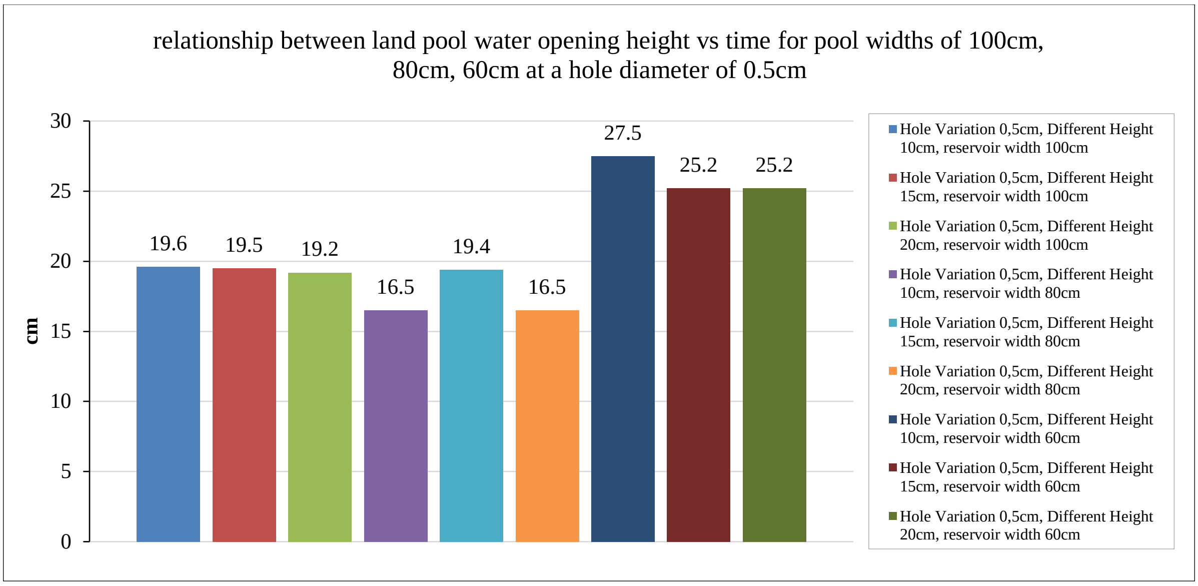


Figure 22. The relationship between water level in the land pond and time with a flow hole diameter of 0.5 cm for all variations

4.2. Research on Water Level in the Land Pond and Tidal Height Difference Model

The research on water levels in the land pond and tidal height difference model was conducted to determine the energy potential alterations for each variation. It examined water levels over time, considering variations in tidal height difference (10, 15, and 20 cm), hole diameters (1.5, 1, and 0.5 cm), and the width of the land pond (100, 80, and 60 cm).

The data summary for all variations in the land pond, with dimensions of 150×100 cm and 150×80 cm, showed significant differences in tidal height potential, especially with flow hole diameters of 1 and 0.5 cm. When the width of the land pond changes, there is an inclination towards increased tidal height magnitude for each variation, with flow hole diameters of 1 cm and 0.5 cm and a decrease with a flow hole diameter of 1.5 cm. Further details are shown in Table 7 and Figures 23 to 25.

Table 7. Summary of the largest tidal height differences in the prototype model

Height Difference	Land Pond Length 150cm × 100cm			Land Pond Length 150cm × 80cm			Land Pond Length 150cm × 60cm		
	Φ1.5cm	**Φ1cm**	**Φ0.5cm**	**Φ1.5cm**	**Φ1cm**	**Φ0.5cm**	**Φ1.5cm**	**Φ1cm**	**Φ0.5cm**
10cm	11.6	22.5	40.4	8.8	21.5	40.6	6	11.6	32.5
15cm	13.3	24.6	42.3	12.1	19	40.6	10.3	13.9	34.8
20cm	18.2	25.3	42.2	15.5	21.4	43.5	16.2	17.5	35.7

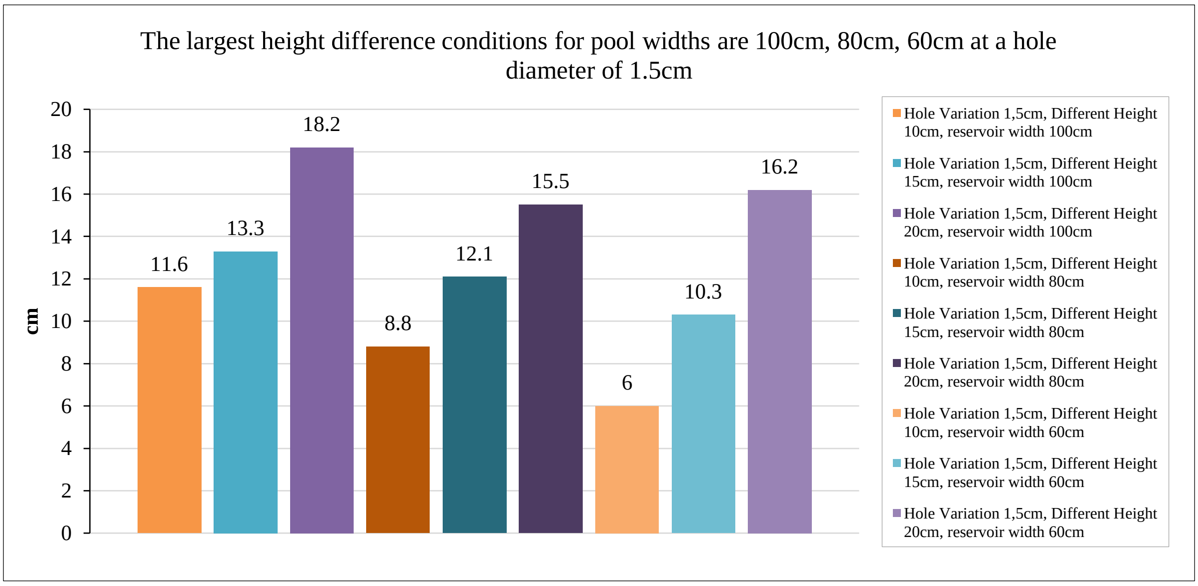


Figure 23. The relationship between water level in the land pond and time with a flow hole diameter of 1.5 cm for all variations

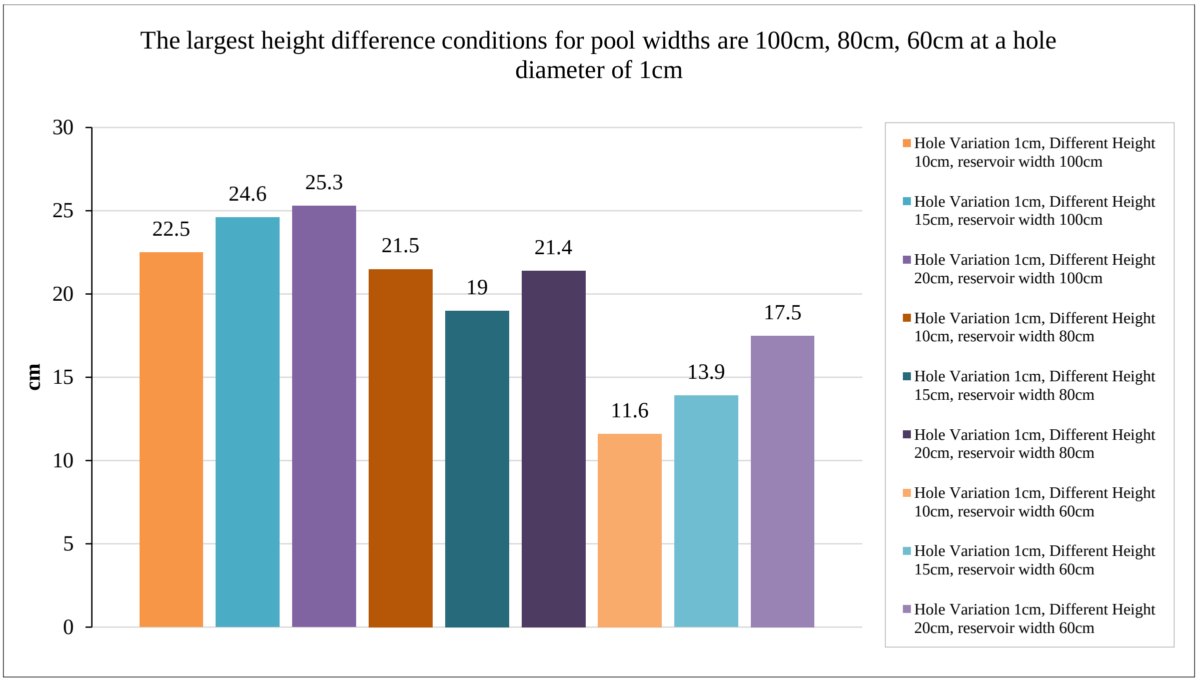


Figure 24. The relationship between water level in the land pond and time with a flow hole diameter of 1 cm for all variations

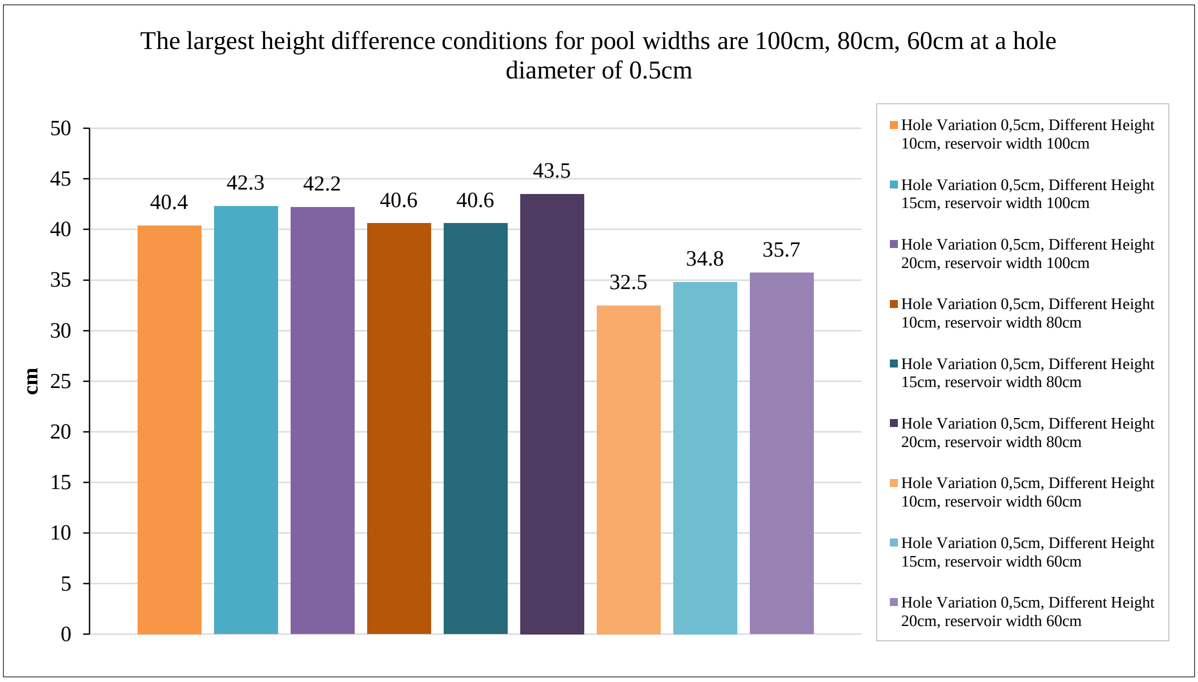


Figure 25. The relationship between water level in the land pond and time with a flow hole diameter of 0.5 cm for all variations

4.3. Research of Tidal Energy Utilization

During a single tidal cycle lasting six hours, the energy produced by E from the daily occurrence of double high tides, known as the Semi Diurnal Tide, is calculated as follows:

$$E = \frac{1}{2} \times (\eta \times \rho \times g \times A \times H^2) \tag{1}$$

Therefore, the energy produced in the designed model varied significantly according to the variations implemented, as shown Table 8 and Figure 26.

Table 8. Relationship between energy and 10 cm height difference

Length of Land Pond (cm)	Width of Land Pond (cm)	Height Difference at 1.5 cm hole	Height Difference at 1 cm hole	Height Difference at 0.5 cm hole	Energy at 1.5 cm hole (kWh)	Energy at 1 cm hole (kWh)	Energy at 0.5 cm hole (kWh)
150	100	10	10	10	146.6	146.6	146.6
150	100	11.6	18.4	27.5	197.3	496.4	1108
150	100	10.2	20.8	36.6	152.5	634.4	1964
150	100	9.6	22.2	39	135.1	722.7	2230
150	100	9.3	22.5	40.4	126.8	742.3	2393
150	100	9.2	21.8	-	124.1	696.8	-
150	100	9.1	21.4	-	242.8	1343	-
150	100	9.8	21.1	-	281.6	1305	-
150	100	9	20.8	-	237.5	1268	-
150	100	8.9	-	-	232.3	-	-
150	100	8.9	-	-	232.3	-	-
150	100	6.9	-	-	139.6	-	-

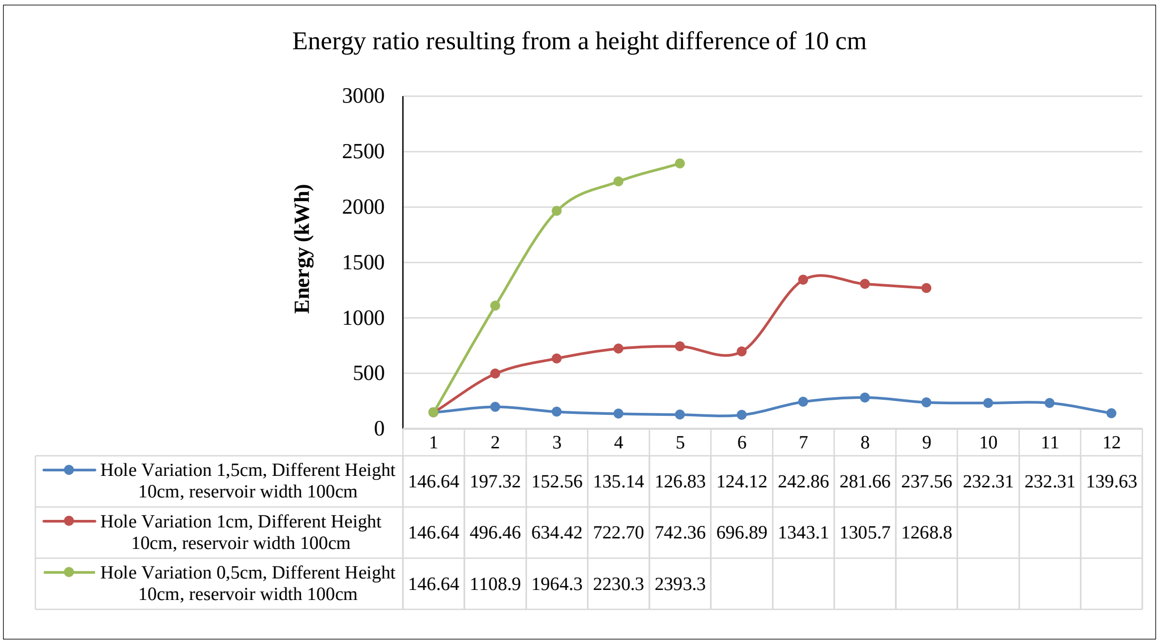


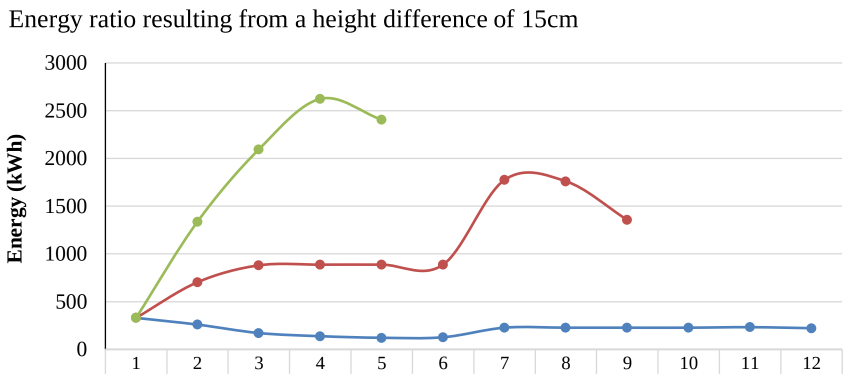
Figure 26. Energy produced at a tidal height difference of 10 cm

Based on the data in Table 8 and Figure 26, several differences in energy potential were observed, specifically in scenarios with a width and height difference of 100 cm and 10 cm, respectively. In the case of a 1.5 cm flow hole diameter, the energy produced is smaller compared to other variations at a 10 cm height difference, although it required a longer capture time, resulting in a maximum energy value of 281.66 kWh. For the 1 cm flow hole diameter, more energy is generated compared to the 1.5 cm variation, but with a shorter capture time, leading to the maximum energy value of 1343.10 kWh. The 0.5 cm flow hole diameter generated the highest energy among all other variations at a 10 cm height difference, with a maximum energy output of 2393.38 kWh. However, it required the shortest time for energy capture compared to other variations.

According to the data Table 9 and Figure 27, significant variations in energy potential were observed, particularly for the scenario with a width and height difference of 100 cm and 15 cm, respectively. In the case of a 1.5 cm flow hole variation, the energy produced is smaller than the other variations at a 15 cm height difference despite requiring a longer capture time. The maximum energy value produced is 259.39 kWh. The 1 cm flow hole diameter produced more energy compared to the 1.5 cm variation, but with a shorter capture time, resulting in the maximum energy value of 1774.80 kWh. The scenario with a 0.5 cm flow hole diameter generated the maximum energy among all other variations at a 15 cm height difference, reaching the highest energy output of 2623.80 kWh. However, it required the shortest time for energy capture compared to other variations.

Table 9. Relationship between energy and 15 cm height difference

Length of Land Pond (cm)	Width of Land Pond (cm)	Height Difference at 1.5 cm hole	Height Difference at 1 cm hole	Height Difference at 0.5 cm hole	Energy at 1.5 cm hole (kWh)	Energy at 1 cm hole (kWh)	Energy at 0.5 cm hole (kWh)
150	100	15	15	15	329.9	329.9	329.9
150	100	13.3	21.9	30.2	259.3	703.3	1337
150	100	10.8	24.5	37.8	171.0	880.2	2095
150	100	9.7	24.6	42.3	137.9	887.4	2623
150	100	9.1	24.6	40.5	121.4	887.4	2405
150	100	9.3	24.6	-	126.8	887.4	-
150	100	8.8	24.6	-	227.1	1774	-
150	100	8.8	24.5	-	227.1	1760	-
150	100	8.8	21.5	-	227.1	1355	-
150	100	8.8	-	-	227.1	-	-
150	100	8.9	-	-	232.3	-	-
150	100	8.7	-	-	221.9	-	-



	1	2	3	4	5	6	7	8	9	10	11	12
Hole Variation 1,5cm, Different Height 15cm, reservoir width 100cm	329.94	259.39	171.04	137.97	121.43	126.83	227.11	227.11	227.11	227.11	232.31	221.98
Hole Variation 1cm, Different Height 15cm, reservoir width 100cm	329.94	703.30	880.20	887.40	887.40	887.40	1774.8	1760.4	1355.6			
Hole Variation 0,5cm, Different Height 15cm, reservoir width 100cm	329.94	1337.4	2095.2	2623.8	2405.2							

Figure 27. Energy produced at a tidal height difference of 15 cm

The data from Table 10 and Figure 28 showed significant differences in energy potential, particularly in the scenario with a width and height difference of 100 cm and 20 cm, respectively. In the case of a 1.5 cm flow hole diameter, the energy produced is smaller compared to other flow hole variations at a 20 cm height difference despite requiring a longer capture time. Additionally, the maximum energy value produced was 485.73 kWh. The 1 cm flow hole diameter generated more energy compared to the 1.5 cm variation, although with a shorter capture time, resulting in the highest energy value of 1803.78 kWh. The scenario with a 0.5 cm flow hole diameter generated the highest energy among all other variations at a 20 cm height difference, with the maximum energy reaching 2611.41 kWh. However, it required the shortest capture time compared to other variations.

Table 10. Relationship between energy and 20 cm height difference

Length of Land Pond (cm)	Width of Land Pond (cm)	Height Difference at 1.5 cm hole	Height Difference at 1 cm hole	Height Difference at 0.5 cm hole	Energy at 1.5 cm hole (kWh)	Energy at 1 cm hole (kWh)	Energy at 0.5 cm hole (kWh)
150	100	20	0	20	586.5	586.5	586.5
150	100	18.2	720.6	34.7	485.7	894.6	1765
150	100	15.5	639.5	41.3	352.3	938.6	2501
150	100	13.5	621	42.2	267.2	931.2	2611.
150	100	12.9	622.6	40.8	244.0	916.4	2441.
150	100	12.6	626.7	-	232.8	909.1	-
150	100	12.2	633.4	-	436.5	1803	-
150	100	12.1	633.7	-	429.3	1774	-
150	100	12	55.97	-	422.3	1760	-
150	100	11.7	-	-	401.4	-	-
150	100	9	-	-	237.5	-	-
150	100	8.4	-	-	206.9	-	-

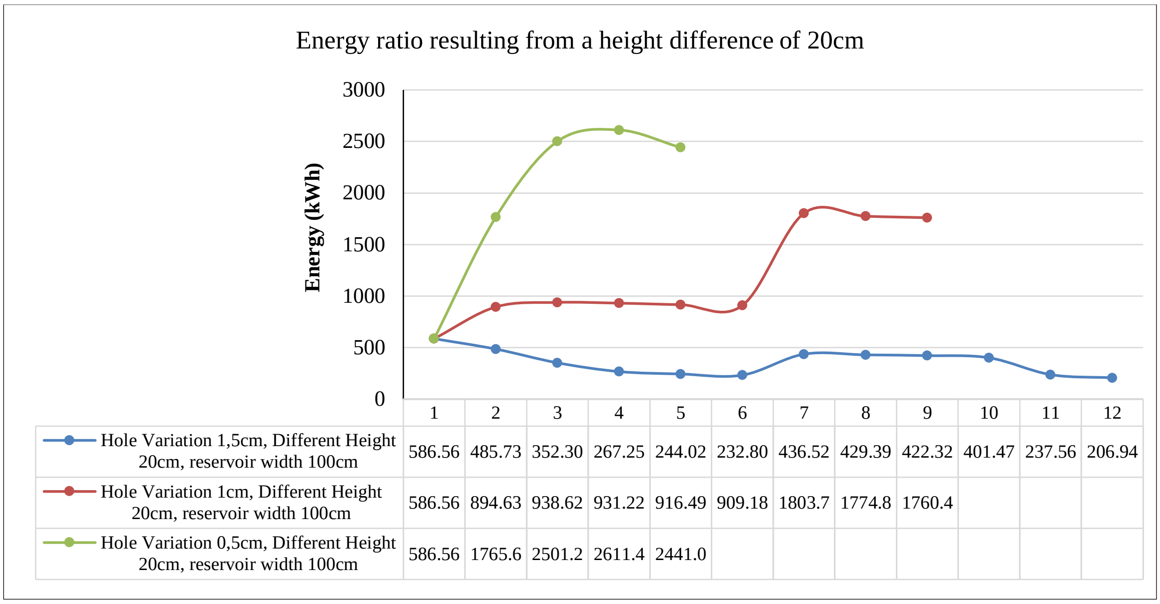


Figure 28. Energy produced at a tidal height difference of 20 cm

Although the developed model is based on predefined variations, the proposed model can also fit variational data with the same feature extraction method. Considering the data with a varying number of parameters, modifications to the model are required especially the validation of the amount of energy generated with the mini generator in the model.

The summary of data all variations showed that the maximum energy potential was achieved with a 1.5cm flow hole diameter at a 20 and 80 cm height difference and width pond, respectively, producing 281.84 kWh of energy. This setup required a longer time compared to other variations with the same flow hole diameter. The energy potential generated for the 1 cm flow hole diameter is 1774.8 kWh and 1803.78 kWh, with height differences of 15 and 20 cm, respectively, with a 100 cm width pond. Finally, with a 0.5 cm flow hole diameter, the energy potential generated is 2623.8 kWh and 2611.4 kWh at height differences of 15 and 20 cm, respectively, with a 100cm width pond. The accuracy of the model improved compared to the others. The model achieved better accuracy than all previous works due to the dataset with more variation samples (Table 11 and Figure 29 to 31).

Table 11. Summary of the largest energy potential in the prototype model

Height Differences	Land Pond Length 150cm × 100cm			Land Pond Length 150cm × 80cm			Land Pond Length 150cm × 60cm		
	Φ1.5 cm	Φ1 cm	Φ0.5 cm	Φ1.5 cm	Φ1 cm	Φ0.5 cm	Φ1.5 cm	Φ1 cm	Φ0.5 cm
10 cm	197.32	742.36	2393.3	90.85	1064	2219.8	31.67	148.9	1858.6
15 cm	259.39	1774.8	2623.8	171.76	803	1933.7	93.34	216.8	2131
20 cm	485.73	1803.78	2611.4	281.84	794.3	2219.8	230.9	297.3	1121.3

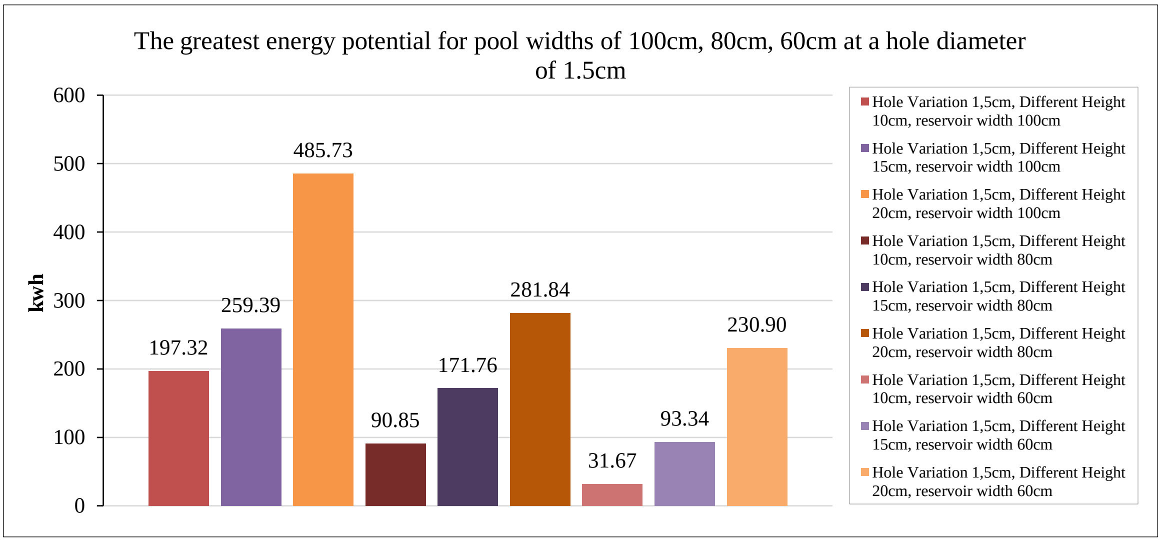


Figure 29. The largest energy potential with a flow hole diameter of 1.5 cm for all variations

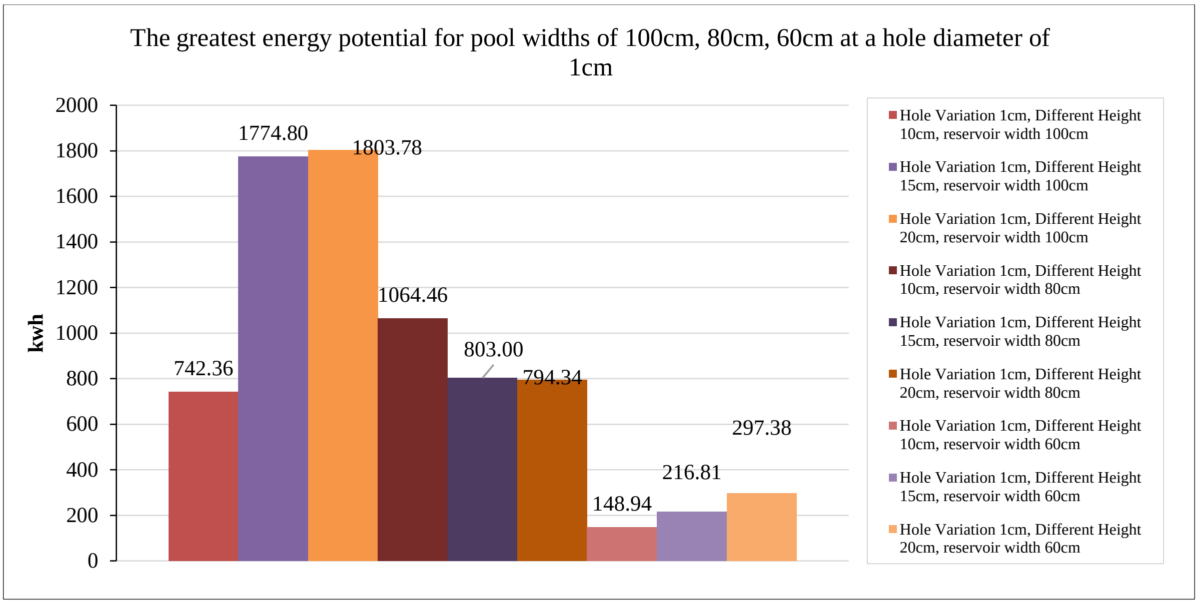


Figure 30. The largest energy potential with a flow hole diameter of 1 cm for all variations

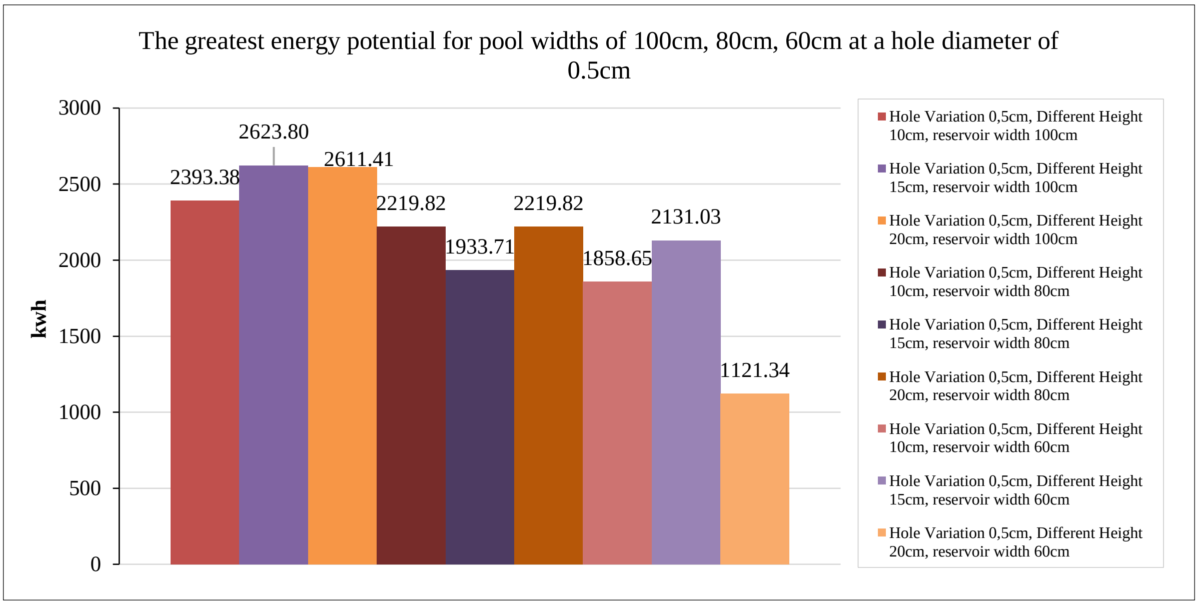


Figure 31. The largest energy potential with a flow hole diameter of 0.5 cm for all variations

5. Conclusions

In conclusion, this research obtained the following outcome:

- The flow hole diameter and height difference parameters affected the duration of water in the land pond. The smaller the land pond or reservoir with a lesser height difference, the longer it took to reach the maximum high tide peak. The variation with pond dimensions of 150 width 60 cm, height difference and flow hole diameter of 10 cm, and 1.5 cm required more time to reach the peak than the other variations.
- The initial height difference, flow hole diameter, and pond dimensions were the variables that affected the height difference in the land pond. A larger initial height difference, pond dimensions, and flow hole diameter resulted in a greater tidal height difference in the land pond. Pond dimensions of 150×100 cm and 150×80 cm showed significant potential for height differences, especially with 1 cm and 0.5 cm flow hole diameters.
- The largest energy potential in the prototype model for the 1.5 cm flow hole diameter was realized at a 20 cm and 80 cm height difference and pond width, respectively, generating 281.84 kWh of energy, which required a longer time compared to the other variations with the same flow hole diameter. For the 1 cm flow hole diameter, at height differences of 15 and 20 cm with a pond width of 100 cm, the generated energy potential was 1774.8 and 1803.78 kWh, respectively. Meanwhile, for the 0.5 cm flow hole diameter, at height differences of 15 cm and 20 cm with a pond width of 100 cm, the generated energy potential was 2623.8 and 2611.4 kWh, respectively.

6. Declarations

6.1. Author Contributions

Conceptualization, A.A.R., F.M., M.A.T., and C.P.; methodology, F.M., M.A.T. and C.P.; validation A.A.R., F.M., M.A.T., and C.P.; formal analysis, A.A.R.; investigation, A.A.R.; resources, A.A.R.; data curation, A.A.R.; writing—original draft preparation, A.A.R.; writing—review and editing, A.A.R., F.M., M.A.T., and C.P.; visualization, A.A.R.; supervision, F.M., M.A.T., and C.P.; project administration, A.A.R.; funding acquisition, A.A.R. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Acknowledgements

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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