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Archimedes Screw Turbine Design for Low-Head River: As a Pico-Hydro Power Generator for Electric Vehicle Charging

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Abstract:
One kind of turbine that capable to run with a low head of less than 1 meter is the Archimedean screw turbine. Its operational efficiency can reach 70%, and most importantly, it is also ecologically beneficial. The main function of an Archimedean screw turbine is to transform the moving water's potential energy into mechanical energy. The research uses Matlab software version R2021a to analyze the design of the turbine analyzing the dimensions of the Archimedean screw turbine with the output power needed to supply the battery of an electric vehicle with a minimum input power of 2,200 watts. The research aims to analyze the factors that influence output performance, and the parameters that influence the the Archimedean screw turbine's performance in supplying the electric vehicle battery. The findings of the study demonstrate that the dimensions of the Archimedean screw turbine design with a head of 1 meter produce an output power of 465.47 watts for one unit of the turbine, to supply the battery of an electric vehicle it requires five units of the Archimedean screw turbine connected in parallel to produce an output power of 2,327 watts or 2.3 kW. This research plays a crucial role in the development of renewable energy. Air pollution from vehicle emissions is one of the largest contributors to carbon pollution. With this research, it is possible to reduce carbon emissions from vehicles, especially in cities with low-head river streams, where these river streams can generate small-scale hydropower electricity using Archimedes screw turbines to supply electric vehicle batteries.

Keywords: Pico-hydro power plant, Renewable energy, Power output, River head, Battery supply, Electric vehicles.

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1. Introduction

Indonesia has renewable energy potential spread throughout the country, including solar, hydropower, wind, geothermal, wave, and biomass. In the context of sustainable development, current energy consumption also has the potential for energy efficiency and conservation (Yusfan et al., 2023). The National Energy Policy Regulation of the Republic of Indonesia No. 79 of 2014, Article 9 letter f, aims to achieve an optimal primary energy mix in 2025, with at least 23% coming from New and Renewable Energy (NRE), and at least 31% coming from NRE in 2050, as long as the economy is satisfied.

Law Number 30 of 2007 concerning Energy, which is founded on the concepts of justice, sustainability, and environmental awareness to promote the development of national energy resilience also energy independence, regulates the energy supply in Indonesia. This strategy has the implication that in order to fulfill domestic energy demands, there is a need for energy diversification, one of which is the creation of New and Renewable Energy (NRE). Government Regulation No. 79 of 2014 pertaining to the National Energy Policy (NEP) is a derivative of this statute (Erdiwansyah et al., 2022).

In the electricity sector, there is also a Presidential Regulation (Perpres) on the utilization of renewable energy, namely Presidential Regulation No. 14 of 2017 concerning the Acceleration of Power Infrastructure. And Ministerial Regulation of Energy and Mineral Resources Number 50 of 2017 concerning the Utilization of Renewable Energy Sources for Electricity Supply.

From the perspective of energy as a development asset, renewable energy has a significant impact in driving green, sustainable, and low-carbon economic systems. Long-term conscious development has become a trend worldwide, in response to the increasing population, human needs, and human activities that cause environmental damage.

Based on performance evaluations, Indonesia's NDC commitment for the following term must show improvement over the preceding time. On November 4, 2016, the Paris Agreement became operative, 30 days following the submission of ratification documents by more than 55 nations, accounting for 55% of the global greenhouse gas (GHG) emissions.

In accordance with Law Number 16 of 2016, which was published on October 25, 2016, Indonesia has ratified the Paris Agreement to the United Nations Framework Convention on Climate Change. Aspirations that have emerged ahead of COP27 are that each country is expected to raise its NDC targets. Based on Climate Action Tracker's calculations (2021), the current NDC targets are still insufficient to hold the global temperature rise, far from the original targets of the Paris Agreement. To achieve this, one of the ways forward is through an energy transition by increasing the usage of renewable energy sources.

In terms of geography and climate, Indonesia is very strategic in achieving many benefits from clean energy and becoming a lighthouse for renewable energy. One of the nations on earth with the greatest potential for renewable energy is Indonesia, so it can produce multiple times more energy than its current potential. If combined with nickel reserves, the main material for electric vehicle batteries, that potential will be even greater (Sulistyo, 2021)

Renewable energy potential, including hydropower, is abundant and can be utilized optimally, but there are limitations in turbine technology to utilize the energy. For medium to high head and discharge, Pelton, Francis, and Kaplan turbines are still relied on, while for low head, they have not been utilized and developed to the maximum potential, even though Indonesia has great potential.

Mini and micro hydro scales are considered possible solutions for hydropower because compared to wind and solar energy, they are less expensive to install and maintain. In addition, Indonesia has the potential to generate new and renewable energy with mini and micro hydro up to 19,385 MW, while the installed capacity is only 197.4 MW and its utilization is only about 1% (Saefulhak et al., 2017). Furthermore, although hydropower is one of Indonesia's energy sources, the Ministry of Energy and Mineral Resources reports that it contributes to electricity supply at a rate of just 6% of the country's total electricity producing capacity. It ranked fourth among energy sources after oil, coal, and gas in 2018 (Wijayanti et al., 2020).

One kind of turbine that has the ability to operate with changing flow rates and low head circumstances (5 m) and still retain great efficiency is the Archimedes Screw Turbine (Williamson et al., 2014)the operating efficiency ranges from 69% on average to over 75% at its highest (Lubitz et al., 2014). It is also environmentally friendly, especially in river habitats, where laboratory tests have shown that fish weighing under 1 kilogram are not harmed by the blade tip at flow speeds less than 4.5 m/s, and rubber can be added to the blade tips at higher flow speeds to further reduce fish injuries (Kiebel et al., 2009).

The Archimedes Screw Turbine may transform mechanical energy from potential energy in flowing water (Lubitz et al., 2014). The process of converting this energy into electrical energy involves the water volume flowing from top to bottom, creating static pressure that hits the turbine blades, causing them to rotate and turn the shaft. The power from the shaft is then transmitted to a generator to produce electrical energy. The electrical energy generated by the generator is then distributed through an inverter. This research can potentially develop renewable energy, particularly mini and micro-hydro power, in low-head river systems spread throughout Indonesia. This research aims to produce scientific studies on micro hydro power generation using the Archimedes Screw Turbine.

The novelty of this research lies in the development of renewable energy, which is a shared responsibility to find solutions for reducing carbon emissions from vehicles that use fossil fuels and to provide a source of energy to supply electric vehicle batteries from zero-emission power generation. It represents a new breakthrough in creating sustainable green energy.

In comparison to relevant previous research, some prior studies focused on designing screw turbines but delved into specific dimensional parameters without further analyzing the power output of these turbines. On the other hand, some previous studies analyzed the power output of screw turbines, but researchers used laboratory experimental methods to obtain power output analysis without designing the screw turbine itself.

The key difference in this research from the relevant previous studies is that it designs the dimensions of screw turbines by analyzing dimensional parameters using formulas from relevant literature through quantitative experimental methods. The analysis of the screw turbine's output dimensions is conducted using Matlab software version R2021a. Furthermore, the research continues by analyzing the parameters influencing the screw turbine's output in supplying electric vehicle battery charging.

This research is expected to serve as a reference for the development of screw turbine usage as a pico-hydroelectric power generator, which can be utilized as a self-sustaining, renewable, and environmentally friendly energy source. This aligns with the primary goals of global climate conferences (COP26 and COP27) and the Indonesian government's focus on utilizing renewable energy sources for electricity generation.

2. Design Method and Parameters

2.1. Experimental Qualitative Method

The experimental research method is considered a scientific method since it adheres to scientific principles, namely being objective, measurable, and concrete/empirical (Sugiyono, 2016). This research method uses formula parameters to analyze the data of the Archimedes Screw Turbine design, to obtain power output that is adjusted to the minimum input supply of electric vehicle batteries. The Matlab software (Rorres, 2000) version R2021a is used to further analyze the variables that affect the Archimedes Screw Turbine's output performance, the variables that affect the turbine's output performance, and the variables that affect the turbine's performance in delivering power to the vehicle's battery.

2.2. Analysis variables

2.2.1. The independent or predictor variables in this study are:

1. The screw turbine’s length (L)
2. The turbine’s overall length (L_B)
3. Diameter of the turbine shaft cylinder (D_i)
4. The screw’s diameter (D_o)
5. The turbine’s outer radius (R_o)
6. The turbine’s inner radius (R_i)
7. Pitch (distance between two adjacent blades of the screw) (Λ)
8. Number of turns in the screw turbine (N)
9. The turbine’s angle of inclination (β)
10. The outer screw’s angle of inclination (α)
11. The inner screw’s angle of inclination (θ)

1.2.2. The dependent or output variables are:

1. The screw turbine's total volume flow rate/total amount of water produced by the screw turbine per unit time (total flow rate) (Q_t)
2. Turbine rotation speed (n)
3. Torque (T)
4. Total torque (T_{total})
5. Water flow velocity in the screw turbine (v)
6. Radial water flow velocity along the screw turbine turns (v_{radial})
7. Axial water flow velocity in the screw turbine (v_{axial})
8. Output power/shaft power (P_{out})
9. Power in the flow (P_{avail})
10. Head (difference in height between the water inlet and outlet) (h)
11. Efficiency (ɳ)
12. Output power of the screw turbine (P_{ASG})

2.3. Parameters that determine the design dimensions of the screw turbine

Turbine Inclination Angle (Rorres, 2000):

$$\beta \leq \alpha \tag{1}$$

$$\beta \leq \theta \tag{2}$$

$$K = \tan \beta \tag{3}$$

β = Turbine inclination angle (°)
α = Inclination angle of the outer screw (°)
K = Screw inclination (dimensionless parameter)
θ = Inclination angle of the inner screw (°)

Pitch (distance between two consecutive blades/turns of the screw) (Rorres, 2000):

$$\Lambda = 2.4R_o \text{ if } \beta < 30° \tag{4}$$

$$\Lambda = 2.0R_o \text{ if } \beta = 30° \tag{5}$$

$$\Lambda = 1.6R_o \text{ if } \beta > 30° \tag{6}$$

Λ = *Pitch* (m)
R_o = Outer radius of the turbine (m)

Volume Ratio

To determine the Volume Ratio, the following equation is used (Rorres, 2000):

$$\upsilon = \frac{V_T}{\pi R_o^2 \Lambda} \tag{7}$$

$$V_T = 1.68\, R_o^2 \tag{8}$$

υ = Volume Ratio (dimensionless parameter)
V_T = Volume of water in one revolution of the turbine (m^3)

Radius Ratio

To determine the Radius Ratio, the following equation is used (Rorres, 2000):

$$\rho = \frac{R_i}{R_o} \quad (0 \leq \rho \leq 1) \tag{9}$$

R_i = Inner radius of the turbine (m)

Pitch Ratio

To determine the Pitch Ratio, the following equation is used (Rorres, 2000):

$$\lambda = \frac{KA}{2\pi R_o} \tag{10}$$

Turbine rotation speed

The equation to determine the Turbine Rotation Speed is as follows (Nuernbergk & Rorres, 2013):

$$n \leq \frac{50}{(2R_o)^{2/3}} \tag{11}$$

Turbine Volume Ratio per one rotation

The equation for determining the Turbine Volume Ratio per one rotation is as follows (Nuernbergk & Rorres, 2013):

$$\lambda v = \frac{V_T \tan_3 \beta}{2\pi^2 R_o}$$

(12)

The equation for determining the water flow velocity in the screw turbine is as follows:

$$V = \frac{Qt}{\frac{\pi}{4} Di^2} \tag{13}$$

Q_t = Total volume flow rate/total discharge (m^3/s)
D_i = Diameter of the turbine shaft cylinder (m)

The calculation of the radial flow velocity along the spiral winding of the turbine (radial velocity) may be done using the equation below:

$$V_{radial} = \frac{\pi\, Di\, n \cos\beta}{60} \tag{14}$$

The determination of the axial flow velocity of water in the helical turbine may be done using the equation below (Nuernbergk & Rorres, 2013):

$$v_{axial} = \Lambda \frac{n}{60}$$

(15)

The calculation of the height difference between two adjacent turbine blades may be done using the equation below (Lubitz et al., 2014):

$$\Delta d = \Lambda \sin(\beta) \tag{16}$$

The following equation may be used to compute the force per unit area caused by hydrostatic pressure on surfaces 1 and 2 (Lubitz et al., 2014):

$$F_1 = \frac{\rho g}{2\cos\beta}(d_o + \Delta d)^2 \tag{17}$$

$$F_2 = \frac{\rho g}{2\cos\beta} d_o^2 \tag{18}$$

The definition states that half of the turbine shaft is immersed in water, where the vertical distance from the water surface to the bottom of the blade (d_o) is such that $R_o = d_o$

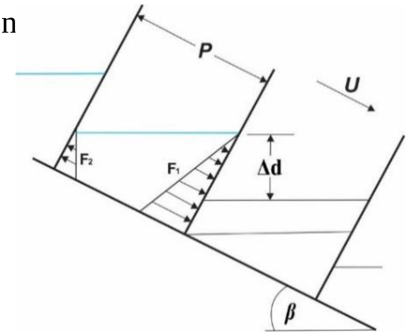


Figure 1. The simple model of forces F_1 and F_2 in a screw turbine.
Sources: Lubitz et al., 2014

The calculation of the volumetric flow rate assuming no leakage losses may be done using the equation below (Lubitz et al., 2014):

$$Q = \frac{NVn}{2\pi} \tag{19}$$

To obtain the volume of water in one cycle of turbine rotation (V), according to Nuernbergk and Rorres (2013), the following equation can be used

$$V = V_T \pi R_o^2 \Lambda \tag{20}$$

The value of V_T is described by Rorres (2000) and can be seen in equation (8).

The volume flow rate due to leakage may be determined using the equation below (Lubitz et al., 2014):

$$Q_l = 2.5\, G_w D_o^{1.5} \tag{21}$$

To obtain G_w as explained by Nuernbergk and Rorres (2013), it is determined as follows

$$G_w = 0.0045\sqrt{D_o} \tag{22}$$

The following equation may be used to determine the volume flow rate where water overflows (Lubitz et al., 2014):

$$Q_o = \frac{4}{15}\mu\sqrt{2g}\left(\frac{1}{\tan\beta} + \tan\beta\right)\left(z_{max} - z_{w}\right)^{5/2} \tag{23}$$

In this equation, μ is a constant value of 0.537, as explained by Lubitz et al. (2014). The filling factor f (f = 1), as illustrated in Figure 2, which is the water's level surface in relation to the z_{axis}, determines the depth of the water at the turbine section (bucket). While the lowest water depth z_{min} is defined as the point where the water surface is at $\theta = \pi$, $r = R_o$ at the surface of the water flow towards the downstream end of the turbine, the highest water depth z_{max} occurs once the bucket is filled, or when the water surface matches with the point $\theta = 2\pi$, $r = R_i$ the surface of the water flow towards the downstream end of the turbine, thus, it can be written as the following equation (Lubitz et al., 2014):

$$z_{min} = -R_o \cos\beta - \frac{\Lambda}{2}\sin\beta \tag{24}$$

$$z_{max} = R_i \cos\beta - \Lambda \sin\beta \tag{25}$$

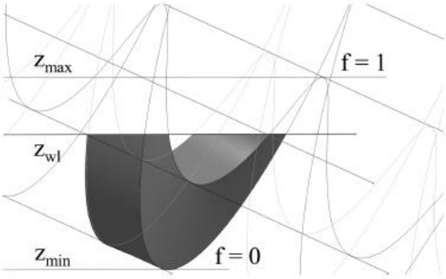


Figure 2. Water level variable. Sources: Lubitz et al., 2014

The height of the water surface for the determined filling factor f is

$$z_{wl} = z_{min} + f\,(z_{max} - z_{min}) \quad (26)$$

The following equation may be used to get the total volume flow rate of water in a helical turbine (the volume of water generated by the helical turbine per unit of time) (Lubitz et al., 2014):

$$Q_t = Q + Q_l + Q_o \quad (27)$$

When calculating the efficiency (η) and power (P), Q_t is substituted for Q in Equations (31), (33), and (34).

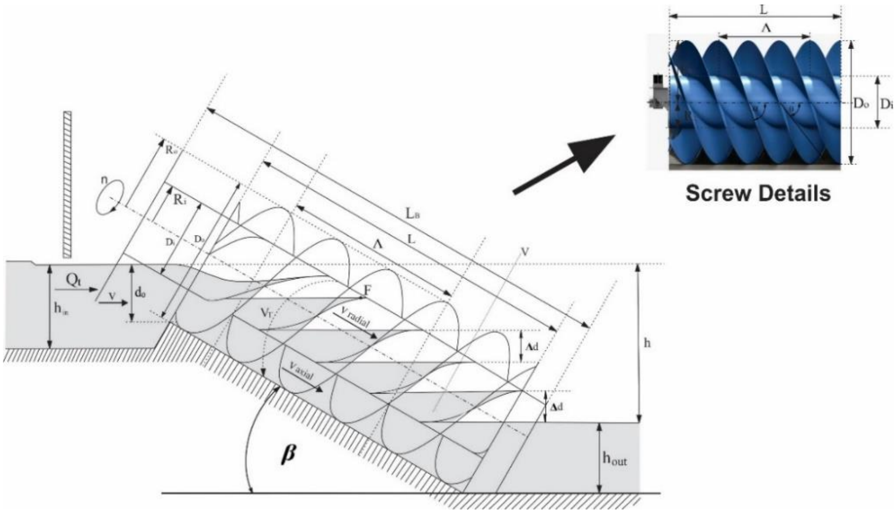


Figure 3. Archimedes Screw Turbine Design Dimensions Sources: Nuernbergk and Rorres, 2013

2.4. *The parameters that affect the output performance of a screw turbine*

This equation may be used for calculating the output power/shaft power of a cross-flow turbine (Lubitz et al., 2014):

$$P_{out} = T_{total}\, n \quad (28)$$

The following equation may be used for calculating the total torque produced by the screw turbine:

$$T_{total} = T\,\frac{LN}{\Lambda} \quad (29)$$

$$T = \int_{r=Ri}^{r=Ro} \int_{\theta=0}^{\theta=2\pi} dT \quad : \quad T = 2\pi R_o - 2\pi R_i \quad (30)$$

The following equation may be used for calculating the available power in the flow of a water turbine (Lubitz et al., 2014) :

$$P_{\text{avail}} = \rho g h Q \qquad (31)$$

g = Gravity (constant: 9.81 m/s²)
ρ = Density of water (constant: 1.000 kg/m³)

The following equation may be used for calculating the head (h):

$$h = L \sin \beta \qquad (32)$$

The following equation may be used for calculating the efficiency of the screw turbine (Lubitz et al., 2014) :

$$\eta = \frac{P_{\text{out}}}{P_{\text{avail}}} \qquad (33)$$

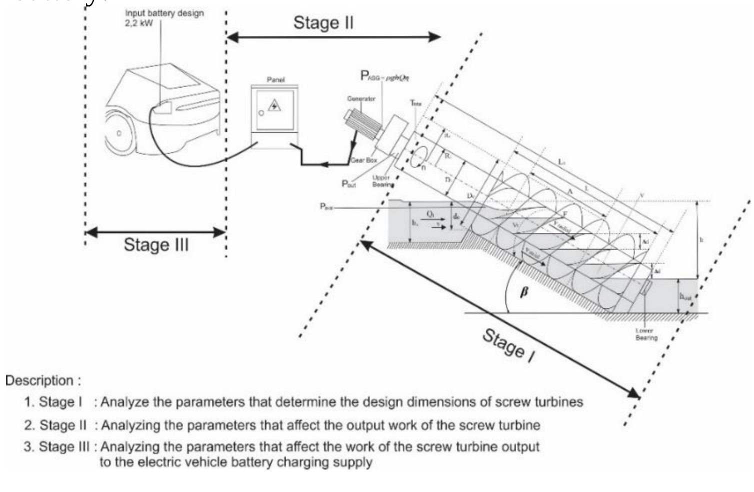
The following equation may be used for calculating the screw turbine's power output (Dellinger et al., 2018):

$$P_{ASG} = \rho g h Q \eta \qquad (34)$$

2.5. Output parameters of the screw turbine concerning the electric vehicle battery charging supply include

The parameters' impact affecting the screw turbine's output performance on the supply of electric vehicle battery charging was analyzed. The validation of research results on output performance was carried out using the power equation created by the screw turbine, which is demonstrated in equation (34). The output power of the screw turbine is influenced by water density (ρ) with a value of 1000 kg/m³, the gravitational constant (g) with a value of 9.81 m/s², total volume flow rate (Q_t), head (h), and turbine efficiency (ƞ).

In determining the appropriate dimensions of the cross-flow turbine for electric vehicle battery capacity, an analysis was carried out on the correlation of output performance between the effect of output power (P_{out}), available power (P_{avail}), total volume flow rate (Q_t), head (h), and efficiency (ƞ) on the increase of screw turbine output power (P_{ASG}), which will then be adjusted to the input capacity of the electric vehicle battery.



Description :
1. Stage I : Analyze the parameters that determine the design dimensions of screw turbines
2. Stage II : Analyzing the parameters that affect the output work of the screw turbine
3. Stage III : Analyzing the parameters that affect the work of the screw turbine output to the electric vehicle battery charging supply

Figure 4. Stages of analysis of the parameters of the screw turbine based on the research objectives

3. Results and discussion

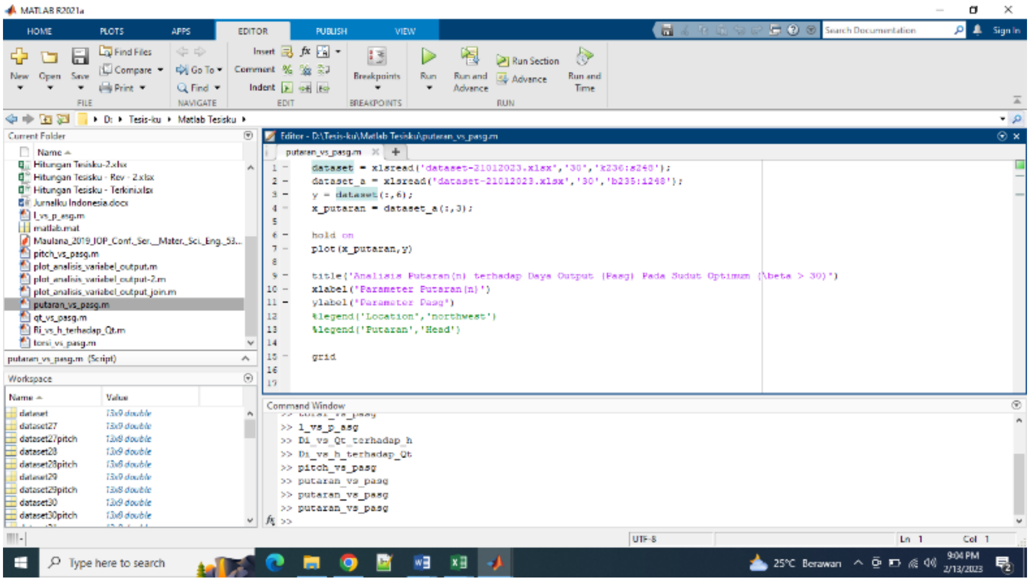
3.1. The initial parameters for design analysis

In the experimental quantitative method using formulas, the author determines the initial design parameters as the basis for obtaining an analysis of effect of the screw turbine's output performance,

Table 1. Determination of initial parameters for design analysis

Parameter	**Value**	**Unit**	**Description**	**Reference**
Do	0.838, …, 1.143	m	Diameter of the screw	Design estimate
Di	0.419, …, 0.572	m	Diameter of the turbine shaft cylinder	Design estimate
R_o	0.419, …, 0.572	m	The turbine’s outer radius	Nuernbergk & Rorres, 2013
R_i	0.210, …, 0.286	m	The turbine’s inner radius	Nuernbergk & Rorres, 2013
N	3	-	Number of coils in screw turbine	Rorres, 2000
L_B	3, …, 4	m	The overall length of the turbine	Design estimate
L	1.34, …, 1.83	m	Length of the screw turbine	Design estimate
Λ	0.671, …, 0.914	m	*Pitch*	Rorres, 2000
β	27, …, 32	°	Tubine inclination angle	Design estimate
α	34	°	The inclination angle of the outer screw	Design estimate
θ	36	°	The inclination angle of the inner screw	Design estimate

to analyze it further, the Matlab software version R2021a is used, where minimum and maximum values can be input to obtain a parameter graph, allowing for the analysis of the correlation of each parameter.



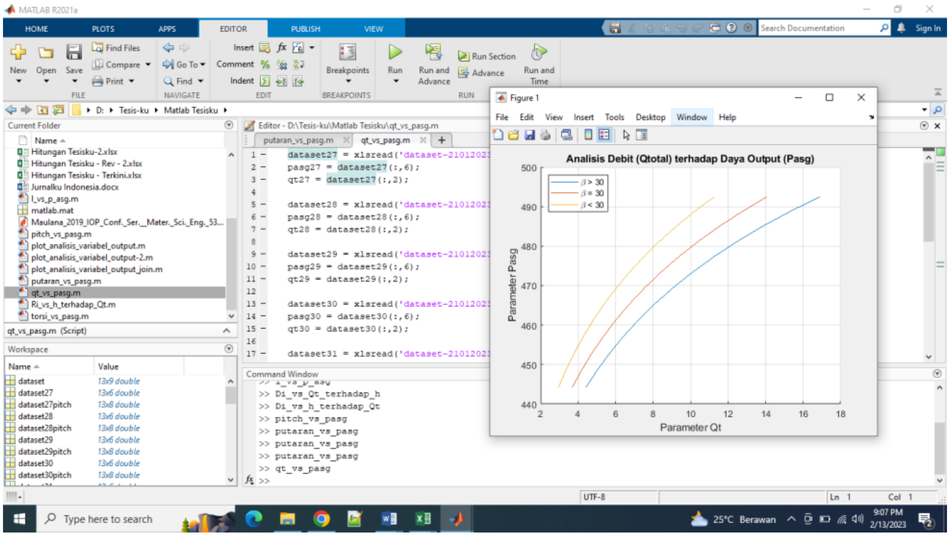
Editor - D:\Tesis-ku\Matlab Tesisku\putaran_vs_pasg.m

```
dataset = xlsread('dataset-21012023.xlsx','30','k236:s248');
dataset_a = xlsread('dataset-21012023.xlsx','30','b235:i248');
y = dataset(:,6);
x_putaran = dataset_a(:,3);

hold on
plot(x_putaran,y)

title('Analisis Putaran(n) terhadap Daya Output (Pasg) Pada Sudut Optimum (\beta > 30)')
xlabel('Parameter Putaran(n)')
ylabel('Parameter Pasg')
%legend('Location','northwest')
%legend('Putaran','Head')

grid
```

Command Window

```
>> l_vs_p_asg
>> Di_vs_Qt_terhadap_h
>> Di_vs_h_terhadap_Qt
>> pitch_vs_pasg
>> putaran_vs_pasg
>> putaran_vs_pasg
>> putaran_vs_pasg
>>
```

Figure 5. Inputting the formula of the determined parameters using Matlab version R2021a



```
dataset27 = xlsread('dataset-2101202
pasg27 = dataset27(:,6);
qt27 = dataset27(:,2);

dataset28 = xlsread('dataset-2101202
pasg28 = dataset28(:,6);
qt28 = dataset28(:,2);

dataset29 = xlsread('dataset-2101202
pasg29 = dataset29(:,6);
qt29 = dataset29(:,2);

dataset30 = xlsread('dataset-2101202
pasg30 = dataset30(:,6);
qt30 = dataset30(:,2);

dataset31 = xlsread('dataset-2101202
```

```
>> Di_vs_Qt_terhadap_h
>> Di_vs_h_terhadap_Qt
>> pitch_vs_pasg
>> putaran_vs_pasg
>> putaran_vs_pasg
>> putaran_vs_pasg
>> qt_vs_pasg
>>
```

Figure 6. The result of the parameter comparison graph on Matlab

3.2. *The optimum angle of the screw turbine*

3.2.1. *Analysis of the correlation head (h) and output power (P_{ASG})*

From the Matlab software results, a graph of the correlation head (h) and output power (P_{ASG}) was obtained by comparing the turbine inclination angle (β). Figure 7 shows the graph results, where the greater the head, the greater the output power produced. However, from the six angles, it can be observed that the 31° angle at low head (below 0.7 meters) can produce the same amount of output power as the other angles. This can lead to the conclusion that the optimum angle for a low head can be seen at 31°.

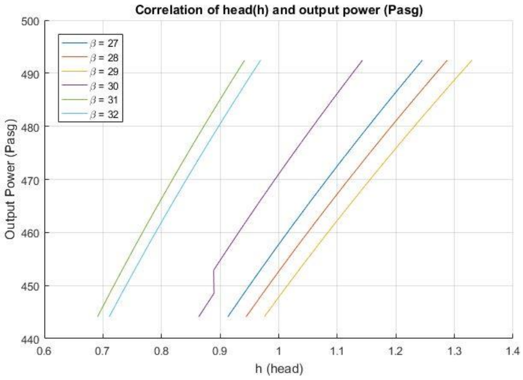


Figure 7. Graph of the analysis of the correlation head (h) and output power (P_{ASG})

One of the crucial elements that affects the turbine's operation and the output power (P_{ASG}) it produces is the head. The correlation head (h) and output power (P_{ASG}) in a screw turbine can be explained as follows.

High head (h) will generate a strong water thrust on the turbine and allow the water to have high kinetic energy when entering the turbine, resulting in high output power (P_{ASG}) of the screw turbine. Low head (h) will generate weak water thrust on the turbine and allow the water to have low kinetic energy when entering the turbine, resulting in low output power (P_{ASG}) of the screw turbine. However, if the head

(h) is too high, the water pressure on the turbine will be too high and may cause damage to the turbine. On the other hand, if the head (h) is too low, the turbine won't be capable to generate as much output power as it should. (P_{ASG}). Therefore, the head (h) in a screw turbine has a significant correlation with the output power (P_{ASG}) generated by the turbine. The selection of the appropriate head can improve the screw turbine's performance and increase the output power (P_{ASG}) generated.

3.2.2. Analysis of the correlation length of the screw turbine (L) and the power output (P_{ASG})

Next, the graph shows the correlation length of the screw turbine (L) and the power output (P_{ASG}), according to Figure 8. The longer the length of the screw turbine, the bigger the power output that may be created. However, at β > 30°, a shorter length of the screw turbine can produce the same power output as the longer one. Thus, the analysis concludes that the optimal angle with a shorter length of the screw turbine is observed at β > 30°.

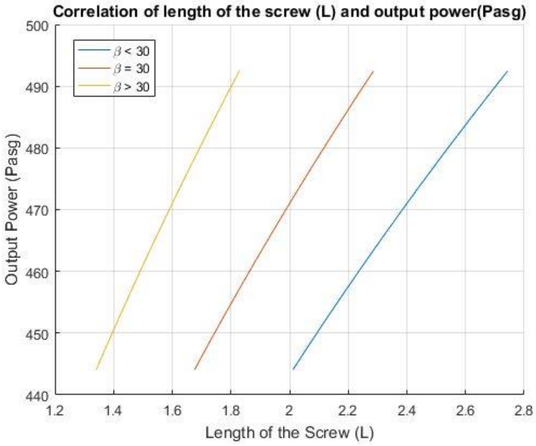


Figure 8. Graphical analysis of the correlation length of the screw turbine (L) and power output (P_{ASG})

The screw turbine's length (L) affects the number of rotations required by the water to pass through the turbine and thus affects its performance. The screw turbine's correlation length (L) and the power output (P_{ASG}) in the screw turbine can be explained as follows.

A short screw length (L) will produce a few rotations required by the water to pass through the turbine. This will result in high water flow velocity and strong water thrust on the turbine, thus the power output (P_{ASG}) of the screw turbine will be high. On the other hand, a long screw length (L) will produce many rotations required by the water to pass through the turbine. This will result in low water flow velocity and weak water thrust on the turbine, so the power output (P_{ASG}) of the screw turbine will be low. However, if the screw length of the turbine (L) is too short, the turbine will not be capable to create optimal power output (P_{ASG}) because the water does not have enough time to provide power to the turbine. Conversely, if the screw length of the turbine (L) is too long, the turbine will become too large and expensive to produce. Therefore, the screw length of the turbine (L) in the screw turbine has a significant correlation with the power output (P_{ASG}) created by the turbine. The efficiency of the screw turbine and the amount of power output (P_{ASG}) produced may both be improved by choosing the proper screw length.

3.2.3. The analysis of the correlation pitch (Λ) and power output (P_{ASG})

The graph showing the correlation pitch (Λ) and power output (P_{ASG}) is presented in Figure 9. It demonstrates that the power output is larger when the pitch (Λ) is longer. However, at β > 30°, a shorter pitch (Λ) can produce the same power output as other angles. According to this research, the optimum angle with a shorter pitch (Λ) is observed at β > 30°.

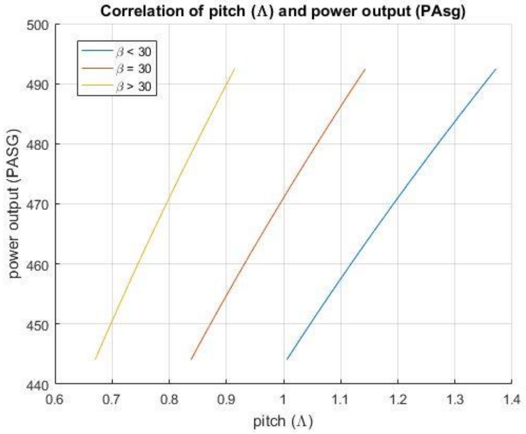


Figure 9. Graph of the analysis of the correlation pitch (Λ) and power output (P_{ASG})

Pitch has an impact on the angle of the turbine blades, which has an impact on the turbine's performance. The correlation pitch (Λ) and power output (P_{ASG}) in a screw turbine can be explained as follows.

A large pitch (Λ) will result in a small angle of inclination of the turbine blades, which will cause the thrust force generated by the screw turbine to be small and not capable to effectively drive the turbine. Therefore, the power output (P_{ASG}) of the screw turbine will be low. A small pitch (Λ) will result in a large angle of inclination of the turbine blades, which will generate a large thrust force and be able to effectively drive the turbine, resulting in a high power output (P_{ASG}) of the screw turbine. However, if the pitch (Λ) is too narrow, the water flow may become turbulent, which can lower the screw turbine's efficiency and the power output P_{ASG}) produced. As a result, there is a substantial relationship between the screw turbine's pitch (Λ) and its power output (P_{ASG}). By selecting the proper pitch, a screw turbine may operate more efficiently and create more power (P_{ASG}).

3.3. The analysis parameter design of Archimedes screw turbine

3.3.1. The analysis of total discharge (Q_t) and head (h) on the power output (P_{ASG})

The study of the total discharge (Qt) and head (h) on the power output (P_{ASG}) of the Archimedes screw turbine is shown in graph 10 as a result. The graph indicates that the larger the total water discharge (Q_t), the higher the power output (P_{ASG}) that is generated. Similarly, for a head, the Archimedes screw turbine produces more power the higher its head (h). The graph shows that all three parameters are directly proportional to each other.

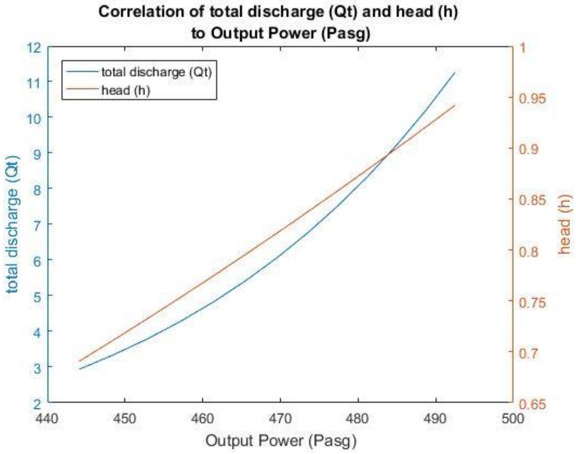


Figure 10. Analysis graph of total discharge (Q_t) and head (h) on the power output (P_{ASG})

The total flow rate (Q_t) is influenced by the diameter and pitch (Λ) (distance between two screw blades) of the Archimedes screw turbine, along with the incoming water flow's velocity (v). The larger the diameter (D_o) and pitch (Λ) of the turbine, the larger the total flow rate (Q_t) that is generated. In addition, the greater the incoming water flow's velocity (v), the larger the total flow rate (Q_t) that is generated.

Head (h) is influenced by the inclination of the Archimedes screw turbine (β), pitch (Λ) (distance between two screw blades), and the incoming water flow's velocity (v). The greater the inclination of the Archimedes screw turbine (β), the larger the head (h) that is generated. The closer the distance between the two screw blades (Λ), the larger the head (h) that is generated. The incoming water flow's velocity (v) also affects the head (h), as the larger the incoming water flow's velocity, the smaller the head (h) that is generated.

The output power (P_{ASG}) - The total flow rate (Q_t) and head (h) have an influence on the Archimedes screw turbine's output power. The larger the total flow rate (Q_t) and head (h) that are generated, the larger the output power (P_{ASG}) that is generated, as can be seen in Equation 34.

Therefore, the larger the total flow rate (Q_t) and head (h) that are generated by the Archimedes screw turbine, the larger the output power (P_{ASG}) that is generated. However, in designing the Archimedes screw turbine, it is important to consider the conditions of the water flow at the installation site, so that it can generate an optimal total flow rate and head.

3.3.2. Analyze the screw turbine length (L) and pitch (Λ) into its power output (P_{ASG})

Graph analysis of the screw length (L) and pitch (Λ) on the power output (P_{ASG}) of the Archimedes screw turbine, Figure 11 shows the graph results. The larger the screw length (L), the greater the power output (P_{ASG}) produced. The same is true for pitch (Λ), the larger the pitch, the greater the power output (P_{ASG}) produced. Therefore, it can be concluded that all three parameters are directly proportional.

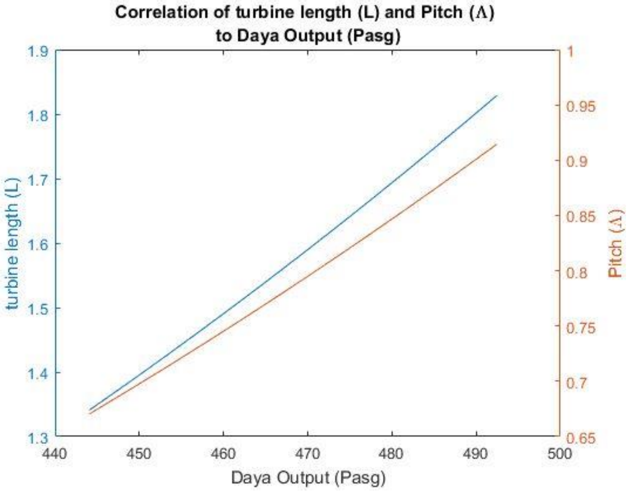


Figure 11. Graph of analysis of screw turbine length (L) and pitch (Λ) on power output (P_{ASG})

The turbine screw's length (L) affects the volume of water (V) that is contained in the turbine at any given time, and therefore, the length of the screw also affects the amount of water flowing through the turbine. The amount of water that can be contained increases with screw length, resulting in higher power output. However, a screw that is too long can also reduce the flow velocity of water (v), thus reducing the efficiency of the turbine (η). Therefore, precise analysis and calculations are needed to determine the optimal length of the screw.

The pitch (Λ) is the distance between two adjacent screw coils. The smaller the pitch, the higher the rotational speed of the blades, resulting in higher power output. However, a pitch that is too small can also reduce the efficiency of the turbine (η). Therefore, precise analysis and calculations are needed to determine the optimal pitch.

In the design of a helical turbine, L and Λ are chosen based on the head (h) and water flow rate. Therefore, in analyzing the power output (P_{ASG}), these factors must also be taken into consideration. Accurate calculations and analysis can help determine the best combination of screw length and pitch to achieve optimal power output.

3.3.3. The analysis of total discharge (Q_t) and shaft diameter (D_o) in Archimedes screw turbine design affects the head (h)

Graph 12 shows the analysis of total flow (Q_t) and turbine shaft diameter (D_o) on the head (h) in an Archimedes screw design. The higher the head (h) of the Archimedes screw, the greater the total flow of water required (Q_t), and the same goes for the diameter of the turbine shaft, which is also directly proportional.

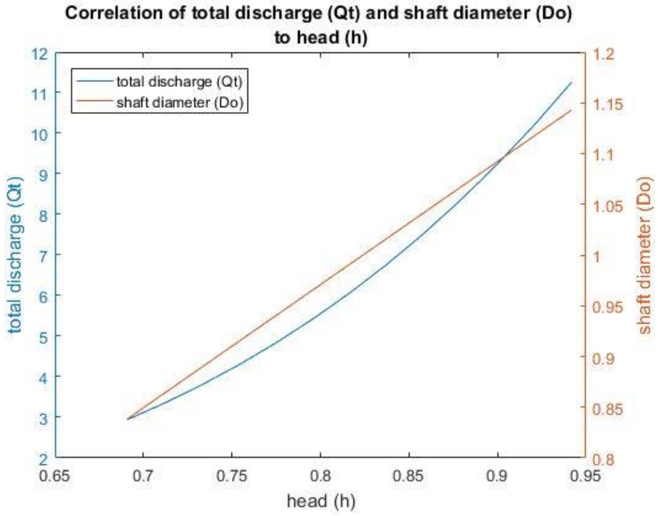


Figure 12. Total discharge (Q_t) and turbine shaft diameter (D_o) analysis on the head (h)

Total discharge (Q_t) is influenced by the diameter and pitch (distance between the screw's two blades) of the Archimedes screw turbine, along with the incoming water flow's velocity. The larger the diameter of the turbine, the greater the total discharge produced, but it should be noted that if the diameter is too large, the incoming water flow's velocity will decrease and reduce the total discharge. Meanwhile, a smaller pitch of the screw turbine will result in a higher total discharge, but a pitch that is too small can reduce the turbine's efficiency.

The Archimedes screw turbine's center shaft, which turns the generator, has the same diameter as the turbine shaft (D_o). The power generated increases with the diameter of the turbine shaft, but it should be noted that a turbine shaft diameter that is too large can make the screw turbine heavier and more difficult to install.

The screw turbine's slope, the separation between the two blades, and the speed of the incoming water flow all have an impact on head (h). The greater the slope of the screw turbine, the greater the heat produced. Additionally, the closer the distance between the two blades (Λ), the more heat is generated. The incoming water flow's velocity also affects the head; the higher the velocity, the smaller the head produced.

Therefore, the head (h) generated by an Archimedes screw turbine increases with the diameter of the turbine and total discharge (Q_t) it produces. On the other hand, the power generated increases with the diameter of the turbine shaft (D_o), but in order to produce the best total discharge, head, and power, the screw turbine's design must be changed to take into consideration the water flow at the installation location.

3.3.4. Analyses of water flow velocity (v) and total discharge (Q_t) on the power output (P_{ASG})

The graph analysis of the velocity of water flow (v) and total discharge (Q_t) against the output power (P_{ASG}) in the Archimedes screw turbine's construction, Figure 13 illustrates how the output power (P_{ASG}) of an Archimedes screw turbine increases with increasing water flow velocity (v). Similar to this, the output power (P_{ASG}) produced increases as the total discharge (Q_t) increases. From the graph, it can be concluded that all three parameters are directly proportional to each other.

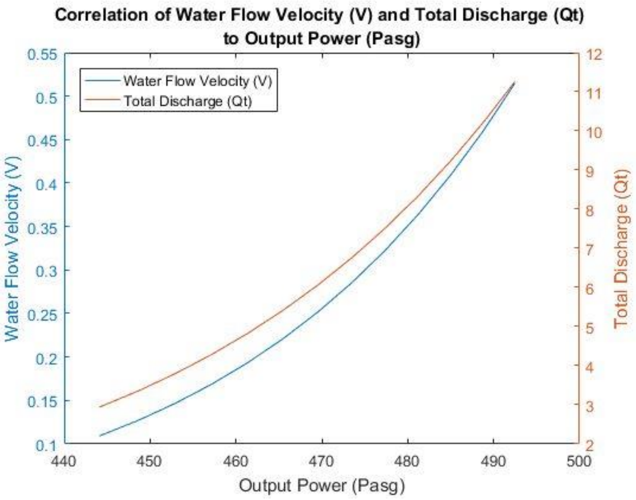


Figure 13. Graph of the water flow velocity (v) and total flow rate/total discharge (Q_t) to power output (P_{ASG})

The velocity of the water flow (v) and total flow rate (Q_t) also affect the power output (P_{ASG}) in the design of an Archimedes screw turbine. The amount of power that may be produced increases with water flow velocity or overall flow rate. This is due to the fact that when water flow velocity and total flow rate rise, water's kinetic and potential energy rises as well, increasing the possibility of producing a larger power output. To make the Archimedes screw turbine function successfully and efficiently, it is crucial to keep in mind a few restrictions when building it.

3.4. The power output of an Archimedes screw turbine in supplying electric vehicle battery charging

After analyzing the factors that impact the output power of the Archimedes screw turbine with simulation graphs through Matlab software version R2021a, the author compared them by substituting the formula equations of the Archimedes screw turbine design parameters, as shown in the following table:

Table 2. Parameters that determine the dimensions of the Archimedes screw turbine design

Do (m)	**Di (m)**	**Ro (m)**	**Ri (m)**	**N**	**LB (m)**	**L (m)**	**Λ (m)**	**n (rad/s)**	**VT (m^3)**
1.143	0.572	0.572	0.286	3	4	1.83	0.914	45.74	0.549
1.118	0.559	0.559	0.279	3	4	1.79	0.894	46.43	0.525

1.092	0.546	0.546	0.273	3	4	1.75	0.874	47.14	0.501
1.067	0.533	0.533	0.267	3	4	1.71	0.853	47.89	0.478
1.041	0.521	0.521	0.260	3	4	1.67	0.833	48.67	0.455
1.016	0.508	0.508	0.254	3	4	1.63	0.813	49.47	0.434
0.991	0.495	0.495	0.248	3	3	1.58	0.792	50.32	0.412
0.965	0.483	0.483	0.241	3	3	1.54	0.772	51.19	0.391
0.940	0.470	0.470	0.235	3	3	1.50	0.752	52.11	0.371
0.914	0.457	0.457	0.229	3	3	1.46	0.732	53.07	0.351
0.889	0.445	0.445	0.222	3	3	1.42	0.711	54.08	0.332
0.864	0.432	0.432	0.216	3	3	1.38	0.691	55.14	0.313
0.838	0.419	0.419	0.210	3	3	1.34	0.671	56.24	0.295

Table 3. Parameters that affect the performance output of the Archimedes screw turbine

***h* (m)**	**T (Nm)**	**Ttotal (Nm)**	**Qt (m^3/s)**	**Vaxial (m/s)**	**Pavail (W)**	**PASG (W)**
0.94	1.79	10.767	11.26	0.697	104018.2	492.46
0.92	1.75	10.528	10.21	0.692	92275.7	488.78
0.90	1.71	10.289	9.25	0.687	81633.9	485.05
0.88	1.67	10.049	8.35	0.681	72011.8	481.26
0.86	1.63	9.810	7.52	0.676	63332.6	477.41
0.84	1.60	9.571	6.76	0.670	55523.2	473.50
0.82	1.56	9.331	6.06	0.665	48515.3	469.52
0.80	1.52	9.092	5.41	0.659	42243.7	465.47
0.77	1.48	8.853	4.82	0.653	36647.7	461.35
0.75	1.44	8.614	4.28	0.647	31669.6	457.16
0.73	1.40	8.374	3.79	0.641	27255.6	452.89
0.71	1.36	8.135	3.35	0.635	23355.3	448.53
0.69	1.32	7.896	2.94	0.629	19921.3	444.09

Several electric vehicle brands in Indonesia can be used as samples for battery input power, such as the 2023 Hyundai Ioniq 5, which had its debut launch in Indonesia on March 31, 2022, the 2023 Honda E, the 2023 Tesla Model X 75D, Toyota bZ4X 2023 and the 2023 Gesits electric motorcycle.

Table 4. Electric vehicle battery specifications

Electric vehicle	**Types of battery**	**battery Capacity**	**Minimum battery input power**
Electric Cars			
Hyundai Ioniq 5 2022	Lithium-ion	58 kWh	2,2 kW AC
Tesla Model X 75D 2022	Lithium-ion	100 kWh	2,2 kW AC
Toyota bZ4X 2023	Lithium-ion	71,4 kWh	2,2 kW AC
Honda E 2022	Lithium-ion	35,5 kWh	2,2 kW AC
Motor Listrik			
Gesits 2022	Lithium-ion	10 kWh	1,98 DC

Based on Table 3, the author chooses a head (h) of 0.80 m, where the ideal height is 1 m, taking into account the size of the Archimedes screw turbine shaft diameter. The Archimedes screw turbine's output power (P_{ASG}) is 465.47 watts for one unit of the turbine, and based on Table 4 above, the average minimum capacity of the input of an electric vehicle battery is 2,200 watts or 2.2 kW. Therefore, the Archimedes screw turbine design can supply the electric vehicle battery by using 5 units of turbines connected in parallel to produce an output power of 2,327 watts or 2.3 kW.

The author then simulated several independent variables to obtain dependent variables in the design of the Archimedes screw turbine. This was done to avoid a design result that is focused on a single variable but rather to test various research variables.

Table 5. Simulation Analysis of Archimedes Screw Turbine Design

No	Description	Independent Variable							h (m)	Dependent Variable			
		Do (m)	Di (m)	Ro (m)	Ri (m)	LB (m)	L (m)	Λ (m)		Ttotal (Nm)	vaxial (m/s)	Qt (m^3/s)	PASG (W)
1	First Data	0,965	0,483	0,483	0,241	3	1,54	0,772	0,80	9,092	0,659	5,41	467,47
2	Simulation 1	0,965	0,483	0,483	0,241	7	5,41	0,772	0,80	31,823	0,659	5,41	1629,15
3	Simulation 2	0,965	0,483	0,483	0,242	5	3,86	0,772	1	22,730	0,659	5,41	1163,68
4	Simulation 3	0,965	0,483	0,483	0,243	10	7,72	0,772	1	45,461	0,659	5,41	2327,36

Table 5 of the simulation analysis of Archimedes screw turbine design, several variables are simulated to obtain a more optimal turbine output, such as the length of the screw turbine (L_B), the pitch length (L), and the head (h).

Simulation 1, Screw turbine length (L_B) = 7 m, Pitch length (L) = 3.86 m, and head (h) = 0.80 m, resulted in a turbine output power of P_{ASG} = 1629.15 W. The obtained power output is greater than the initial data, so to achieve the minimum input capacity of 2.2 kW for electric vehicle batteries, 2 screw turbines need to be combined in parallel, resulting in a total output power of 3,258 watts or 3.2 kW.

Simulation 2, Screw turbine length (L_B) = 5 m, Pitch length (L) = 5.41 m, and head (h) = 1 m, resulted in a turbine output power of P_{ASG} = 1163.86 W. The obtained power output is greater than the initial data, so to achieve the minimum input capacity of 2.2 kW for electric vehicle batteries, 2 screw turbines need to be combined in parallel, resulting in a total output power of 2,327.72 watts or 2.3 kW. From the simulation, it is evident that increasing the head to 1 m while reducing the screw turbine length and pitch length results in a decrease in power output.

Simulation 3, Screw turbine length (L_B) = 10 m, Pitch length (L) = 7.72 m, and head (h) = 1 m, resulted in a turbine output power of P_{ASG} = 2327.36 W. The obtained power output is greater than the initial data, so to achieve the minimum input capacity of 2.2 kW for electric vehicle batteries, only 1 screw turbine is required to produce an output power of 2,327.36 watts or 2.3 kW. In this simulation, the writer increased the screw turbine length and pitch length compared to the first and second simulations, while keeping the head at 1 m, which resulted in a higher turbine power output than simulations 1 and 2.

4. Conclusion

1. The turbine shaft diameter (D_i) = 0.483 m, screw turbine diameter (D_o) = 0.965 m, number of turns (N) = 3, shaft radius (R_i) = 0.241 m, screw turbine radius (R_o) = 0.483 m, screw turbine shaft length (L_B) = 3 m, screw length (L) = 1.54 m, pitch (Λ) = 0.772 m, shaft rotation (n) = 51.19 rad/s, water flow velocity (v) = 7.40 m/s, turbine inclination angle (β) = 31°, outer screw inclination angle (α) = 34°, and inner screw inclination angle (θ) = 36° are the characteristics that define the screw turbine's design dimensions.
2. Head (h) = 0.80 m, total torque (T_{total}) = 9.09 Nm, total discharge (Q_t) = 5.41 m^3/s, shaft power (P_{out}) = 465.47 W, power available in the flow (P_{avail}) = 42,243.73 W, and screw turbine output power (P_{ASG}) = 467.47 W are the factors that impact the screw turbine’s performance output.
3. The screw turbine’s output power about the supply for charging an electric vehicle battery was obtained from software simulation using Matlab version R2021a and equation formulas, resulting in output power of (P_{ASG}) = 465.47 watts for 1 unit of screw turbine. With the average minimum input capacity of an electric vehicle battery at 2,200 watts or 2.2 kW, the screw turbine design can supply the electric vehicle battery by using 5 screw turbines connected in parallel, producing an output power of 2,327 watts or 2.3 kW. (The data above serves as the initial data), next the writer simulated variables to obtain a more optimal turbine output power, such as screw turbine length (L_B), pitch length (L), and head (h) based on the analysis results:

a. Simulation 1, Screw turbine length (L_B) = 7 m, Pitch length (L) = 3.86 m, and head (h) = 0.80 m, resulted in a turbine output power of P_{ASG} = 1629.15 W. The obtained power output is greater than the initial data, so to achieve the minimum input capacity of 2.2 kW for electric vehicle batteries, 2 screw turbines need to be combined in parallel, resulting in a total output power of 3,258 watts or 3.2 kW.

b. Simulation 2, Screw turbine length (L_B) = 5 m, Pitch length (L) = 5.41 m, and head (h) = 1 m, resulted in a turbine output power of P_{ASG} = 1163.86 W. The obtained power output is greater than the initial data, so to achieve the minimum input capacity of 2.2 kW for electric vehicle batteries, 2 screw turbines need to be combined in parallel, resulting in a total output power of 2,327.72 watts or 2.3 kW. From the simulation, it is evident that increasing the head to 1 m while reducing the screw turbine length and pitch length results in a decrease in power output.

c. Simulation 3, Screw turbine length (L_B) = 10 m, Pitch length (L) = 7.72 m, and head (h) = 1 m, resulted in a turbine output power of P_{ASG} = 2327.36 W. The obtained power output is greater than the initial data, so to achieve the minimum input capacity of 2.2 kW for electric vehicle batteries, only 1 screw turbine is required to produce an output power of 2,327.36 watts or 2.3 kW. In this

Declaration of Competing Interest

The authors declare that they have no known financial or interpersonal disputes that may have affected the research reported in this paper.

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Notation

In this paper, the symbols listed below are employed.

Alphabet

D_i = Diameter of the turbine shaft cylinder (m)

D_o = Diameter of the screw (m)

d_o = Verticali distancei fromi the water surface to the bottom of the screw (m)

F_1 = Surface force as a function of area (N)

F_2 = Surface force as a function of area (N)

g = Gravity (constant: 9.81 m/s^2) (m/s^2)

h = Head (m)

K = Screw inclination (-)

L = The screw turbine’s length (m)

L_B = The turbine’s overall length (m)

N = Coils in screw turbine’s number (-)

n = Turbine rotation speed (rad/s)

P_{ASG} = The screw turbine’s output power (W)

P_{avail} = Power available in the flow on screw turbine (W)

P_{out} = Output power/shaft power on screw turbine (W)

Q = Flow rate in terms of volume assuming no leaks (m^3/s)

Q_l = Volume flow rate for leakage losses (m^3/s)

Q_o = Volume flow rate where water spills over (m^3/s)

Q_t = Flow rate of water on screw turbine’s total volume (m^3/s)

R_i = The turbine’s inner radius (m)

R_o = The turbine’s outer radius (m)

T = Torque (Nm)

T_{total} = Total torque (Nm)

V = Water volume in one cycle of turbine rotation (m^3)

V_T = Water volume in one rotation of the turbine (m^3)

v = Water flow velocity in the screw turbine (m/s)

v_{radial} = Radial water flow velocity along the screw turbine turns (m/s)

v_{axial} = Axial water flow velocity in the screw turbine (m/s)

z_{max} = Maximum water depth (m)

z_{min} = Minimum water depth (m)

z_{wl} = Water surface elevation for the filling factor determined by f (m)

symbol

β = Turbine inclination angle (°)

α = The outer screw's inclination angle (°)

θ = The inner screw's Inclination angle (°)

Δd = Difference in height between two adjacent turbine blades (m)

Λ = Pitch (distance between two adjacent blades of the screw) (m)

ρ = Water's density (constant: 1.000 kg/m^3) (kg/m^3)

ɳ = Efficiency of the screw turbine (−)

μ = Discharge coefficient (constant: 0.537) (−)

ρ = Radius ratio (−)

υ = Volume ratio (−)

λ = Pitch ratio (−)

$\lambda\upsilon$ = Turbine volume ratio per one rotation (−)

(-) = Dimensionless parameter

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