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Feasibility Study of Energy Production from Small Archimedes Turbines on the Coast of Bandar Abbas and Calculation of Efficiency Optimization Parameters by Linear Programming

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ABSTRACT

In this study, in addition to assessing the conditions in the coastal region of Bandar Abbas, the feasibility of utilizing Archimedes torsional turbines for renewable energy production in this area was investigated through a combination of field measurements and numerical simulations. Field studies included the measurement of environmental conditions, depth, and vessel traffic. The determination of a safe depth was based on these measurements. Additionally, the current patterns were assessed in the field, measuring key parameters like salinity, electrical conductivity, and density. To further develop the results, a numerical simulation was conducted using the ROMS numerical model to establish the hydrodynamic current patterns in the target area. Upon reviewing the outcomes with the SOLVER program and employing linear programming methods, effective constraints derived from field monitoring were created. The study explored the optimal energy efficiency of Archimedes torsional turbines under different inclinations relative to the seabed and angular velocities. The research and simulations revealed that varying the tilt of the vertical axis of the turbine within the range of 5 to 15 degrees significantly impacted the turbine's efficiency. The highest efficiency, at 75 %, was achieved at a 15-degree angle with a turbine rotation speed of 150 rpm. This result is particularly notable, considering the low slope of the studied area.

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1. INTRODUCTION

Fast depleting resources of fossils fuels and their environmental effects have forced humans to look away and seek renewable sources for sustainable development. Among all renewable sources, hydropower continues to be a promising source for energy generation and energy storage. This chapter covers advanced and emerging technologies related to hydropower plants by discussing plant classifications, turbine types, flow instabilities, and market optimization. It provides a detailed overview of the recent efforts to increase the operational range of hydraulic turbines in order to reach exceptional levels of flexibility.

Although Iran is one of the oil-rich countries in the world and has huge natural gas resources due to its high potential in the coastal areas, it can save a considerable amount of energy using the currents of waves and tides. Problems in the use of fossil fuels, as well as increasing environmental pollution, have led many developed countries to use these alternative energy sources. According to the International Renewable Energy Agency, from 2010 to 2020, the installation of renewable energy equipment from the sea and ocean has more than doubled (Figure 1). Iran has a huge maritime potential and high potential for renewable energy. Tidal energy, as one of the most important and suitable renewable sources of marine energy, can supply part of the country's energy demand and be an alternative to reduce fossil energy consumption for electricity generation. Exploiting the tidal range in the coastal strip using barriers to block coastal waters, and estuaries in a high or low position and considering tidal cycles help harness this energy. The tidal range varies from region to region because it is dependent on the longitude and latitude of a location, the hydrodynamics of the region, and the type of seabed. One of the advantages of tidal energy is its predictability as well as its seasonal fluctuations, which will lead to sustainable energy production over the years. In recent years, tidal energy has become less common among renewable energies, which highlights the need for research and study in this area. Tidal power farms and sites off the coast of Europe are currently generating renewable energy.

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There are generally different ways to use tidal currents in energy production, including tidal turbines, Archimedes torsion, tidal dams, floating structures, tidal kites, and finally artificially intelligent turbines. In the Persian Gulf, due to the low speed of coastal currents and its shallow depth, the use of heavy equipment is not cost-effective and practical, but the use of small equipment such as Archimedes torsional turbines is feasible. This turbine is one of the oldest machines used in the past and continues to function today. This equipment is known as small-scale power plants and is now widely used on the coasts of different parts of the world to produce clean and renewable energy. Low maintenance costs and ease of working with this equipment are other advantages. Archimedes torsional turbines are less harmful to marine ecosystems due to their construction (Khan et al., 2019). Archimedes turbines are slow and perform well in low currents. Due to their symmetrical shape, they can generate energy in tidal currents and, if the optimal angle and tidal velocity are calculated, the efficiency reaches above 70 % (Khan et al., 2019). Due to its simpler design than other tidal energy generation methods, the construction of the Archimedes turbine is much less expensive than other types of turbines.

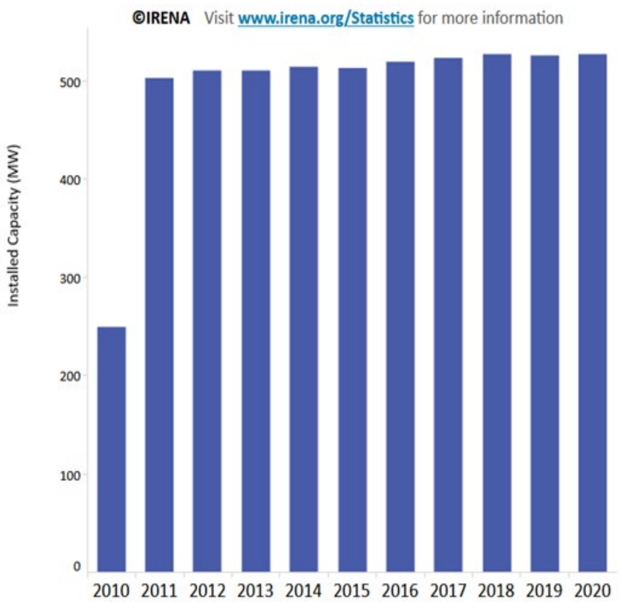

Figure 1. Installation process and use of renewable energy production equipment at sea and ocean from The International Renewable Energy Agency (IRENA)

2. BACKGROUND RESEARCH

Although the Archimedes turbine is capable of operating well in a wide range of flow values, the ability to operate at variable speeds increases this capability and leads to increased turbine efficiency (Borah, 2015). One of the good features of using this type of turbine is that its length can be determined in proportion to the installation location and flow rate by users, in addition, its flexibility brings about increased efficiency in different locations under various conditions.

In the construction of the Archimedes turbine, the parameters are divided into two categories: external and internal (Figure 2). Some of external parameters are external radius Ro, final length of pipe, and slope of the K screw. Internal parameters include the internal radius of the Ri cylinder, blade slope P, and number of blades (Saroinsong et al., 2016). The hydraulic power of the Archimedes wheel turbine in watts is obtained from Equation (1) (YoosefDoost & Lubitz, 2020):

$$P_{hyd} = \rho.g.Q.H = \rho.g.m.\Delta y \tag{1}$$

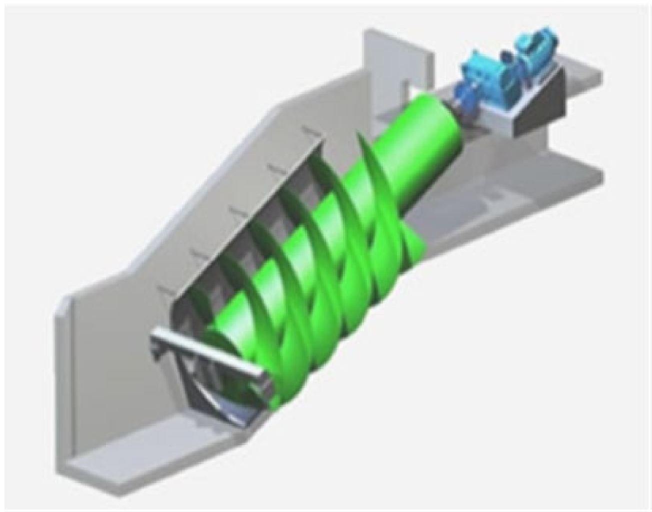

Figure 2. View of the Archimedes screw turbine (Saroinsong et al., 2016)

where ρ is water density, g gravity acceleration, Q flow rate, m number of turns, and Δy the difference in blade height on the slope. The power of a torsional turbine P is equal to the product of the torsion multiplied by T at the angular velocity of the rotation, ω, in watts, calculated by Equation (YoosefDoost & Lubitz, 2020):

$$P = T.\omega = T.\frac{2n\pi}{60} \tag{2}$$

Finally, the efficiency of the torsion turbine is (YoosefDoost & Lubitz, 2020):

$$\eta = \frac{P}{P_{hyd}}.100\ \% \tag{3}$$

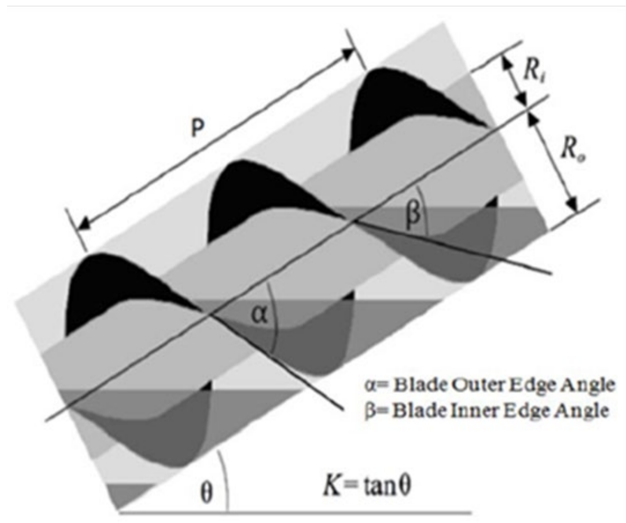

Figure 3. View of the inner and outer profiles of Archimedes turbine (Saroinsong et al., 2016)

Various researches and studies have been done on the conversion of currents, waves, and tides into energy.

Generally, the relevant studies done in Iran are of general and overview types while, in other parts of the world, they involve simulation, optimization, and improvement of the efficiency of Archimedes torsional turbines in a more specialized way. In a study, the feasibility of harnessing renewable energy from the Persian Gulf's sea has been explored. The utilization of the robust currents within the Persian Gulf is suggested as a pivotal factor (Kumar et al., 2016). In a separate study, a floating turbine was designed to leverage vertical and reciprocating tidal wave movements. Following the modeling phase, the energy production efficiency of this system was evaluated. The modeling results indicated that this turbine design exhibits commendable efficiency for energy generation on islands and adjacent coastlines (Seif Jahromi, 2016; Zabihian, 2004). To investigate the feasibility of wave energy absorption via the oscillator column system, proper modeling was used and it was found that if the height of the input waves increased by 10 %, the power of the device would increase by 40 %. In a study conducted in India, the Archimedes torsional turbine was considered as a small-scale power plant and its efficiency was improved by 85 % to 90 % upon performance enhancement (Katabdari, 2011). Another study scrutinized the relationship between external parameters impacting the efficiency of the Archimedes torsional turbine and its internal components, demonstrating that variables such as flow velocity and turbine blade thickness have a direct influence on the turbine's efficiency (Kumar et al., 2016; Suraya et al., 2015). Research on sustainable energy development using Archimedes turbines demonstrated that this type of turbine reduced sedimentation and erosion of the installation site of this equipment (YoosefDoost & Lubitz, 2020). A study on the orientation and angle of Archimedes turbines and their relationship with turbine efficiency concluded that orientation at a 22-degree angle would increase the efficiency of the 4W device by 1.4 % to 49 % (Borah, 2015).

3. METHOD AND MATERIAL

3.1. Basic studies

On the feasibility of using tidal energy, the most important point is to study the depth of the area to immerse the equipment and calculate the minimum safe depth, which is not in the path of the vessels. Moreover, the distance of dynamic systems from the shore is another important parameter in locating the equipment installation site (Kumar et al., 2016). The data required for the depth of the area were obtained from the GEBCO (General Bathymetric Chart of the Ocean) database as well as data from the surveying organization (Zarezadeh et al., 2021). Another important point to consider in examining the feasibility of equipment deployment is the distance of these tools from the habitats of birds and marine animals. Referring to Figure 4, on the eastern part of the coast, there is a gradual change in slope and depth. After covering a distance of 6 to 7 km, it reaches a depth of 8 meters. In contrast, on the western part, this depth is attained after only 1 to 2 km. The eastern coast of Bandar Abbas is predominantly influenced by the tidal zone and features a mild depth gradient.

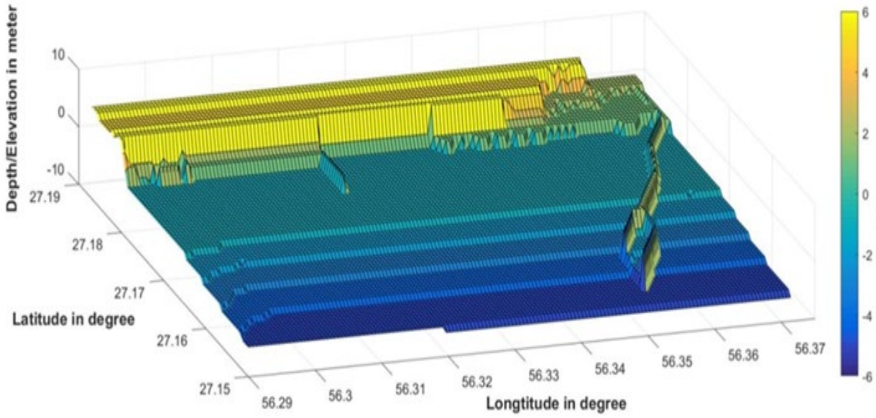

Figure 4. Bathymetry of the study area (Zarezadeh et al., 2021)

3.2. Field measurments

Field measurements are required to perform calculations related to current velocity and effective parameters in the leading study. As shown in Figure 5, for the measurement of current speed vectors and directions, the ADCP[2] device was positioned on the southern side of the pier, located at a distance of 500 meters from the shoreline. Additionally, another ADCP unit was placed on the eastern side of Bandar Abbas beach, precisely at 27.1 degrees latitude and 56.3 degrees longitude. To choose the right place to install the ADCP device, a place with suitable measuring conditions such as flat installation, distance from the post and height, a minimum flow rate of 8 cm/s, and the distance from electric and magnetic fields (Mueller & Wagner, 2013), was selected and ADCP was installed at a depth of 7 m in that location within 30 days, taking into account the presence of spring tide[3] and neap tide[4]. Based on the depth of the area and water level changes, the ADCP device with a frequency of 600 kHz was used (Mueller & Wagner, 2013). To record the current in both x and y directions, the settings of the ADCP device were configured at two time intervals in two layers with a thickness

[2] An acoustic doppler current profiler (ADCP) is a hydroacoustic current meter similar to a sonar and is used to measure water current velocities over a depth range using the Doppler effect of sound waves scattered back from particles within the water column.

[3] Tide around new moon and full moon when the Sun, Moon, and Earth form a line.

[4] Tide when the Moon is at first quarter or third quarter, the Sun and Moon are separated by 90° when viewed from the Earth.

of 2 meters. Over a 30-day measurement period, more than 4300 current velocity data were obtained. Of note, the values obtained for the current are average values at the time interval and the spatial interval specified in the device settings. The T-Tide software package is used to monitor and control tidal current data and eliminate potential outliers. Amplitude and phase of different harmonics were obtained at a confidence level of 95 %. According to the predictions, the main components of the semidiurnal and diurnal tides are M2, S2, K1, O1[5], each of which has a characteristic amplitude of oscillation and phase (Seif Jahromi, 2016). In addition to measuring inlet current velocity using ADCP, various parameters, including salinity, density, water turbidity, and temperature, were measured and monitored by CTD at 11 stations for verification and calibration. Outlier data and normality tests were conducted on this dataset. At a 95 % confidence level, the data showed no outliers and exhibited a normal distribution.

Figure 5. Position of field measurement of current and effective parameters and installation of ADCP device

3.3. ROMS simulation

Because field measurements were conducted at several stations, simulations were needed to survey the entire area. ROMS numerical model was used to simulate and study the tidal current pattern in the region. ROMS[6] is a model that is used dramatically by researchers around the world due to its algorithm type, high efficiency, and appropriate output results, and its wide application (Zarezadeh et al., 2021). As ROMS is an open-source model, it undergoes updates and algorithm improvements to align with the specific conditions of each region and adapt to new events. This iterative process enhances the model's stability, resulting in consistent and reliable output results. The model is analyzed and estimated using flow field data by Reynolds three-dimensional equations.

$$\frac{\partial}{\partial x}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h^3}{12\mu}\frac{\partial p}{\partial y}\right)=\frac{\partial y}{\partial x}\left(\frac{\rho h(u_a+u_b)}{2}\right)+\frac{\partial}{\partial y}\left(\frac{\rho h(v_a+v_b)}{2}\right)+\rho(w_a-w_b)-\rho u_a\frac{\partial h}{\partial x}-\rho v_a\frac{\partial h}{\partial y}+h\frac{\partial \rho}{\partial t} \quad (4)$$

where p is fluid film pressure, x and y are the bearing width and length coordinates, z is fluid film thickness coordinate, h is fluid film thickness, μ is fluid viscosity, ρ is fluid density, u, v, w are the bounding body velocities in x , y , z directions, respectively, and a and b are subscripts denoting the top and bottom bounding bodies, respectively.

In order to simulate the study area, a 5 km stretch of the beach in Bandar Abbas, along with a 9 km section perpendicular to the shore, was taken into account. Consequently, the model includes a dry boundary along Bandar Abbas beach and three open water boundaries. Given that field data were solely collected at open boundary 2, determining the currents at Boundaries 3 and 4 necessitated the initial model implementation for the entire Persian Gulf. After reaching a steady state, the ROMS model utilized tidal current data from T-Tide for other open boundaries. Depending on the specific area and the regions influenced by tides, a nested network was employed to simulate the entire area (Table 1). ADCP field measurement data were used to estimate the simulation accuracy in the study area (Zarezadeh et al., 2021). After setting the initial inputs of the model, it was calibrated and tidal data were employed to validate the results on open boundaries. After networking, delimitation, and boundary conditions, tidal data were generated and its information was incorporated into the ROMS model. The duration of the model is 30 days and in the study area, it is defined at time intervals of 600 seconds (Table 1). After defining all the required parameters, the model was implemented based on the output of current velocities u and v in the study area and on the coast of Bandar Abbas.

4. RESULTS AND DISCUSSION

4.1. Analysis of measurment and simulation monitoring results

Coastal tidal currents have different speeds and directions at different times. First, all the data are statistically analyzed, such that if there is outlier, this data is excluded from the calculations. For this purpose, the Grubb test was used at a 95 % confidence level, which indicated the absence of outliers in the measurement data. According to the simulated current pattern in the region, maximum velocity is 89.59 cm/s in the bed layer during the measuring month while the value of 93.81 cm/s is superficial. As expected, the maximum velocities occurred at intervals of new and full moons. WRplot software was employed to draw the rose current diagram, indicating the existence of two dominant streams (Figure 6). The mainstream is to the north, the coast of Bandar Abbas, and the tidal current is to the southwest. Considering the orientation and angle of the Nakhle Nakhoda pier towards the coast of Bandar Abbas, this direction of the mainstream is the main cause of sedimentation and erosion rates around the pier.

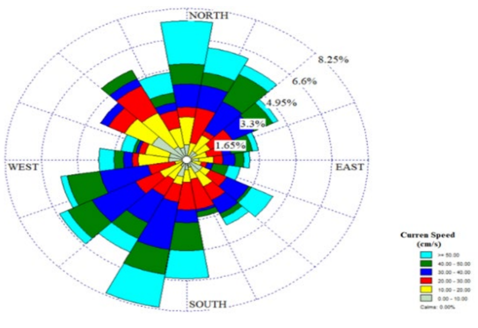

Figure 6. Diagram of the dominant rose current

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[5] K1 and O1 are tidal diurnal harmonic; M2 and S2 are tidal simidiurnal harmonic.

[6] Regional Ocean Models (ROMS).

The time course of the velocities is in accordance with the tidal period of one month in the region. The study of asymmetry in the tidal current indicates the dominance of one of the currents, which is called the dominant tide or dominant wave. Figure 7 shows the directional distribution of tidal currents with respect to periodicity. The maximum flood tidal current is 93.81 cm/s and the maximum ebb tidal current is 81.60 cm/s. This difference due to the asymmetry of the tidal current velocity leads to a change in the balance of sediment transport and in the long run, the sediment transport will go to the bay and form sedimentary hills (Borah, 2015). Measurement of important data such as salinity, temperature, acidity, and density by CTD in the operation range shows that the data have a normal distribution (Table 2). These data can also be used to analyze the feasibility of using Archimedes torsional turbines.

Table 1. Variables in the nesting for ROMS simulation (Zarezadeh et al., 2021)

Nesting name	Longitude	Latitude	Time Resolution (Second)	Space Resolution(m)
Nesting 1	56.34E-56.36E	27.16N-27.18N	600	50
Nesting 2	56.28E-56.34E	27.14N-27.17N	600	500
Nesting 3	50.01E-56.61E	24.09N-30.11N	3600	10000

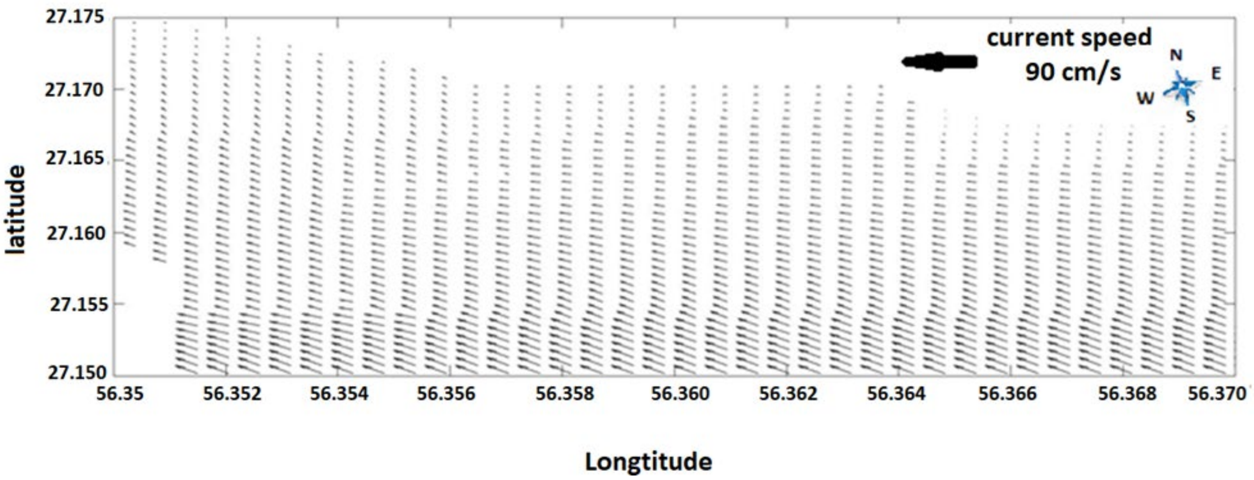

Figure 7. Current pattern simulated by ROMS in the study area

Table 2. Distribution of important parameters in the field measurement

Station number	Longitude	Latitude	Conductivity	Salinity	Dissolve oxygen	Oxygen	pH	chl-a	Turbidity
1	56.350	27.153	50.806	37.393	27.481	1.952	5.680	1.414	26.510
2	56.360	27.160	50.397	37.412	30.240	2.164	4.657	1.616	19.788
3	56.362	27.163	49.200	36.718	30.412	2.198	4.802	2.268	13.149
4	56.367	27.156	49.442	37.022	30.565	2.210	4.202	1.819	6.342
5	56.364	27.154	50.498	37.557	29.522	2.113	5.610	1.165	7.111
6	56.362	27.152	50.541	37.525	29.258	2.091	5.549	2.549	10.962
7	56.360	27.150	50.760	37.482	29.172	2.076	5.665	1.579	24.551
8	56.363	27.148	50.887	37.434	28.954	2.056	6.532	1.719	11.770
9	56.367	27.152	50.847	37.476	28.954	2.057	5.615	1.579	10.277
10	56.367	27.152	50.730	37.485	29.202	2.080	5.787	1.553	15.277
11	56.369	27.154	50.619	37.504	29.215	2.085	5.110	1.169	8.292
12	56.350	27.153	50.806	37.393	27.481	1.952	5.680	1.414	26.510
13	56.360	27.160	50.397	37.412	30.240	2.164	4.657	1.616	19.788
14	56.367	27.156	49.442	37.022	30.565	2.210	4.202	1.819	6.342
15	56.364	27.154	50.498	37.557	29.522	2.113	5.610	1.165	7.111
16	56.362	27.152	50.541	37.525	29.258	2.091	5.549	2.549	10.962
17	56.360	27.150	50.760	37.482	29.172	2.076	5.665	1.579	24.551
18	56.358	27.148	50.887	37.434	28.954	2.056	6.532	1.719	11.770
19	56.363	27.148	50.847	37.476	28.954	2.057	5.615	1.579	10.277
20	56.367	27.152	50.730	37.485	29.202	2.080	5.787	1.553	15.277
21	56.369	27.154	50.619	37.504	29.215	2.085	5.110	1.169	8.292

The uniformity of temperature, density, and salinity parameters in the measurement and simulation range and the normal distribution of this data at a 95 % confidence level indicate the correct choice of the study site.

4.2. Evaluation results for Archimedes screw turbine

The output of field measurement data as well as the output data of the model and parameters by CTD can be used to analyze and evaluate the feasibility of using the Archimedes torsional turbine. According to Relationships 1 to 3 and using the SOLVER program[7], important values are analyzed and suggestions are made about suitable values that have high efficiency. Based on Equations 1 and 2, different parameters are effective in determining the efficiency of the torsional turbine. Therefore, only a number of parameters are considered variable while others are constant. The efficiency of a torsional turbine depends on the geometry of the turbine and the changes in fluid flow (Saroinsong et al., 2016). A noteworthy point about torsional turbines is the combination of different parameters; therefore, the variation in the values of paramters affects each paramter. This mutual impact that parameters have on each other should be considered in optimizing their efficiency. It is not possible to modify all these parameters in the optimization process; thus, as a result of a large number of parameters and ambiguity in the optimization process, only some parameters are considered variable. In this research, the current velocity and the angular velocity of rotation will be selected as variable parameters.

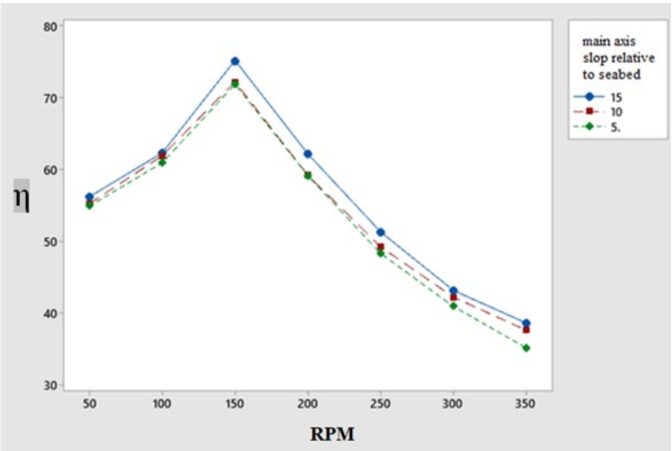

Figure 8. Comparison of efficiency changes in terms of turbine incline relative to beneath and rotational speeds (RPM)

Torsional turbine performance is calculated and estimated based on Equation 3. Figure 8 shows turbine efficiencies at three angles of 5 %, 10 %, and 15 %. According to this optimization, the maximum efficiency is at an angle of 15 degrees to the bed and 150 rpm.

5. CONCLUSIONS

The use of the output of the ROMS model in optimization calculations and finding the optimal value of RPM from coastal current data in an area with a gentle slope are the innovations of this research. The study area has not been explored enough for the use of renewable energy due to its gentle slope, high humidity, and high temperature. The primary hypothesis of this research was whether the coastal area of Bandar Abbas with a gentle slope and low current speed could be a proper place for the installation of the Archimedes turbine. Since this type of turbine is mainly used in canals and river beds, its use near the coast with constant coastal current remains the basic question of this research. Is it economical to use this type of turbine?

Due to the importance of energy consumption in the country and the relatively low cost of Archimedes turbines, this type of turbine can be used as a pilot on the coast of Bandar Abbas to generate limited energy. This turbine is not only eco-friendly but also inexpensive. These features help reduce damage to the environment, facilitate job creation, and contribute to appropriate research in this field. The diagram in Figure 9 shows the research process in summary.

Based on the findings from field data and simulations, it can be concluded that the gentle slope of the coastal area can be offset by modifying the speed of the tidal current.

Due to the shallow depth and gentle slope of the coastal region in Bandar Abbas, coupled with the low speed of the tidal current, the utilization of an Archimedes turbine is a cost-effective and appropriate choice for this area.

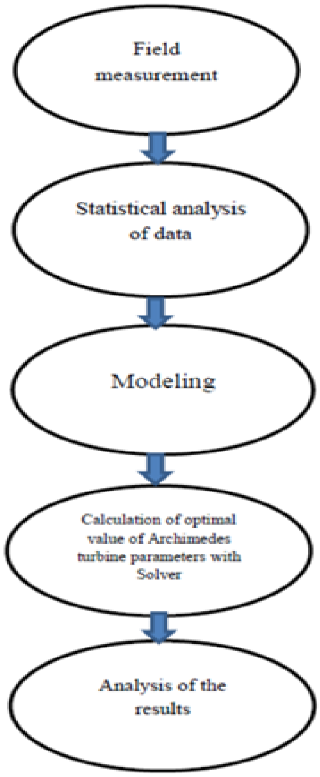

Figure 9. Flowchart to describe research steps

6. ACKNOWLEDGEMENT

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NOMENCLATURE

P	Water density (kg/m^3)
G	Gravity acceleration (m/s^2)

[7] Solver is a Microsoft Excel add-in program that can use for what-if analysis. Use Solver to find an optimal (maximum or minimum) value for a formula in one cell subject to constraints, or limits, on the values of other formula cells on a worksheet.

Q	Flow rate (m^3/s)
M	Number of turns
P	Power of a torsional turbine (w)
Ro	External radius (cm)
Ri	Internal radius (cm)
Greek letters	
Ω	Angular velocity of the rotation (Radian/s)
η	Efficiency of the torsion turbine (%)

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