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Levelized Tariff Evaluation of Hydrokinetic Energy Project: A Case Study

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Abstract—**Hydrokinetic technology, which extracts the kinetic energy of flowing water without the need for large reservoirs, is an emerging renewable energy option for sustainable power generation. The study presents a technical and financial assessment of a hydrokinetic farm deployed in the 1.0 km canal stretch in Uttarakhand, India. The proposed farm, consisting of 200 turbines supported by gearboxes, generators, pontoons, supporting structures, and anchoring systems, is capable of generating 2.42 GWh of net saleable electricity annually. The total Capital Expenditure (CapEx) is estimated as 0.528 million USD, with the gearbox contributing the maximum share due to high gear ratio requirements, followed by the turbine. The first year Operation and Maintenance (O&M) cost is calculated as 0.0217 million USD. Considering O&M costs, depreciation, interest on term loan, interest on working capital, and return on equity, the levelized tariff of electricity generation is determined as 0.045 USD/kWh. Sensitivity analysis reveals that the tariff is most influenced by CapEx. A 20% reduction in CapEx decreases the tariff to 0.036 USD/kWh, comparable to solar (0.032 USD/kWh) and wind (0.029 USD/kWh) electricity tariffs. The results confirm the techno-economic viability of canal-based hydrokinetic farms and highlight their potential as a competitive renewable energy solution.**

Keywords—**hydrokinetic technology, power generation, capital expenditure, levelized tariff, sensitivity analysis**

I. INTRODUCTION

Energy plays a vital role in the progress and development of any nation. In recent times, global warming and climate change have shifted the focus of energy generation from fossil fuels to renewable sources. Among Renewable energy resources, hydro power remains one of the most reliable and widely adopted source [1]. Traditional hydropower generation typically involves the construction of large dams to create a head, which is then utilized for power generation. However, hydrokinetic technology offers an alternative approach by harnessing the kinetic energy of flowing water. This kinetic energy is converted into mechanical energy using a hydrokinetic turbine [2]. Based on the orientation of the rotational shaft, these turbines can be broadly classified into axial flow and cross-flow types. Cross-flow turbines, with rotational axis perpendicular to flow direction, are suitable for canal and river applications. Savonius, helical Savonius, Darrieus, Gorlov turbines are few examples of cross-flow turbines [3].

The concept of hydrokinetic technology is similar to that of wind technology, where the maximum theoretical efficiency of energy conversion is limited to 59.3%, known as the Betz limit [4]. The efficiency limit is low compared to that of conventional hydropower turbines. The available hydrokinetic turbines couldn't even reach the Betz limit either. Researchers have made several efforts to enhance the performance by improving the turbine design. To generate a large amount of power, similar to a wind farm, a hydrokinetic farm is developed by installing several turbines. The performance of the farm depends on the optimal spacing between the turbines [5].

Performing only the technical investigation and focusing on enhancing power generation is insufficient to make a technology commercially viable. That's why, along with the technical investigation, financial analysis is also essential; however, this aspect has received limited attention from researchers [6]. In financial evaluation, key economic parameters such as levelized tariff of electricity, levelized cost of energy generation, net present value, payback period, discounted payback period, and internal rate of return are typically assessed [7]. The present study emphasizes the levelized tariff of electricity and its sensitivity analysis.

II. LITERATURE REVIEW

The performance of the Savonius turbine is influenced by the design parameters such as aspect ratio, end plate ratio, overlap ratio, twist angle, and number of blades [6]. Patel *et al.* [8] investigated the effect of aspect ratio at a fixed overlap ratio and reported a maximum power coefficient (C_{Pmax}) of 0.265 at an aspect ratio of 1.826. Rengma and Subbarao [9] demonstrated that a helical Savonius turbine with a 90° blade twist, an aspect ratio of 1.8, and an overlap ratio of 0.16 achieved superior performance, with a C_{Pmax} of 0.258, compared to the conventional and modified Savonius hydrokinetic turbine. A similar 90° twist angle was also adopted by Mosbahi *et al.* [10, 11]. Thiyagaraj *et al.* [12] examined the influence of the number of blades and overlap ratio, identifying the optimum values of two blades and an overlap ratio of 0.2, yielding a C_{Pmax} of 0.14. Jeon *et al.* [13] proposed the optimum endplate ratio as 1.1 times the diameter of the turbine; this value was also adopted by several other researchers for end plate diameter [14, 15]. Overall, the C_{Pmax} of helical Savonius turbines is typically around 0.2. Owing to this low power coefficient, a hydrokinetic farm was proposed to enhance overall energy extraction [16–18].

Sood and Singal [19] applied the wake recovery distance concept to determine the downstream turbine spacing. Wake recovery distance refers to the length required for approximately 85%–95% of the upstream velocity recovery, and it is generally recommended as the minimum spacing between upstream and downstream turbines [20–22]. Reddy and Bhosale [22] reported that the wake recovery distance lies in the range of 19D–25D for a helical Darrieus turbine. In addition, several researchers had suggested lateral spacing between turbines in the range of 4D–6D [17, 23, 24].

Several commercial hydrokinetic turbines are available in the market, including the Free stream Darrieus water turbine, Gorlov helical turbine, Water current turbine, DuoGen, SailGen, Davidson Hill Ventury turbine, Current 025 series turbine, and EnviroGen 005 Series turbine [25]. Since most of these turbines are developed internationally, their deployment in India would be costly due to additional expenses in capital investment (CapEx) and Operation and Maintenance (O&M). Lopez *et al.* [26] reported a higher Levelized Cost of Energy (LCOE) for tidal farms compared to other renewable energy sources due to uncertainties in the input parameters. However, the LCOE was expected to decrease as the technology matures.

India possesses an extensive canal network of about 126,334 km, offering significant untapped hydrokinetic potential [27]. If harnessed effectively, this resource can contribute to meeting the country's growing energy demand while simultaneously supporting irrigation needs. Nag and Sarkar [17] estimated the cost of energy to be 0.091 USD/kWh for a hydrokinetic farm with a triangular arrangement of the turbine for the Barakar river in Jharkhand, India. Similarly, Uttarakhand, a state in India with its vast network of canals and rivers [28], holds considerable hydrokinetic potential. Despite this, little research has been conducted to explore the techno-economic feasibility of the hydrokinetic farm.

The present study aims to investigate the techno-economic feasibility by estimating the power generation potential of a hydrokinetic farm along a 1.0 km stretch of a canal in Uttarakhand, India. In addition, the CapEx and O&M expenses will be estimated. Further, the levelized tariff of electricity generation will be evaluated and compared with other renewable energy sources.

III. METHODOLOGY

A 1.0 km stretch of a canal in Uttarakhand is selected to establish a hydrokinetic farm. The canal has a base width of 53.5 m, with a depth ranging from a minimum of 3.13 m to a maximum of 4.2 m. The flow velocity varies between 1.96 m/s and 2.3 m/s. The velocity duration curve, presented in Fig. 1. is used to estimate the total annual power generation.

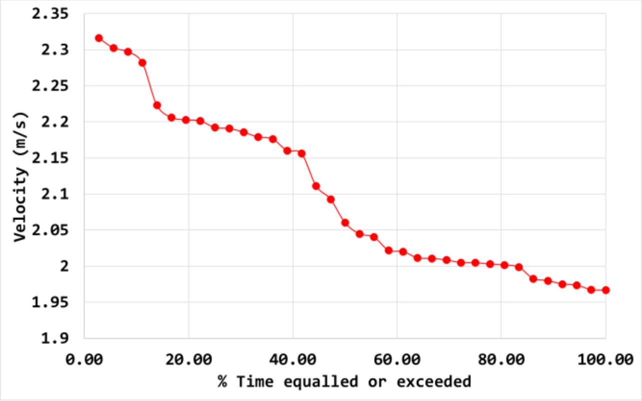

Fig. 1. Velocity duration curve for the canal.

For power generation, a cross-flow helical Savonius turbine with a 1.0 m diameter, 1.8 Aspect ratio, 90° twist angle, and 1.1D endplate diameter, 3 mm blade thickness, and C_{Pavg} of 0.22 has been considered due to its simple structure, better performance, and high starting torque.

According to the study conducted by Sood and Singal [14] on optimal turbine spacing, a rectangular arrangement is adopted with a longitudinal spacing of 40D and a lateral spacing of 6D, with additional spacing included to minimize damming and blockage effects and to ensure sufficient velocity recovery. A schematic representation of the proposed hydrokinetic farm is shown in Fig. 2.

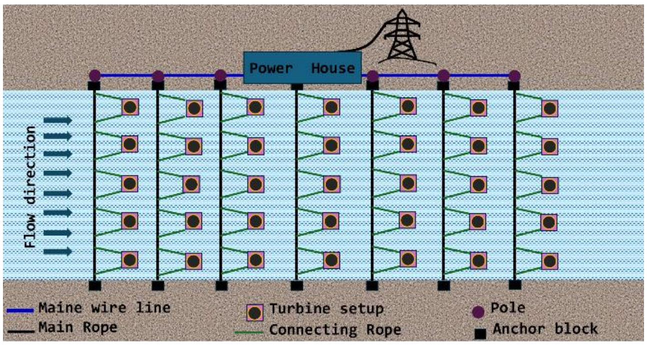

Fig. 2. Schematic representation of a hydrokinetic farm.

The farm setup consists of turbines, generators, gearboxes, pontoons, and supporting structures. Each unit is floated in the canal and tied using connecting ropes, main ropes, and anchor blocks to prevent it from flowing with the water. Electric wires are laid along the ropes, and to minimize the cost of electric wires, the powerhouse is positioned at the center of the farm. The cost of all components is obtained from manufacturers, technical reports, and market surveys, assuming large-scale production.

The procedure adopted to estimate the levelized tariff is outlined in the following steps [2, 29]:

Step 1: Estimation of the total number of turbines in the canal.

$$No.of\ turbine\ in\ a\ row\ (N_r) = \frac{Length\ of\ the\ canal}{40D} \tag{1}$$

$$No.of\ turbine\ in\ a\ column\ (N_c) = \frac{W - 12D}{6D} + 1 \tag{2}$$

$$Total\ no\ of\ turbines\ (N) = N_r \times N_c \tag{3}$$

Step 2: Calculation of gross energy generation (P_t, Wh).

$$P_t = \left(\eta_g \times \eta_G \times \eta_{con}\right) \times \left(0.5 \times C_{Pavg} \times \rho \times A \times V^3\right) \times N \times t \tag{4}$$

Step 3: Calculation of net energy generation (kWh).

$$Net\ energy\ genration = \ Gross\ enrgy\ generation - Auxiliary\ energy\ consumption \tag{5}$$

Step 4: Calculation of fixed cost.

$$\begin{aligned} &Fixed\ cost \\ &= \text{O\&M Expenses} + \text{Depreciation} \\ &+ \text{Interest on term loan} + \text{Interest on working} \\ &+ \text{Return on Equity} \end{aligned} \tag{6}$$

Step 5: Calculation of per unit tariff.

$$Per\ unit\ tariff = \frac{Yearly\ fixed\ cost}{Yearly\ net\ energy\ generation} \tag{7}$$

Step 6: Calculation of Discount Factor (DF).

$$DF = \frac{1}{(1 + discount\ rate)^{n-1}} \tag{8}$$

Step 7: Calculation of the discounted tariff.

$$Discounted\ tariff = Per\ unit\ tariff \times DF \tag{9}$$

Step 8: Calculation of Levelized tariff.

$$Levelized\ tariff = \frac{\sum_1^n Discounted\ tariff}{\sum_1^n Discount\ factor} \tag{10}$$

where, η_g is the gearbox efficiency (0.9), η_G is the Generator efficiency (0.95), η_{con} is the power drive efficiency (0.93), ρ is the density of water (kg/m^3), A is the frontal area of the turbine (m^2), V is the flow velocity (m/s), t is the time (h), and n is the year of the project.

The financial assumptions for the study are adopted from the latest Central Electricity Regulatory Commission (CERC) of India guidelines, and the details are mentioned in Table 1.

Table 1. Financial parameters for the hydrokinetic project

S.No.	Parameters	Value
1.	Project life	25 years
2.	Debt to equity ratio	70:30
3.	Loan tenure	16 years (including 1 year moratorium period)
4.	Annual loan interest rate	10.75%
5.	Depreciation	First 15 years—4.67% Reaming years-Equally distributed
6.	Annual Interest rate on working capital	12%
7.	Return on equity	First 20 years—17.65 % After 20 years—20%
8.	O&M expenses	First year—4.10% Escalation rate—5.25%
9.	Discount rate	10.73%
10.	No. of days in a year	365

Utilizing Eqs. (1)–(10) along with the financial parameters mentioned in Table 1, the levelized tariff of electricity generation is estimated. Further, a sensitivity analysis is performed considering a 20% variation in the cost of major components such as turbine, gearbox, generator, anchoring, electric wire, wire rope, transformer, supporting structure, and pontoons. Along with this, the effect of 20% variation in CapEX, O&M cost, and discount rate has also been observed. For currency conversion, an exchange rate of 1 INR equals 0.011 USD is applied.

IV. RESULT AND DISCUSSION

This section presents the results for the estimated annual power generation, CapEx and O&M expenses, levelized tariff of electricity generation, and sensitivity analysis, as outlined in the following subsections.

A. Annual Power Generation

For a hydrokinetic farm employing 1.0 m diameter helical Savonius turbines with a longitudinal spacing of 40D, 25 turbines can be arranged along the 1.0 km canal length in a row (Eq. (1)). Considering the canal base width of 53.5 m and a lateral spacing of 6D, eight turbines can be positioned across the width in a column (Eq. (2)). Thus, a total of 200 turbines are deployed in the canal stretch. Consequently, the installation requires 200 gearboxes, 200 permanent magnet synchronous generators, 200 supporting structures, and 200 pairs of pontoons. Using Eq. (4) and the velocity duration curve presented in Fig. 1, the total annual power generation is estimated as 2.57 GWh. Accounting for auxiliary consumption of 1% (0.024 GWh), and a plant availability reduction of 5% (0.129 GWh), the net annual saleable power is calculated as 2.42 GWh (Eq. (5)).

B. Capital Expenditure (CapEx) and O&M Costs

The cost of the major civil and electromechanical components, such as anchoring, turbine, gearbox, generator, supporting structure, electric wire, wire rope, transformer, pontoon, current transformer and potential transformer, and 11 kV circuit breaker, is obtained from manufacturers, industrialists, and market surveys. Since the technology is still in its early development stage and some uncertainties exist regarding installation and unforeseen expenses, an additional 25% has been added to the estimated cost to account for minor components and other expenses. The total project CapEX is estimated to be 0.528 million USD. The percentage distribution of cost across different components is illustrated in Fig. 3.

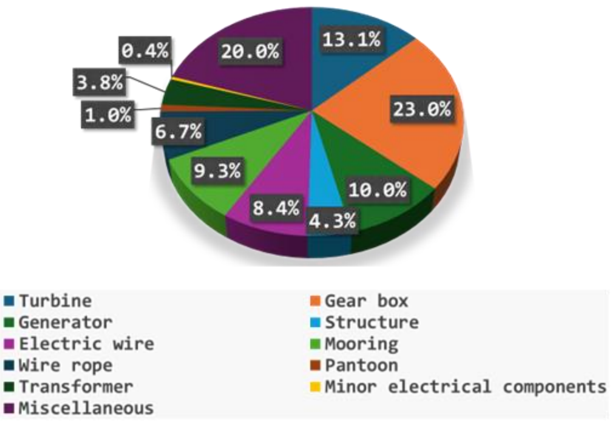

Fig. 3. Cost distribution of different components under CapEx.

As shown in Fig. 3, the gearbox contributes the largest share of the CapEx, primarily due to the need for a high gear ratio to match the low rotational speed of the turbine with the generator requirements. Miscellaneous costs form the next major portion, followed by the turbine, which accounts for approximately 13% of the total CapEx. The mooring, which includes the anchor block and earth excavation, represents 10% of the CapEx. Under the minor electric components category, the cost of circuit breaker, CT and PT, and relay are added. The O&M expense for the first year of operation is estimated as 0.0217 million USD, with an annual escalation rate of 5.25% applied for subsequent years.

C. *Levelized Tariff*

Considering the financial parameters mentioned in Table 1, annual O&M expenses, depreciation, interest on term loan, interest on working capital, and return on equity are estimated for the entire 25-year project life. For the first year of operation, these costs are calculated as 0.022 million USD (O&M), 0.025 million USD (depreciation), 0.038 million USD (interest on term loan), 0.003 million USD (interest on working capital), and 0.028 million USD (return on equity), as shown in Fig. 4. The year-wise variation of all these costs are shown in Fig. 5. O&M expenses steadily increase over time because of the escalation rate, which is reasonable since older plants require more maintenance. Depreciation is 0.025 million USD annually for the first 15 years and is equally distributed thereafter at 0.011 million USD per year.

Return on equity remains constant with a value of 0.028 million USD until year 20, after which, for the following year, it is estimated as 0.032 million USD. Interest on working capital increases gradually, reflecting its dependency on O&M costs.

Interest on the term loan is payable until the 15th year, after which no further payments are required. By adding all these components, the annual fixed cost is determined (Eq. (6)). Further, using Eqs. (7)–(10), the levelized tariff of electricity generation is estimated as 0.045 USD/kWh. This value is less than the levelized tariff of small hydro power projects (<5 MW capacity) in Uttarakhand, India, reported as 0.058 USD/kWh [30], indicating that hydrokinetic projects are cost-competitive.

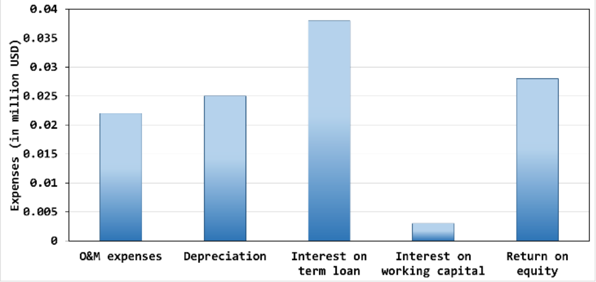

Fig. 4. Different expenses for the first year.

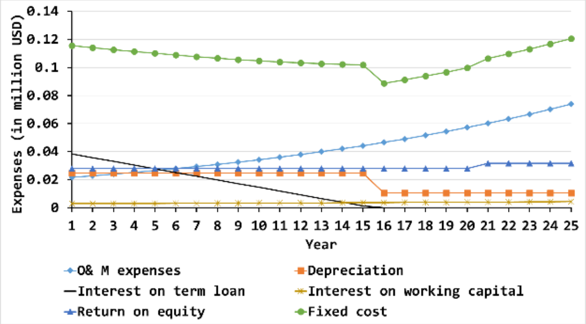

Fig. 5. Yearly variation of fixed cost and its components.

D. *Sensitivity Analysis*

A sensitivity analysis has been conducted by varying key parameters by ±20% from their base values, as shown in Fig. 6. The reduction in the cost of different components results in lower CapEx, which in turn lowers the levelized tariff of electricity generation. This demonstrates that as the technology matures and component costs decline, hydrokinetic projects will become more financially viable. Among the civil and electromechanical components, the levelized tariff is most sensitive to the gearbox, followed by the turbine, generator, anchoring, electric wire, wire rope, transformer, and supporting structure. Pontoons and discount rate exhibit minimal influence on the levelized tariff. When comparing the effect of variation in CapEx and OpEx expenses, the levelized tariff is more sensitive to CapEx than OpEx. A 20% increase in CapEx increases the levelized tariff by 19.56% leading to a value of 0.053 USD/kWh, while a 20% reduction decreases it by 19.56%, yielding 0.036 USD/kWh. This lower value is comparable to solar (0.032 USD/kWh [31]) and wind tariff (0.029 USD/kWh [32]). Further, a 20% increase in O&M expenses resulted in a 6.3% increase in levelized tariff (0.048 USD/kWh), while a 20% decrease reduces it by 6.7% (0.042 USD/kWh). These results confirm that project economics are primarily driven by capital investment rather than O&M expenses.

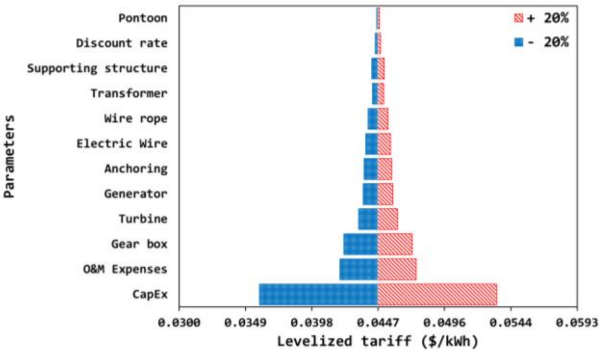

Fig. 6. Sensitivity analysis for levelized tariff.

V. CONCLUSION

Hydrokinetic technology offers a promising and reliable approach to generate clean energy in cost cost-effective manner. In the study, the levelized tariff of a hydrokinetic farm installed under a 1.0 km stretch of a canal in Uttarakhand, India, is analyzed, and the following conclusions are drawn:

- The hydrokinetic farm, consisting of 200 turbines, can generate 2.42 GWh of net saleable energy annually.
- The total CapEx for the hydrokinetic farm is estimated to be 0.528 million USD, with the gearbox contributing the largest share, followed by miscellaneous and turbine. The O&M expenses for the first year are estimated as 0.0217 million USD.
- Under base conditions, the levelized tariff of electricity generation is 0.045 USD/kWh.
- The levelized tariff is highly sensitive to CapEx. If the CapEx is reduced by 20%, the tariff also drops by 20%, coming down to 0.036 USD/kWh, a feasible outcome as the technology matures and component costs decline.
- Among electromechanical and civil components, the gearbox has the greatest impact on tariff, followed by turbines, generators, anchoring, electric wire, wire rope, and transformer.

The study demonstrates that the technology is techno-economically viable and can serve as a competitive renewable energy option. For future work, assessments may be extended to other rivers and canal systems to evaluate broader applicability.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Upendra Bajpai carried out the research work, performed the data analysis, and prepared the manuscript. Manoj Sood contributed to the wake recovery distance and provided valuable inputs during the review and refinement of the manuscript. Sunil Kumar Singal offered critical insights and revisions and granted the final approval of the article. All authors had approved the final version.

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