Assessing Power Generation and Financial Viability of Hydrokinetic Farms in Canal Environments with Varying Turbine Diameters: A Case Study

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Abstract. The growing need to expand renewable energy generation has drawn attention to hydrokinetic technology. This study evaluates the impact of turbine size on the techno-economic viability of a hydrokinetic farm through a case study of a canal in Uttarakhand, India. Two configurations, one with 0.5 m diameter helical Savonius turbine (Case 1) and the other with 1.0 m diameter helical Savonius turbine (Case 2), both deployed over a 1 km canal stretch, have been investigated. For cases 1 and 2, the total number of installed turbines is calculated as 850 and 200, respectively. The net annual energy generation is estimated as 2.57 GWh for Case 1 and 2.42 GWh for Case 2. The total capital expenditure has been found to be USD 0.736 million for Case 1 and USD 0.528 million for Case 2. The levelized tariffs are calculated as 0.058 USD/kWh and 0.045 USD/kWh for Case 1 and Case 2, respectively. Further, sensitivity analysis revealed that capital expenditure is the most influential parameter, followed by O&M expenses and discount rate. Overall, the study highlights that Case 2 offers better techno-economic viability than Case 1, providing useful insights for researchers, developers, and investors in planning hydrokinetic farms.

1 Introduction

Renewable energy technologies are receiving more attention worldwide as they play an important role in addressing climate change and meeting the growing demand for energy [1]. Among these, hydrokinetic technology, which makes use of the kinetic energy of flowing water, holds huge potential because flowing water is available in abundance in almost every country. The concept is quite similar to wind energy, but hydrokinetic systems can generate electricity even at low water velocities and are generally more reliable, since water flow velocity varies less compared to wind velocity [2].

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Hydrokinetic technology harnesses the kinetic energy of flowing water and converts it into mechanical energy through devices such as turbines, oscillating surge flaps, oscillating water columns, and wave point absorbers [3]. Among these, turbines have attracted the most research attention. Hydrokinetic turbines are broadly classified into two categories: axial-flow turbines, where the rotor shaft is aligned parallel to the flow direction, and cross-flow turbines, where the rotor shaft is perpendicular to the flow direction [4]. Examples of cross-flow turbines include the Savonius, Darrieus, and Gorlov turbines, which are particularly suitable for canal and riverine environments. The Savonius turbine, in particular, is widely studied because of its simple design and low cost, although its performance remains relatively modest. To address this limitation, researchers explored various design modifications, such as changes in overlap ratio, aspect ratio, twist angle, and blade profile, to improve its performance. Despite these efforts, the power output of a single Savonius turbine remained low.

However, A significant amount of power can be produced when multiple hydrokinetic turbines are installed together at a site, following a concept similar to wind farms. In a hydrokinetic farm, the overall power generation scales with the number of turbines deployed [5]. However, efficient farm design requires careful determination of the optimum spacing between turbines, which is mostly governed by the wake recovery distance [6]. Neary et al.[7] experimentally studied wake behaviour by analysing velocity profiles and suggested that downstream turbines could be installed when 80–85% of the upstream velocity had recovered. In contrast, Proven et al. [8] proposed a more conservative threshold of 90% velocity recovery. For lateral spacing, several studies have reported different recommendations: Nag et al. [9] suggested 4D (numerically), Chalaca et al. [10] reported 4.16D (experimentally), and Fakhri et al. [11] proposed 5.83D (numerically). From these findings, it can be inferred that for longitudinal spacing, 80-90% velocity recovery is generally acceptable, while for lateral spacing, a distance in the range of 4D-6D is sufficient. In addition to technical analysis, financial investigation is also essential to evaluate the competitiveness of hydrokinetic technology against other renewable energy options. Economic viability is typically assessed using indicators such as Net Present Value (NPV), Levelized Tariff, Payback Period (PP), Levelized Cost of Energy (LCOE), and Internal Rate of Return (IRR). Many researchers have used Hybrid Optimization of Multiple Energy Resources (HOMER) software to estimate NPV and energy generation costs [9]. For emerging technologies with low readiness levels, López et al. [12] proposed a dedicated model for LCOE estimation, highlighting that costs were expected to decrease and competitiveness would improve as the technology matures. Similar conclusions were drawn by Segura et al. [13], emphasizing that economic feasibility will strengthen over time with continued technological advancements. Nag & Sarkar [9] estimated the cost of energy as ₹ 8.22/kWh for a microhydrokinetic power plant for the Barakar river, Jharkhand, India.

India, with its vast network of rivers and canals, holds significant potential for hydrokinetic energy generation [14]. However, as the technology is still in its early stages, limited research has been carried out on the site-specific techno-economic feasibility of hydrokinetic farms. This makes it essential to conduct both technical and financial viability assessments within the Indian context.

The present study investigates the techno-economic feasibility of deploying a hydrokinetic farm along a 1 km stretch of a canal in Uttarakhand, India. The analysis is carried out theoretically using turbines with two different diameters. The objectives of the study are as follows:

- To evaluate the annual net energy generation potential of a hydrokinetic farm using turbines of 0.5 m and 1.0 m diameters.
- To estimate the levelized tariff for both turbine cases and assess their economic competitiveness.

- To perform a sensitivity analysis to identify the most influential parameters affecting the project's financial viability.

2 Methodology

Uttarakhand, a state in India, is abundant in canals and rivers, offering significant potential to harness hydropower available in the form of kinetic energy. For this study, a canal because of its controlled flow from Uttarakhand, has been selected. The canal has a base width of 53.5 m. The available discharge date of the canal for previous year (2015-2020) is collected by contacting the concerned authority and based on this data, both the flow duration curve and velocity duration curve have been plotted as shown in Fig. 1. The Fig. 1 indicates that the flow velocity ranges between 1.96 m/s and 2.3 m/s, conforming that the selected site is suitable for power generation as velocity above 1 m/s are considered adequate. Additionally, the canal maintains a minimum depth of 3.13 m, further reinforcing its suitability for hydrokinetic turbine deployment.

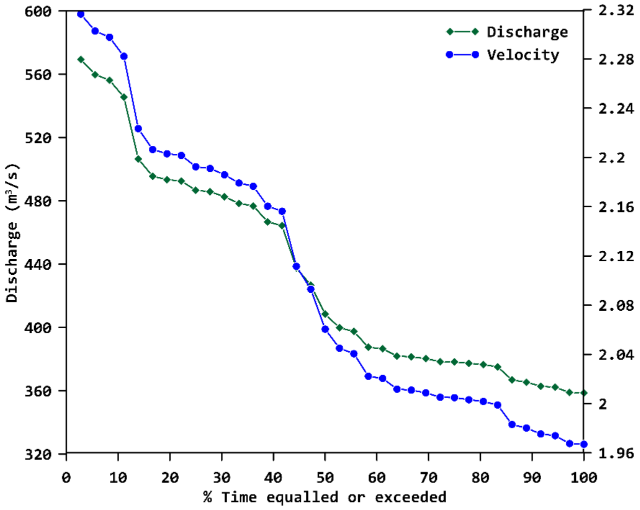

Fig. 1. Discharge and flow velocity duration curve.

Further, a helical Savonius turbine with an aspect ratio of 1.8, an end plate ratio of 1.1 times the turbine diameter, a twist angle of 90°, and an overlap ratio of 0.2 is selected for the study. Two different cases are considered: Case 1 with 0.5 m diameter turbines and Case 2 with 1.0 m diameter turbines. Both sizes of turbines are installed along a 1.0 km stretch of the canal. Based on the literature review, the average power coefficient for a helical Savonius turbine has been taken as 0.2. Here, for a rectangular arrangement of the turbines, the optimum spacing between the turbines both in the lengthwise and widthwise directions has been finalised from the literature. Using this spacing, the number of turbines that can be installed in a row along the length ((Eq. (1)) and in a column along the width is calculated (Eq. (2)). Finally, the total number of turbines that can be installed along the 1.0 km stretch of the canal is estimated (Eq. (3)).

$$Turbines\ along\ length\ (in\ a\ row)\ (n_r) = \frac{Length\ of\ the\ canal}{Longitudinal\ turbine\ spacing} \tag{1}$$

$$Turbines\ along\ width\ (in\ a\ column)(n_c) = \frac{Width\ of\ the\ canal - 2 * lateral\ spacing\ between\ turbines}{Lateral\ spacing\ between\ turbines} + 1 \tag{2}$$

$$Total\ number\ of\ turbines\ (n) = n_r \times n_c \tag{3}$$

A schematic of the hydrokinetic farm has been shown in Fig. 2. As described earlier, the turbines are arranged in a rectangular layout both row-wise and column-wise. Each turbine setup includes the supporting structure, turbine, gearbox, generator, pontoons, and it is tied to the main rope by connecting ropes, which prevents it from drifting with the water flow.. The main ropes are held taut across the canal width using anchor blocks. Electric cables for transmitting the generated power are laid along the connecting rope and then along the main rope. Later on, the total generated power is transferred to the power house, assumed to be located at a distance of 500 m from the start of the farm, by a main electric wire line. The design parameters of all components are estimated based on the maximum flow velocity of 2.5 m/s.

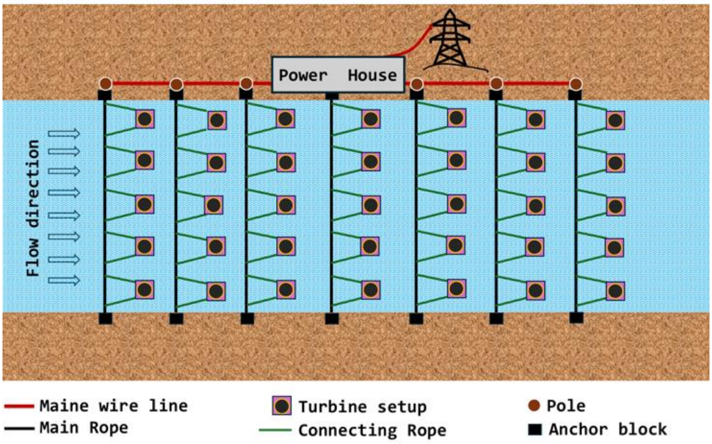

Fig. 2. A Schematic of a hydrokinetic farm.

Using the velocity variation curve, the power output of a single turbine is estimated based on its power coefficient and frontal area, as mentioned in Eq. (4).

$$Power\ generated\ one\ turbine\ (P) = \eta_g \times \eta_G \times \eta_{con} \times \left(0.5 \times C_{Pavg} \times \rho \times A \times V^3\right) \tag{4}$$

Where P is the power generated by one turbine, η_g is the gearbox efficiency, η_G is the generator efficiency, η_{con} is the power drive efficiency, ρ is the water density, A is the turbine frontal area, and V is the flow velocity. The gross energy generation is then calculated as mentioned in Eq. (5).

$$Gross\ energy\ generation\ (P_{t,}Wh) = P \times N \times t \tag{5}$$

where N is the number of turbines and t is the time of operation.

Further, the net energy generation is estimated by subtracting the losses due to plant availability reduction and auxiliary consumption as mentioned in Eq. (6).

$$\begin{aligned} Net\ energy\ generation(P_{net}) & \\ &= P_t - Energy\ generation\ reduction_{plant\ unavailability} \\ &- Auxiliary\ consumption \end{aligned} \tag{6}$$

The gearbox efficiency (η_g), generator efficiency (η_G), and power drive efficiency (η_{con}) is considered as 0.9, 0.95, and 0.93, respectively.

For the financial analysis, the parameters recommended by the Central Electricity Regulatory Commission (CERC), Government of India, have been adopted. The selected parameters are as follows: -

- A debt-to-equity ratio of 70:30 is considered.
- The loan tenure is 16 years, including a 1-year moratorium period, with an annual interest rate of 10.75%.
- Depreciation of the plant is assumed at 4.67% per year for the first 15 years, with the remaining value distributed equally over the remaining life of the project.
- The annual interest rate on working capital is taken as 12%.
- Return on equity is assumed as 17.65% for the first 20 years, and 20% thereafter.
- Operation and maintenance (O&M) expenses are considered as 4.10% of capital expenditure (CapEx) in the first year, with an annual escalation of 5.25% for further years.
- A discount rate of 10.73% and 365 operating days per year are considered.

The capital expenditure (CapEx) is estimated based on cost data collected through market surveys, consultations with manufacturers and industry experts, and information available on online platforms. Using this CapEx along with the financial parameters prescribed by CERC, the annual O&M expenses, depreciation, interest on term loans, interest on working capital, and return on equity are calculated for each year of the project life. These cost data are then utilized in the financial model to compute the levelized tariff, as expressed in Eq. (7-11), which serves as the principal indicator to determine techno-economic feasibility of the project.

$$Fixed\ cost\ (FC) = \text{O\&M Expenses} + \text{Return on Equity} + \text{Depreciation} + \text{Int erest on working capital} + \text{Interest on term loan} \tag{7}$$

$$Per\ unit\ tariff\ (PUT) = \frac{Annual\ FC}{Annaul\ P_{net}} \tag{8}$$

$$Discount\ factor\ (DF) = \frac{1}{(1+r)^{n-1}} \tag{9}$$

$$Discounted\ tariff\ (DT) = PUT \times DF \tag{10}$$

$$Levelized\ tariff\ (LT) = \frac{\sum_1^n DT}{\sum_1^n DF} \tag{11}$$

In addition, a sensitivity analysis has been conducted to evaluate the impact of key parameters on the project's feasibility. Variations of ±25% are considered for CapEx, O&M expenses, and discount rate. For currency conversion, an exchange rate of 1 INR equals 0.011 USD has been applied.

3 Results

3.1 Annual Energy Generation

Based on the research conducted by Sood and Singal [5], and with additional consideration for blockage and damming effects, a turbine spacing of 40D along the channel length and 6D across the channel width (where D is the turbine diameter) has been considered. Using this longitudinal (along length) and lateral spacing (along width), the total number of turbines for Case 1 and Case 2 are determined as 850 and 200, respectively, using Eq. (1-3). For each case, a number equals to number of turbines, generators, gearboxes, supporting structures, and pontoons will be required. The gross energy generation by the hydrokinetic farm is calculated using Eq. (4) and Eq. (5) and estimated as 2.73 GWh for Case 1 and 2.57 GWh for Case 2. After accounting for plant availability reduction (5%) and auxiliary consumption (1%), energy losses of 0.14 GWh and 0.026 GWh for Case 1, and 0.13 GWh and 0.024 GWh for Case 2 have been estimated. Consequently, the net annual energy generation is estimated as 2.57 GWh for Case 1 and 2.42 GWh for Case 2 (Eq. (6)).

3.2 Capital and O&M Expenses

The cost breakdown of different major components, such as turbines, gearboxes, generators, supporting structures, electric wires, moorings (covering anchor block and excavation work), wire ropes, pontoons, transformer, and minor electrical components (covering circuit breaker, current transformer and potential transformer, and relay) of the plant has been presented in Table 1.

Table 1. Cost breakdown for hydrokinetic farm.

	Case 1	**Case 2**
Components	**Cost (in million USD)**	**Cost (in million USD)**
Turbines	0.131	0.069
Gear boxes	0.108	0.122
Generators	0.136	0.053
Structures	0.053	0.022
Electric wires	0.047	0.045
Moorings	0.051	0.049
Wire ropes	0.033	0.035
Pontoons	0.008	0.005
Transformer	0.020	0.020
Minor electrical components	0.002	0.002
Miscellaneous	0.147	0.106
Total Cost	**0.736**	**0.528**

To account for uncertainty and unforeseen expenses, an additional 25% of the total component cost has been included under the miscellaneous category. Since hydrokinetic technology is an emerging technology, and cost estimates carry inherent uncertainties, this additional provision is a practical and necessary measure. Using this approach, the total capital expenditure (CapEx) is estimated as 0.736 million USD for Case 1 and 0.528 million USD for Case 2. Case 2 requires gearboxes with higher gear ratios, resulting in a higher total gearbox cost compared to case1, still the overall project cost is significantly lower due to the reduced expenditure on other components. In Case 1, 850 turbines, generators, structure assemblies are needed to cover the 1 km canal length, whereas in Case 2, only 200 units are sufficient to achieve similar power generation. This substantial reduction in the number of turbines, generators, and supporting structures leads to significant cost savings that outweigh the increased cost of gearboxes. Consequently, the overall capital cost for Case 2 is lower, highlighting the benefit of economies of scale, where installing fewer, larger-capacity turbines becomes more cost-effective than deploying a greater number of smaller units.

The percentage-wise distribution of CapEx across different components is illustrated in Fig. 3. For Case 1, the largest contribution comes from miscellaneous costs, followed by turbines, generators, gearboxes, supporting structures, moorings, and electrical wires. Other components contribute less than 5% of the CapEx. In Case 2, however, gearboxes form the largest cost share, followed by miscellaneous costs, turbines, generators, moorings, and electrical wiring, with the remaining components again contributing less than 5%.

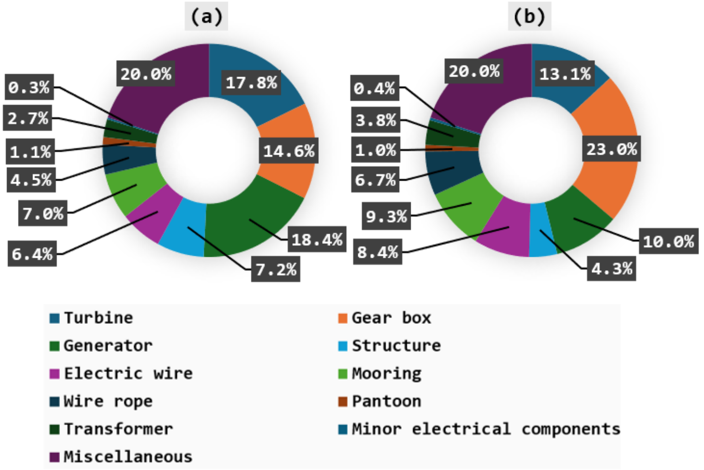

Fig. 3. Percentage wise distribution of cost of different components (a) Case 1 and (b) Case 2.

3.3 Levelized tariff estimation

Using the financial parameters described in Section 2, the annual costs for O&M expenses, return on equity, depreciation, interest on working capital, and interest on the term loan have been estimated over the 25-year project life. For the first year of operation, these costs for Case 1 are 0.030, 0.039, 0.034, 0.003, and 0.054 million USD, respectively. In comparison, the corresponding values for Case 2 are 0.022, 0.028, 0.025, 0.003, and 0.038 million USD. As shown in Fig. 4, the overall expenditure in Case 2 remains lower across all categories, indicating better financial feasibility compared to Case 1.

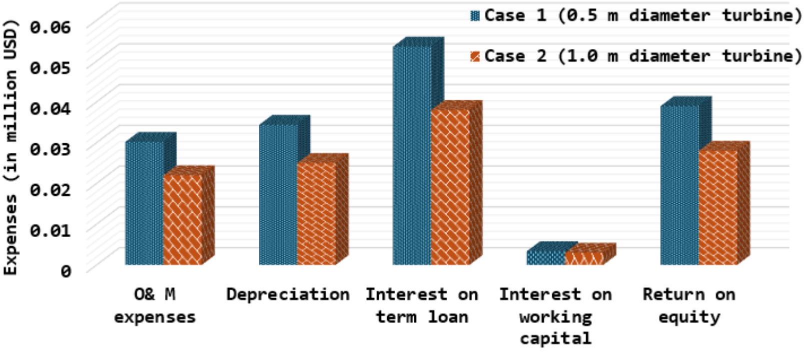

Fig. 4. Fixed cost components for first year.

The year-wise distribution of these costs over the 25-year project life for Case 1 and Case 2 is shown in Fig. 5 and Fig. 6, respectively. O&M expenses gradually increase over time, reflecting the need for more frequent maintenance as the plants get older. Depreciation remains constant during the first 15 years, at 0.034 million USD for Case 1 and 0.025 million USD for Case 2. From the 16th year onwards, depreciation decreases to 0.015 million USD and 0.011 million USD,for case 1 and case 2, respectively. Return on equity is 0.039 million USD (Case 1) and 0.028 million USD (Case 2) up to the 20th year, after which it increases slightly to 0.044 million USD (Case 1) and 0.032 million USD (Case 2). Interest on working capital also rises gradually due to the yearly increase in O&M expenses, reaching 0.005 million USD for Case 1 and 0.004 million USD for Case 2 in the 25th year. In contrast, interest on the term loan decreases each year as the principal is repaid, and becomes zero after the 15th year when the loan is fully settled for both cases.

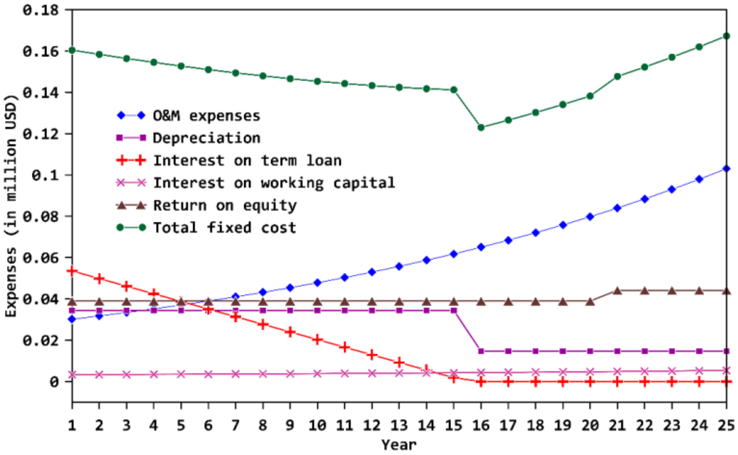

Fig. 5. Annual distribution of fixed costs and their components for case 1.

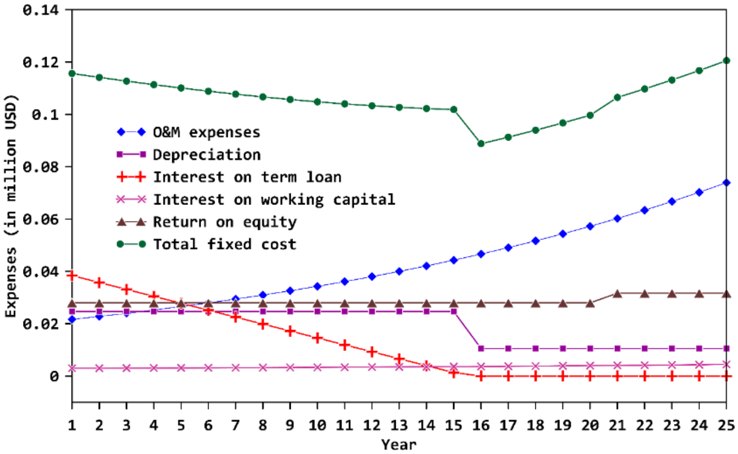

Fig. 6. Annual distribution of fixed costs and their components for case 2.

The combined effect of these cost components is reflected in the total fixed cost. In the first year, this is estimated as 0.16 million USD for Case 1 and 0.12 million USD for Case 2. Using Eq. (7-11), the levelized tariff is calculated as 0.058 USD/kWh for Case 1 and 0.045 USD/kWh for Case 2. The levelized tariff estimated in this study (0.045-0.058 USD/kWh or ₹4.09–5.27/kWh) is notably lower than the levelized cost of energy (₹8.22/kWh) reported by Nag and Sarkar [9]. This difference primarily can be attributed to variations in site characteristics, energy generation scale, and selected financial parameters. The present study focuses on a canal-based hydrokinetic farm operating under steady and controlled flow conditions, which requires comparatively lower civil infrastructure than a riverine environment. Furthermore, the higher energy generation estimated in the study (2.4–2.6 GWh annually) compared to 0.40 GWh/year reported by Nag and Sarkar [9] contributes to the reduced tariff. Thus, the scaling effect, resulting from larger overall capacity and more efficient utilization of infrastructure, plays a significant role in lowering the levelized tariff.

These results indicate that Case 2, which incorporates the larger-diameter turbine, is more techno-economically feasible than Case 1 with the smaller 0.5 m turbine. Notably, the levelized tariff of Case 2 is even lower than that of small hydropower projects in Uttarakhand, highlighting the competitiveness of hydrokinetic projects.

3.4 Sensitivity analysis

A sensitivity analysis has been carried out by varying key financial parameters such as CapEx, O&M expenses, and the discount rate, by ±25% for Case1 and Case 2 as shown in Fig. 7(a) and Fig. 7(b), respectively. The results reveal that CapEx exerts the greatest influence on the levelized tariff, whereas the discount rate has the least impact. For Case 1, a 25% increase in CapEx, O&M costs, and discount rate raises the levelized tariff to 0.073, 0.063, and 0.059 USD/kWh, respectively, making the system less competitive compared to other renewable technologies. In contrast, Case 2 demonstrates strong resilience: even with a 25% increase in these parameters, the levelized tariff values remain at 0.056, 0.048, and 0.045 USD/kWh, highlighting the financial feasibility of larger turbine configurations.

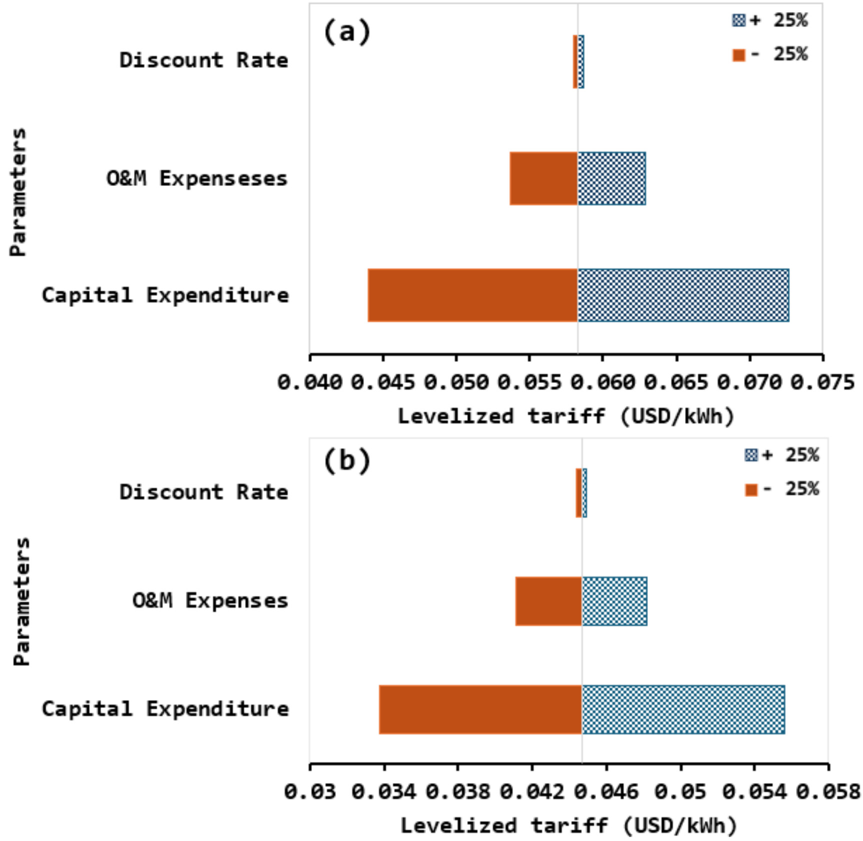

Fig. 7. Sensitivity assessment for levelized tariff (a) case 1 (b) case 2.

As the technology matures, reductions in CapEx, O&M costs, and discount rate are expected, further improving economic performance. A 25% reduction in CapEx leads to a substantial decrease in levelized tariff, 24.6% for Case 1 (yielding 0.044 USD/kWh) and 24.5% for Case 2 (yielding 0.034 USD/kWh). The levelized tariff for Case 2 is nearly comparable to solar (0.032 USD/kWh) and wind power (0.029 USD/kWh), underscoring the competitive potential of hydrokinetic systems in the renewable energy market. Similarly, a

25% reduction in O&M costs and discount rate reduces the levelized tariff of Case 1 to 0.054 and 0.058 USD/kWh, while for Case 2, the corresponding values are 0.041 and 0.044 USD/kWh. These results confirm that, although the discount rate has a minimal effect, CapEx reduction plays a critical role in enhancing feasibility.

4 Conclusions

The present study investigates the techno-economic viability of a hydrokinetic farm deployed over a 1 km stretch of a canal in Uttarakhand, India, considering two cases: 0.5 m diameter helical Savonius turbines (Case 1) and 1.0 m diameter helical Savonius turbines (Case 2). The key findings of this study can be summarized as follows:

- The hydrokinetic farm is estimated to generate 2.57 GWh of net annual energy for Case 1 and 2.42 GWh for Case 2, indicating slightly higher energy production with smaller-diameter turbines.
- The total capital expenditure is calculated as USD 0.736 million for Case 1 and USD 0.528 million for Case 2, corresponding to a ratio of 1.4:1 relative to Case 1.
- The levelized tariff is estimated as USD 0.058/kWh for Case 1 and USD 0.045/kWh for Case 2.
- From a technical perspective, Case 1 is more favorable due to higher energy output. However, when both technical and economic factors are considered, Case 2 emerges as the more viable option.
- Among the factors such as capital expenditure, O&M expenses, and discount rate, capital expenditure has the greatest impact, followed by O&M expenses and the discount rate.

Future studies could extend this work by assessing additional economic feasibility parameters, exploring different turbine configurations, and evaluating sites with varying hydrological conditions to provide broader insights into hydrokinetic farm deployment.

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