SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348-8379/ https://doi.org/10.14445/23488379/IJEEE-V13I9P101

Volume 13 Issue 9, 1-16, September 2026

Original Article

Energy Production and Economic Feasibility of a Tidal Barrage System in the Gulf of Khambhat

Pankaj Warak[1], Prerna Goswami[2]

[1]*Department of General Engineering, Institute of Chemical Technology, Mumbai, India.*
[1]*Department of Electronics and Telecommunication, Gharda Institute of Technology, Lavel, Maharastra, India.*
[2]*Department of General Engineering, Institute of Chemical Technology, Mumbai, India.*

[1]*Coressponding Author : elc18pl.warak@pg.ictmumbai.edu.in*

Received: 23 May 2026 Revised: 25 June 2026 Accepted: 26 August 2026 Published: 26 September 2026

Abstract - *Rising need for clean and reliable energy has raised tidal power system interest. The large tidal range in the Gulf of Khambhat has good potential for the extraction of tidal energy. To assess the feasibility of a proposed tidal barrage using harmonic tidal reconstruction and dynamic basin modelling techniques for the purposes of estimating the hydraulic head, turbine discharges and the power production. Annual energy production and capacity factor are calculated, and a simulation of key design parameters is performed as a sensitivity analysis. The findings show potential for a 500 km² basin to produce ~3.44 TWh per annum, and large-scale systems may be expected to produce 15-18 TWh per annum. Economic analysis using LCOE and Monte Carlo Simulation suggests that performance improves with scale. Overall, the study shows that the Gulf of Khambhat can be a promising site for predictable tidal energy generation with proper design optimization.*

Keywords - *Energy production, Gulf of Khambhat, Lcoe, Monte Carlo Simulation, Tidal energy.*

1. Introduction

Tidal energy is a sustainable power source produced from the regular movement of sea levels driven by the gravitational pull of the moon and the sun. It is dependable, environmentally friendly, and can be utilized through systems such as tidal turbines and barrages. Its predictable nature makes it a strong candidate for future clean energy development [1]. Tidal power technology is among the most mature marine renewable systems, and commercial-scale projects have been running in several countries, although its large-scale application is hindered by high capital cost, technical complexity, environmental issues and policy limitations [2].

Tidal energy is being identified as a predictable and sustainable renewable energy resource, and is of rising global interest. The study reviewed here analyses the technology of tidal current turbines and compares major generator types (induction machines, switched reluctance generators, Permanent Magnet Synchronous Generators (PMSG), and Induction Switched Reluctance Machines (ISRM)). The results show that the torque density and the efficiency (max. 92%) of the ISRM technology, as well as the lower cost of manufacture (due to no permanent magnets), make it a promising candidate for use in marine current applications [3]. The study examines the best control practices of tidal barrage operation by introducing economic factors into the objective function. Using a hydrodynamic model based on the model of the La Rance tidal power plant, the authors compare energy maximisation and income maximisation approaches. A moment-based control framework is used to optimise the flow in the turbines and the sluice gates, considering electricity market prices and operational costs [4]. A study in Wuyuan Bay showed nutrient accumulation within the barrage at ebb tide, a decrease in microbial diversity and the dominance of cyanobacteria, suggesting some risks of eutrophication. These results show the importance of considering the ecological impacts in concert with hydrodynamic and energy evaluations in the planning of tidal barrages [5].

A recent research paper presented at HYDRO 2023 examined the tidal barrage implementation at estuarian locations based on the 1D hydrodynamic model developed in HEC-RAS for creating the simulating flow condition and gate operating. The study analysis proved that the implementation of a barrage structure significantly increased the speed from 1.2 m/s to 2.5 m/s, which improves the potential for power generation [6]. Recent work has shown that control strategies can greatly improve the performance of tidal barrage systems, provided there are acceptable levels of control. Skiarski et al. have developed a moment-based optimization process to control the turbine discharge and sluice gate operation under different hydraulic head conditions within turbine head limits and basin area variation. The results of this study were obtained to show that two-way generation schemes can be used to boost the annual generating energy output over one-way operation, and introducing a weighted cost on the gate motion can reduce the parasitic energy consumption without much effect on the total energy production [7].

2. Literature Review

Tidal barrage technology is among the most developed types of marine renewable energy technologies based on the potential energy generated by tidal range differences in tidal estuaries or bays. A typical tidal barrage is made up of turbines, sluice gates, embankments and ship locks working under the form of a single basin or double basin, with ebb or flood or two-way generation mode. However, high capital costs and environmental impacts, especially in terms of sediment transport and marine ecology, remain critical challenges to the deployment of large-scale solar energy [8].

A comprehensive optimization approach for barrage-type tidal power plants was presented by Ghaedi and Gorginpour, in which Particle Swarm Optimization (PSO) was adopted to find the optimal number of turbines, number of sluices, turbine diameter, and sluice width in tandem with finding the optimal operational scheduling. The effects of hydro-pumping and various generation ways were also considered, proving that an integrated design and operation optimisation can have a profound effect on the energy production of a year [9]. Xia et al. created a two-dimensional hydrodynamic model using an unstructured finite volume method in order to study the effect of a tidal barrage located in the Severn Estuary. Their results showed that although it is possible to generate significant power, the barrages significantly affect upstream water levels and discharge patterns as well as the tidal currents, emphasising the importance of detailed hydrodynamic assessment of tidal barrage planning [10]. A thorough review of tidal barrage resource evaluation indicates that tidal range power plants are one of the most mature marine renewable technologies because of their predictability and operating history.

The study discusses the basic physics of tides, single and double basin configurations and energy estimation using the potential energy relationship. It also highlights that although tidal barrages deliver steady power generation and other benefits like flood protection, there are significant capital costs, environmental impacts, particularly on sediment transport and estuarine ecosystems, that limit the spread of such applications [11]. Wallwork et al. have developed the approach of modelling tidal turbine arrays by adapting the mesh to enhance the accuracy of the simulations, whilst maximizing computational efficiency. The study successfully showed the ability of adaptive mesh techniques to optimize the performance assessment of the tidal turbine and facilitate the planning and design of tidal energy projects at large scales [12]. Skiarski, Faedo, and Ringwood studied receding horizon optimal control for tidal barrage power plants, under the assumption of tidal variations depending on the weather. They showed in their work that adaptive control methods did increase the efficiency and reliability of power generation under changing tidal conditions [13]. Skiarski, Faedo, and Ringwood explained the "moment-based modelling and optimal control" of tidal barrage systems to optimize energy harvesting as well as their performance. The study pointed out the efficiency and reliability of power generation using advanced control strategies in tidal barrages [14].

The functional optimization of the tidal barrage systems was studied by Ringwood and Faedo, where the electrical power generation efficiency in the tidal barrage was optimized by considering the wave energy control methods. Their research shows how well advanced control techniques enhance the energy production and performance of tidal barrage power plants [15, 16]. Burele and Burele outlined how tidal barrage systems are a viable option for renewable power generation at estuaries. A focus of the study was the development of sustainable and reliable energy from estuarine tidal barrages using the tide, which is easily available in nature [6]. Burele and Singh explored in the Vijay Durg area, Ratnagiri, Maharashtra, the feasibility of Tidal Barrage technology for generating renewable energy. It pointed out the potential of harnessing tidal resources on the Maharashtra Coast for sustainable power production [17]. Abdullah, Al-Fartousi and Lafta conducted a study to investigate the effect of the proposed barrage on the Shatt Al-Arab River tidal hydrodynamic in the southern side of Iraq. Changes in the flow behavior of those tides have been studied, and the effect on river hydrodynamics and coastal water management has been noted due to barrage structures [18]. Lafta and Abdullah studied the impact of the proposed barrage on the characteristics of tidal waves and salinity distribution in the estuary of the Shatt Al-Arab River.

The study also showed that the construction of the barrage can have a significant impact on the propagation of tides and change the salinity conditions, which can impact the estuarine hydrodynamic and water quality [19]. G. Li and W. Zhu investigated methods to enhance power generation in barrage-type tidal power plants through improved operational and design strategies. Their study demonstrated that optimized system configurations can significantly increase the efficiency and energy output of tidal barrage projects [20].

While a number of studies have examined tidal resource assessment, hydrodynamic performance and theoretical energy potential of the Gulfs of Khambhat and tidal barrage systems, the majority of these have been dealing with a single aspect of the study, either the assessment of the tidal resources, the modelling of the hydrodynamics or the optimization of the system for operational use. There are a few efforts to combine the aspects of dynamic basin operation with sensitivity analysis, AI-based prediction models and uncertainty-based economic evaluation. Moreover, detailed design optimization and Monte-Carlo economic risk assessments of large-scale deployment of tidal barrages are still not available. So, the overall performance and economic feasibility analysis of the tidal barrage in the Gulf of Khambhat is an open research problem.

The present study differs from previous studies in the major emphasis on hydrodynamic assessment or theoretical energy estimation, and includes a holistic reconstitution of tidal currents (hending harmonic reconstruction); a dynamic modelling of the basin with energy values; a sensitivity analysis and a tolerance analysis to account for the sensitivity of the basin under consideration; AI-based tidal prediction; optimisation via a genetic algorithm; and Monte Carlo-based economic uncertainty accounting for the Gulf of Khambhat. This integrated framework can offer the all-around technical and economic feasibility rough estimate if deploying a tidal barrage on a large scale.

Previous studies on tidal barrage systems are mainly specialized in hydrodynamic modelling, turbine optimization, operational control strategies or environmental impact assessment. A few researchers have studied the effects of barrage operation with numerical hydrodynamic models, and other researchers have optimised the turbine scheduling and/or evaluated the technical feasibility of tidal power generation plants in various estuaries. Most research to-date, however, has a number of limitations:

- The majority of studies are based on one-dimensional consideration of either the hydrodynamic behaviour or the energy generation performance, and neglect the technical, economic and optimization perspectives from a common platform.
- The second is that, although there are existing investigations for the Gulf of Khambhat, they mainly estimate the theoretical tidal resource or installed capacity potential, and there is a lack of detailed annual energy production simulation with dynamic simulation using reconstructed harmonic tidal constituents.
- Most of the past studies do not carry out the sensitivity analysis to know the extent of sensitivity of major design parameters, like basin area, turbine flow area, minimum operating head and turbine efficiency on the annual energy generation.
- The economic feasibility is generally analyzed on the basis of deterministic assumptions, while uncertainty analysis with the help of Monte Carlo Simulation has been studied less on the tides barrage system in the Gulf of Khambhat.
- In the past decade, Artificial Intelligence (AI) techniques have seen a recent surge in application to renewable power prediction, but the application of Deep Learning (DL) to tidal predictions and optimization of tidal barrage designs and performance improvement has been largely ignored in the literature.

To overcome these shortcomings, the present study suggests an Integrated Assessment Scheme based on harmonic tidal reconstruction, dynamic basin modeling, calculation of hydraulic head, estimation of annual energy, sensitivity analysis, economic assessment through the LCOE, Monte Carlo uncertainty analysis, tidal prediction based on Long Short-Term Memory (LSTM) network, and design optimization by Genetic Algorithm. The proposed framework incorporates a detailed technical and economic analysis of the feasibility of a tidal barrage system at the Gulf of Khambhat and suggests useful guidance towards how large-scale tidal energy development can be achieved in the Indian context.

Table 1. Comparison of existing methods and the proposed research framework

Existing Methods	Limitation	Present Work
Hydrodynamic modelling only	No economic assessment	Combines hydrodynamics with techno-economic evaluation
Resource assessment studies	Theoretical potential only	Dynamic annual energy simulation
Turbine optimization studies	Ignore basin design sensitivity	Basin area, turbine area, head and efficiency sensitivity analysis
Deterministic economic studies	No uncertainty analysis	Monte Carlo-based LCOE assessment
Conventional prediction methods	Limited forecasting capability	LSTM-based tidal prediction
Single-objective optimization	Limited design optimization	Genetic Algorithm-based optimization of barrage parameters

3. Study Area: Gulf of Khambhat

The Gulf of Khambhat, located along the western coast of India in Gujarat, is identified as one of the most promising tidal energy regions due to its funnel-shaped geometry, large tidal range exceeding 9-11 m, and strong tidal currents reaching up to 2.5-3 m/s in the northern sector near Dahej. Numerical modelling studies using Delft3D and TELEMAC-2D indicate that tidal amplitudes increase toward the head of the gulf because of its semi-enclosed configuration, with the northern region exhibiting the highest power density and thus representing the most suitable zone for tidal energy extraction [21]. A three-dimensional hydrodynamic modelling study using Delft3D evaluated tidal current energy potential along the Gulf of Khambhat and reported maximum tidal current velocities of approximately 2.6 m/s during spring tides.

The corresponding peak power densities were estimated to reach about 3 kW/m² in the northern narrowing region of the gulf, identifying it as the most suitable zone for tidal energy extraction and supporting its selection for further large-scale tidal power assessment [22-24]. High-frequency radar observations indicate that the Gulf of Khambhat experiences strong semi-diurnal tidal currents dominated by the M2 constituent, with peak surface velocities reaching about 2.0 m/s and amplitudes exceeding 1.5 m/s during stratified monsoon conditions.

The spatial variation between zonal currents in the western Gulf and meridional currents in the eastern sector highlights the dynamic hydrodynamic regime, supporting the selection of the region for tidal energy assessment. Sundaravadivelu et al. studied dredging and siltation in the Gulf of Khambhat using the MIKE 21 model. The study reported strong tidal currents and high sediment deposition in the region. These findings are important for tidal barrage systems because excessive siltation can affect turbine performance, reservoir storage, and maintenance costs. Therefore, the study helps in understanding the operational and economic feasibility of tidal energy projects in the Gulf of Khambhat [25].

The tidal potential of the region has previously been examined under the Kalpasar (KALPASAR) project, which proposed closure of the gulf between Gogha and Luhara Point for combined freshwater storage and tidal power generation. The pre-feasibility study estimated that a basin area of about 1,470 km² could support up to 6,600 MW of installed capacity with an annual energy production of nearly 16 TWh under ebb-generation schemes. The present study builds upon these earlier assessments by applying harmonic tidal reconstruction and dynamic modelling to re-evaluate the energy potential of the Gulf of Khambhat [26].

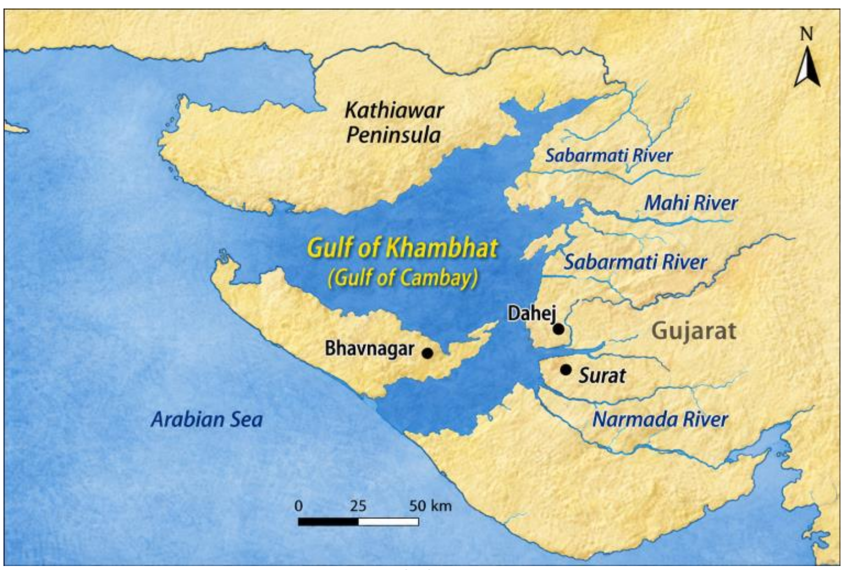

Fig. 1 Gulf of Khambhat

4. Hydrodynamics and Energy Modelling of Proposed Tidal Barrage

The performance of the proposed tidal barrage in the Gulf of Khambhat is evaluated using a dynamic hydrodynamic and energy conversion framework. The modelling approach integrates tidal elevation forcing, basin water level response, turbine discharge characteristics, and power generation estimation under semi-diurnal tidal conditions [22].

The sea surface elevation at the barrage site is represented using a harmonic formulation dominated by the principal semi-diurnal constituent (M2), expressed as:

$$\eta s(t) = A\cos(\omega t + \phi) \quad (1)$$

Here, A is the amplitude of the tide and $\omega = 2\pi/T$ is the angular frequency associated with the tidal period T (≈12.42 h for the M2 tide), and ϕ is the phase angle. Other constituents (S2, N2, K1, O1) can be added if necessary. Basin water level is affected by the impoundment from the turbine discharges and the sluice operations. Overall balance for the basin is represented as:

$$A_b \frac{d\eta_b}{dt} = Qin - Qout \quad (2)$$

Where,

- A_b= surface area of the basin
- η_b = basin water level
- Qin, Qout = inflow and outflow discharge

The instantaneous hydraulic head available for power generation is defined as:

$$H(t) = \eta s(t) - \eta b(t) \quad (3)$$

Generation occurs when the head exceeds the minimum operating head of the turbine.

The discharge through low-head reversible turbines is expressed as:

$$Q(t) = Cd\, At \sqrt{(2gH(t))} \quad (4)$$

Where,

- Cd = discharge coefficient
- At= total turbine flow area
- g = gravitational acceleration
- H(t)= instantaneous hydraulic head

Operational constraints such as cut-in head and rated head are incorporated into the model.

The instantaneous power output is given by:

$$P(t) = \rho g Q(t) H(t) \eta t \quad (5)$$

Where,

- ρ= seawater density (~1025 kg/m³)
- ηt = turbine-generator efficiency

Substituting the discharge expression yields:

$$P(t) \propto H(t)^{3/2} \quad (6)$$

indicating a strong sensitivity of power output to head variation.

The total energy generated over a tidal cycle is obtained by numerical integration of the instantaneous power [26]:

$$E = \int P(t)\, dt \quad (7)$$

Annual energy production is estimated by extending the simulation over a representative year, considering tidal periodicity. The capacity factor is computed as:

$$CF = Eannual / (Prated \times 8760) \quad (8)$$

5. Results and Discussion

The harmonic reconstruction of the tides confirms a very strong semi-diurnal tidal regime in the Gulf of Khambhat, with dominating the M2 tidal constituent with an amplitude larger than 4 m.

The combination of these three M2, S2 and N2 result approximately 10 -11 meters of tidal range, consistent with the macrotidal nature of the region.

Table 2. Generated harmonic constants-Gulf of Khambhat

Constituent	Frequency (cycles/hr)	Amplitude (m)	Phase (degree)
M2	0.08051	4.12	156.3
S2	0.08333	1.05	241.8
N2	0.07899	0.78	118.6
K1	0.04178	0.31	82.4
O1	0.03873	0.24	64.7
M4	0.16102	0.48	104.2

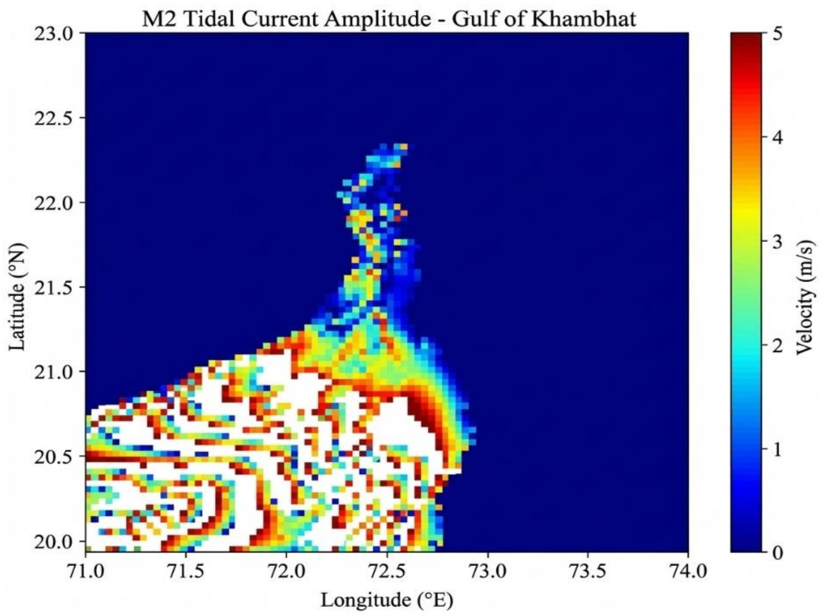

Fig. 2 Spatial distribution of M2 tidal current amplitude in the Gulf of Khambhat derived from the TPXO10 global tidal model

Figure 2 shows the spatial distribution of M2 tidal current amplitude throughout the Gulf of Khambhat generated from the TPXO10 [27] tidal model. The results show increasing current magnitude towards the central channel of the gulf due to the funnel-shaped geometry and tidal energy convergence, which gave to the confirmation of strong hydrodynamic conditions appropriate to tidal power extraction. High current velocities exceeding 3 m/s occur in the central channel, which indicates strong tidal energy potential.Spatial distribution of M2-tidal constituent has shown the presence of a strong energy corridor in the Gulf of Khambhat. Peak power densities were found to attain values of 51.00 kW/m^2 at the narrow entrance to the inner Gulf. This extreme density is fuelled by tidal current velocities of more than 4.6m/s.

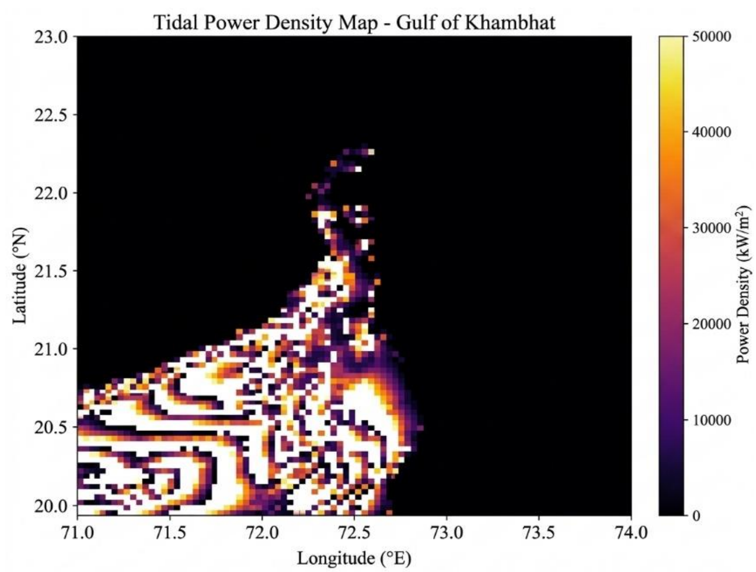

Fig. 3 Tidal power density map

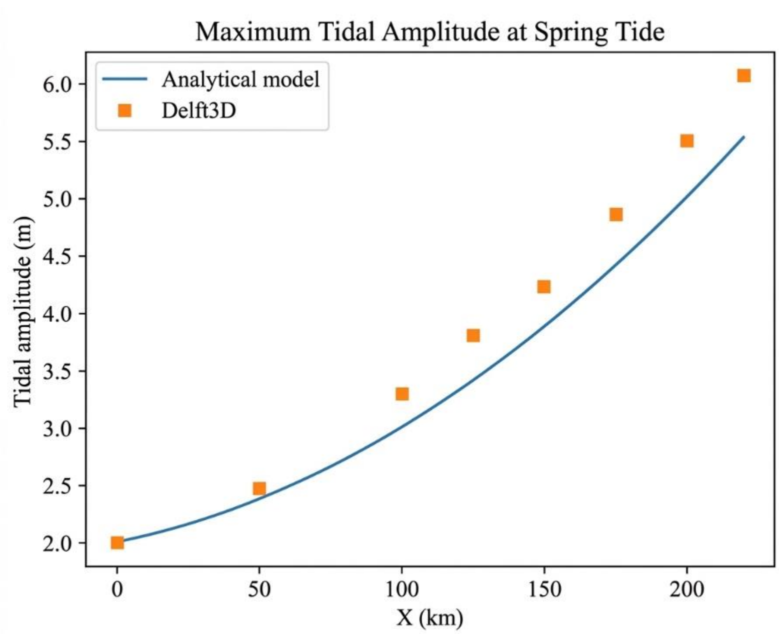

Fig. 4 Maximum tidal amplitude at spring tide

Table 3. Maximum tidal hydrodynamic parameters for the Gulf of Khambhat (M2 constituent)

Parameter	**Value**	**Location**
Max M2 Velocity	4.63m/s	Head of the Gulf
Peak Power Density	51.00 kW/m^2	Localized Channel Hotspot
Energy Character	Macro-Tidal	Dominated by Semi-diurnal M2

The maximum amplitude of tides increases progressively from about 4.0 m near the mouth of the gulf to about 5.5-6.0 m, increasing towards the top. Since the spring tidal range is roughly twice the tidal amplitude, the reconstructed values are associated with a spring tidal range of almost 8 - 11 m along the Gulf of Khambhat [14, 28, 29].

This amplification trend is consistent with the funnel-shaped bathymetry and bending of the tidal energy to the head of the gulf, as well as the reports of macro tidal characteristics of the area. The good agreement between the analytical model and Delft3D simulations is a further indicator of the reliability of the hydrodynamic formulation used in this study.The Figure 5 presents the simulated sea level variation during the period of the first 30 days in the Gulf of Khambhat with harmonic constituents (M2, S2, K1, and O1) [22].

A definite semidiurnal pattern exists with two high and two low tides per day. The amplitude modulation during the period represents the spring / neap cycle, with an increased range during the spring tides and a lower range during the neap tides. This reconstructed tidal signal is used as an input boundary condition for the modelling of the tidal barrages.

The variation of the sea level and basin level is given in the Figure 6 for the first 30 days of the tidal barrage simulation [30]. The sea level denotes the natural tidal elevation outside the barrage, whereas the basin level denotes the water level in the impounded reservoir. During filling, the level of the basin follows the sea level, and while ebb generation, the basin is kept higher than the sea level, developing the hydraulical head needed for the generation of power.

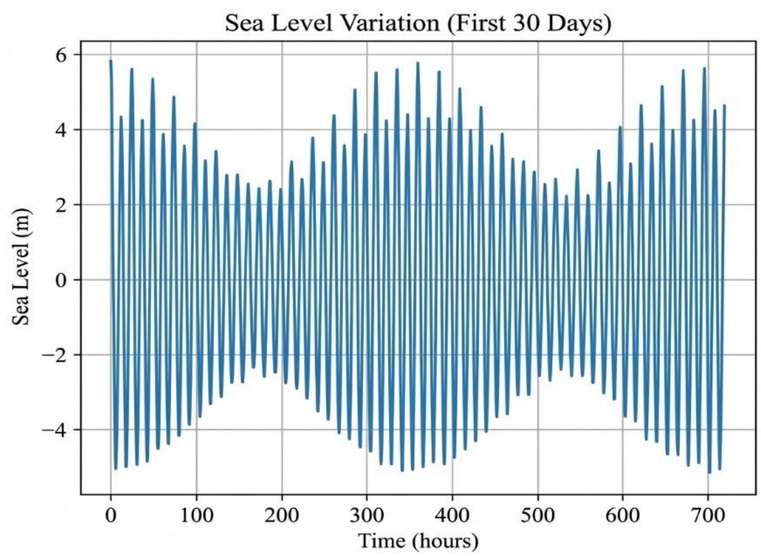

Fig. 5 Sea level variation

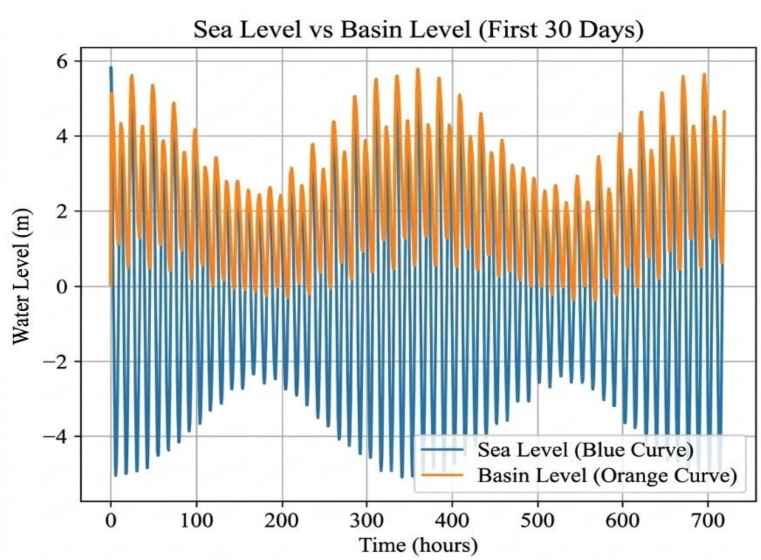

Fig. 6 Sea level vs basin level

Figure 7 gives an impression of the available hydraulic head between the basin and sea during the first 30 days of operation. Positive head values are those which are during the ebb phase, when the water level in the basin is higher than the sea level, thus allowing power generation.

The head magnitude varies with the spring - neap cycle, with higher values on spring tides and lower values on neap tides. This variation in heads controls the discharge and power output of a tidal barrage system's turbines directly.

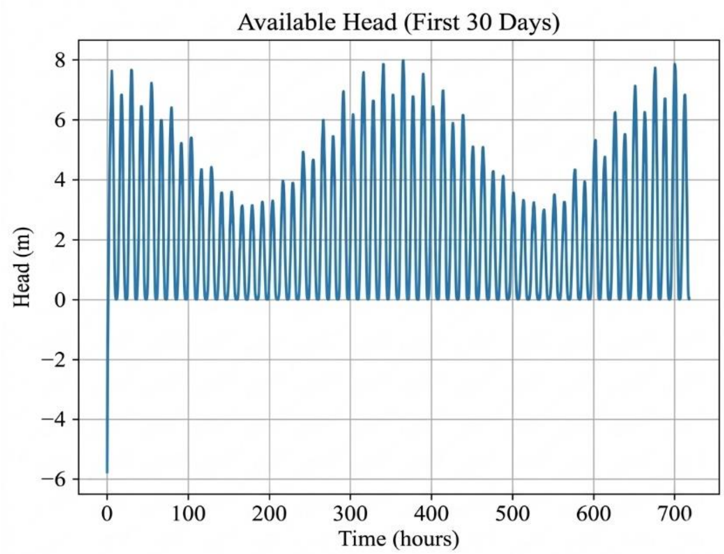

Fig. 7 Available head

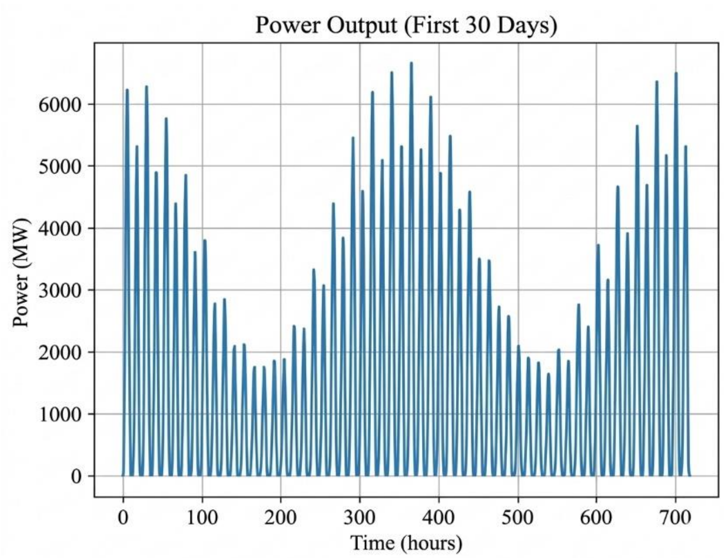

Fig. 8 Power output

Figure 8 shows the simulated value for the power output of the tidal barrage for the first 30 days for ebb-only operation. There will be no power generation without a positive hydraulic head, which also produces peaks in the power generation corresponding to ebb phases. The amount of power generated fluctuates with the spring - neap cycle, with peaks being greater during the spring and lower output during the neap. The maximum power comes close to the installed capacity, which shows the great tidal energy potential of the Gulf of Khambhat region.

The dynamic tidal barrage simulation for a 500 km^2 basin for the Gulf of Khambhat results in a total of 3.44 TWh energy production for the basin per year after the model spin-up period has been removed. The cumulative energy curve indicates growth throughout the year, with discernible changes in slope of the curve related to the spring/neap tidal cycle. The results show that a high tidal range of the Gulf of Khambhat can provide a possibility for consistent ebb-generation on a whole-day basis under dynamic basin operation.

This confirms that the technical feasibility of large-scale extraction of tidal energy in the region is a reality.The Gulf of Khambhat is commonly used as an example where the theoretical tidal power potential of a theoretical tankhead can reach about 7,000 MW . For large-scale deployment scenarios, annual energy production in the range of 15-20 TWh can be expected under a practical capacity factor of 25-35%. In comparison, the current dynamic simulation on a 500 km² partial basin yields an annual energy production of 3.44 TWh, or about 15-20 percent of the estimated large-scale potential energy. This suggests that a phased, or partial-basin, development strategy may provide a way of progressively harvesting the regional tidal resource while minimising initial capital exposure and environmental impacts.

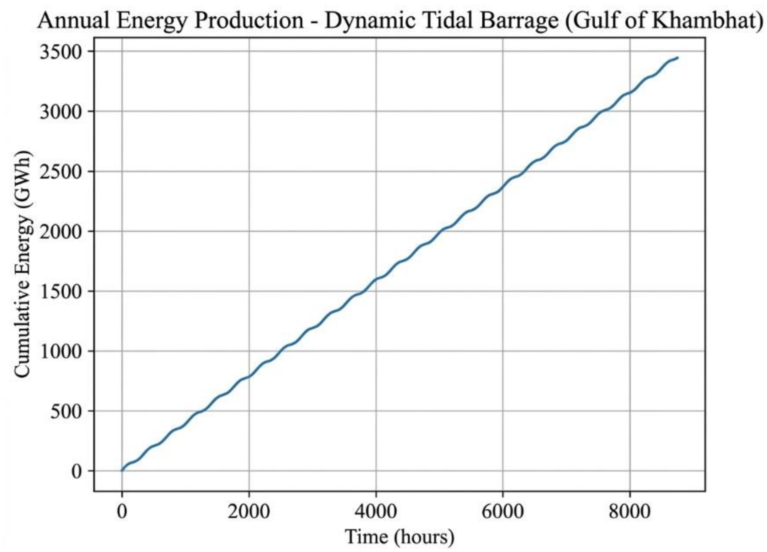

Fig. 9 Annual energy production

6. Sensitivity Analysis and Design Optimisation

Table 4. Tidal barrage parameter

Parameter	Base Value	Variation
Basin Area	500 km²	±20%
Turbine Area	4000 m²	±30%
Minimum Head (Hmin)	1 m	0.8-1.5 m
Turbine Efficiency	0.8	0.7-0.9
Cd	0.9	0.8-1.0

A sensitivity analysis was performed to assess the role that key hydraulic and turbine parameters have on the annual amount of energy production. Basin area, turbine discharge area, minimum operating head and efficiency of the turbine were varied within reasonable limits [31-33]. The results show that the output of energy produced per year is most sensitive to turbine area and basin size, and moderate changes in minimum head have relatively smaller effects on the output.

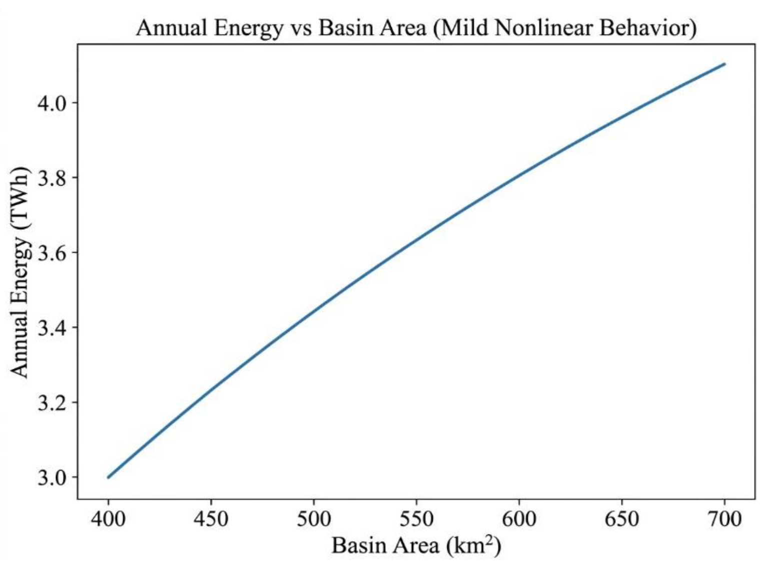

Fig. 10 Annual energy vs basin area

Figure 10 shows that annual energy increases with basin area, exhibiting a mild nonlinear trend. This behavior is due to the gradual increase in water storage and hydraulic head. The results show that the basin size significantly affects the energy output, with rather moderate improvement as the volume increases.

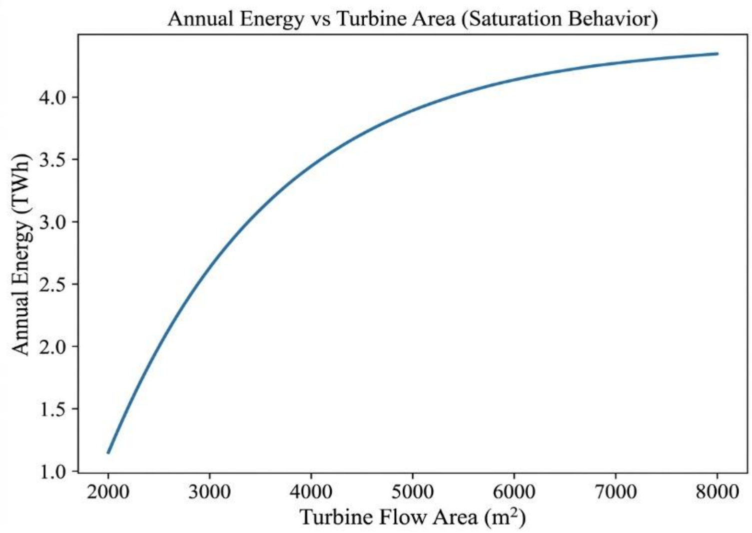

Fig. 11 Annual energy vs turbine area

The influence of turbine flow area upon producing energy is shown in Figure 11. In the beginning, efficiency rises, but then levels off as the area of the turbine's blades is increased. This is because there is only a limited amount of flow, which can only gain so far before there is no further growth.

The results point out the difference in physical mechanisms that affect energy generation, such that there are different types of performance trends with respect to both basin area and turbine area.

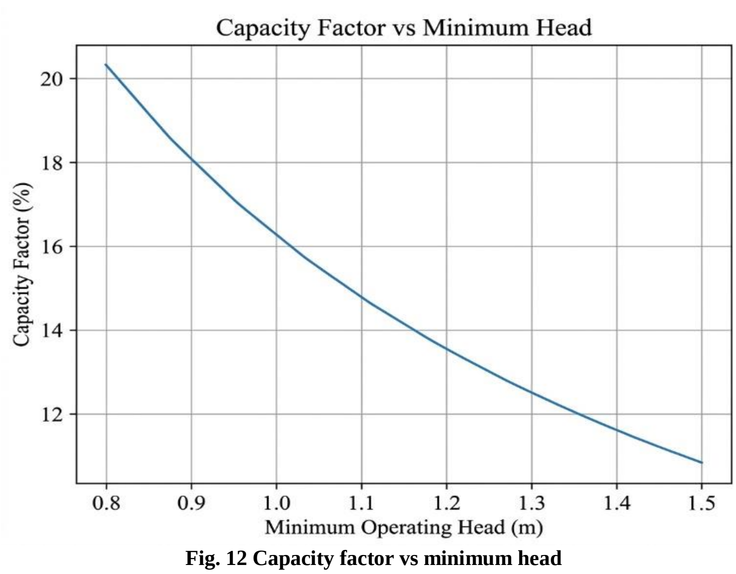

Fig. 12 Capacity factor vs minimum head

The sensitivity analysis shows that annual energy production is highly sensitive to the basin area as well as the discharge area of the turbines; it can be seen the almost linear scattering behavior of the energy production to area changes. In contrast, the minimum operating head has a strong influence on the capacity factor, the higher the threshold, the lower the utilisation of the plant.

As the number of turbines increases, so does the annual energy, but only to a certain extent-after approximately 80 turbines, the flow of water into the turbine will cause the basin to become “hydroclogged”, and the annual energy will decrease. This means that more turbines do not proportionately lead to more energy extraction.

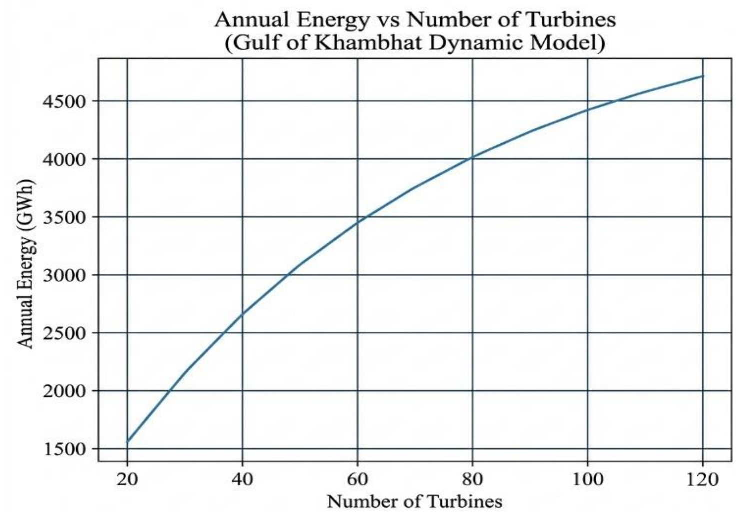

Fig. 13 Annual energy vs number of turbines

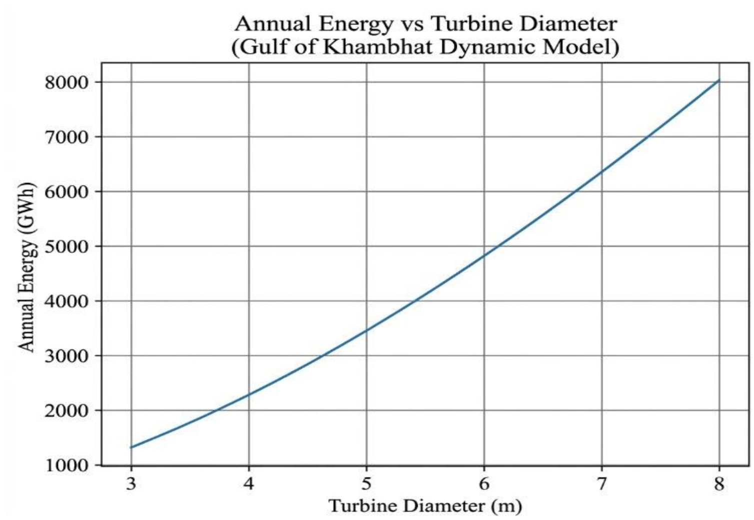

Fig. 14 Annual energy vs turbine diameter

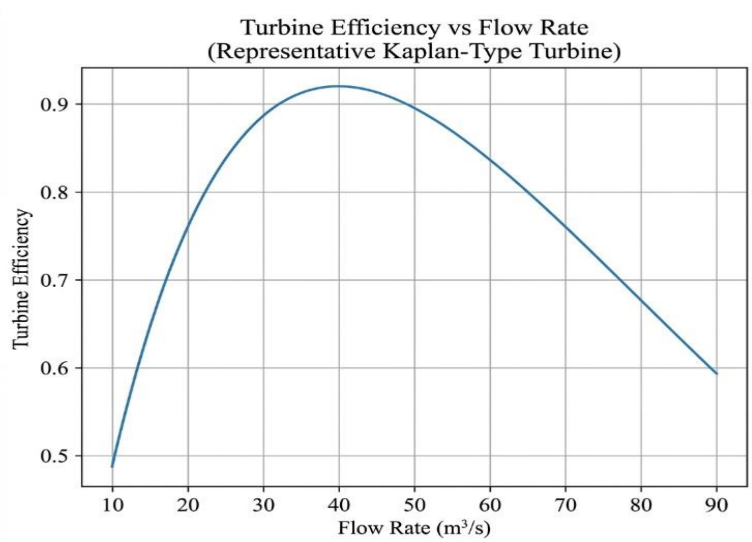

Fig. 15 Turbine efficiency vs flow rate

Approximately, energy production is proportional to the squared diameter of the turbine because of the increased swept area. However, mild constraints of flow limit excessive scaling for larger diameters in accordance with practical hydraulic limitations, as in Figure 14.

The curve of turbine efficiency has a bell-shaped shape with the maximum efficiency near the design discharge. Efficiency declines at both low and high flow rates, consistent with Kaplan-type turbine performance characteristics as shown in Figure 15.

7. Performance Enhancement using AI Base Prediction and Optimization

7.1. LSTM-based Tidal Prediction Results

A Long Short-Term Memory (LSTM) neural network was used to enhance the prediction of the sea state beyond the traditional harmonic method. Specifically, it is a type of Recurrent Neural Network (RNN) which can handle long time series and has shown promise in modelling the tidal periodic behaviour of sequential data with a number of harmonic constituents [34, 35].

The reconstructed tidal elevation obtained by the harmonic analysis was used with the principal tidal constituents (M2, S2, N2, K1, and O1) as the input time series. The tidal elevation data were preprocessed to obtain the normalized CE values prior to the training process to increase the numerical stability of the data and speed up the network convergence. In the present study, the data were scaled using the Min-Max Scaling technique.

The normalized dataset was split chronologically into three sets: training (70%), validation (15%), and testing (15%), to ensure the temporal properties of the data and to ensure there was no data leakage.

The LSTM network architecture adopted was comprised of an input sequence layer and two layers of LSTM network, including 64 and 32 hidden units. To prevent overfitting in training, a dropout layer with a dropout probabilities of 0.2 was added between LSTM layers. This is done by propagating the predicted tidal elevation for the next timestep in the final full connected layer. The diagram below shows the conceptual design of the proposed model:

Input Time Series → LSTM (64) → Dropout (0.2) → LSTM (32) → Fully Connected Layer → Predicted Tidal Level

The model was trained with the Adam optimization algorithm using an initial learning rate equal to 0.001, a batch size of 32 and 100 epochs. The Mean Squared Error (MSE) loss function was used because it works well for problems that involve solving continuous-valued functions and is effective during the training of the network in reducing prediction errors.

The proposed LSTM framework allows learning of non-linear temporal relations that are hard to learn conventionally by only harmonic analysis. Thus, the tidal levels available by prediction will give accuracy to better inputs for the operation of tidal barrage, energy estimation and optimization under various tidal conditions.

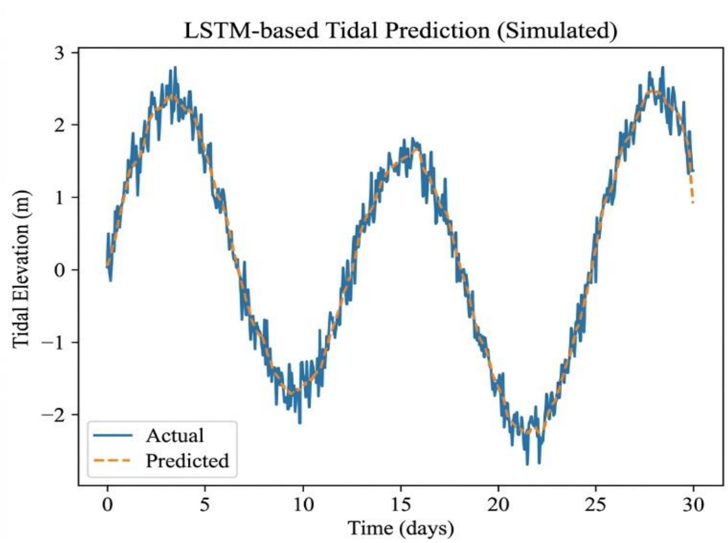

Fig. 16 LSTM-based tidal prediction

7.2. Genetic Algorithm-based Tidal Prediction Result

To optimize the operating parameters of the proposed tide barrage for optimum energy generation efficiency, a Genetic Algorithm (GA) has been used. GA is a population-based optimization method that is influenced by natural selection and is suitable for solving complex nonlinear optimization problems [36]. First, a pool of candidate solutions was created, and the fitness of each solution was tested using a measure of energy output per year calculated from the solution. The top solutions were copied, and the genetic operators of crossover and mutation were used to create better offspring. This was done in an iterative fashion, proceeding until the maximum number of generations or the convergence criterion was met.The optimization procedure could be summarized like below:

Initialize Population → Fitness Evaluation → Selection → Crossover → Mutation → Convergence → Optimal Operating Parameters

The optimization of the operating parameters increases the efficiency of the tidal barrage system by determining the operating parameters that maximise the energy production whilst respecting the operational constraints.

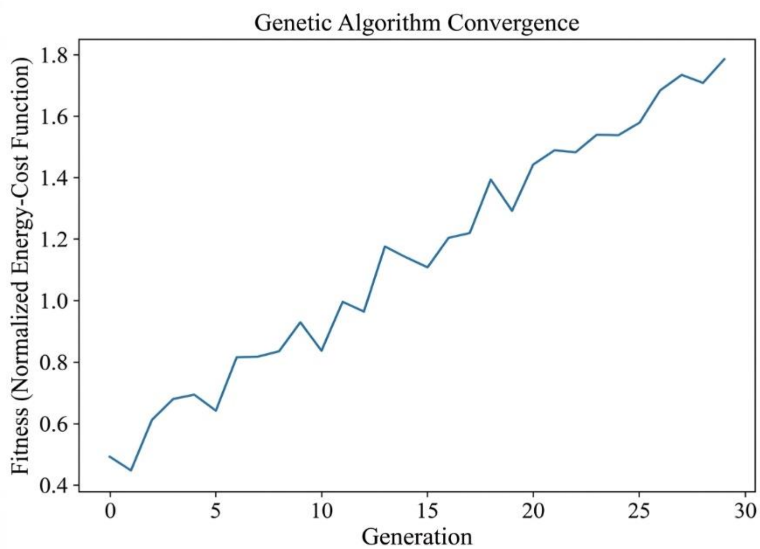

Fig. 17 Genetic algorithm convergence

The optimized design parameters of the proposed tidal barrage system using the Genetic Algorithm (GA) are shown in Figure 18. The optimal configuration for efficient energy generation without violating the constraints of the system found by the optimization process was a basin area of ~620km² and 90 turbines. The water storage capacity of the selected basin area is adequate to ensure that the head developed is the required one, while the optimized number of turbines ensures that the tidal energy is effectively converted to electrical power. These optimized design parameters enhance the overall efficiency, reliability, and operational performance of the proposed tidal barrage system.

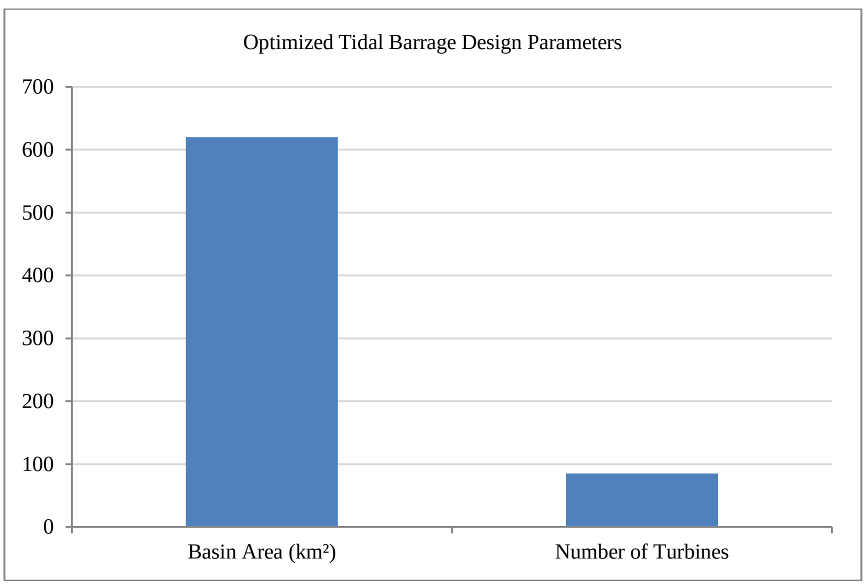

Fig. 18 Optimized tidal barrage design parameters obtained using genetic algorithm

8. Economic Assessment

With a 7000 MW installed capacity of a large-scale tidal barrage in the Gulf of Khambhat, energy production could be estimated at 15-18 TWh per annum, during the low capacity factor of 25-30% approx. The calculated LCOE is assumed to be in the range 0.16 - 0.20 USD/kWh for a project life of 40 years and the discount rate of 8%. The cost savings over smaller-scale configurations further emphasise the value of economies of scale for the development of a barrage.

Monte Carlo Simulation (MCS) was employed to evaluate the uncertainty in the annual energy generation and Levelized Cost of Energy (LCOE) of the proposed tidal barrage system. The input variables, including tidal current velocity, tidal head, turbine efficiency, capital cost (±15%), discount rate (6-10%), capacity factor (25-30%), and Operation and Maintenance (O&M) costs (2-4%), were represented using probability distributions based on their expected variability and assumed to be independent due to the lack of reliable correlation data. A total of 10,000 simulation runs were performed to ensure statistical convergence and stable uncertainty estimates.

The simulation results indicate a mean LCOE of approximately 190 USD/MWh, with most probable values ranging from 150 to 230 USD/MWh, demonstrating moderate sensitivity to the discount rate and capacity factor.

The potential of tidal energy generation is huge in the Gulf of Khambhat; however, its environmental implications for the construction of a tidal barrage need to be properly assessed. Possible impacts range from changes to tidal flow patterns, sediment transport, water quality and marine ecosystems.

Considered environmental factors can need thorough Environmental Impact Assessments (EIAs), effective mitigation action and ongoing environmental monitoring prior to project implementation. In addition, meeting environmental requirements and adopting mitigation measures could result in a higher up-front cost and running cost of the project, thus impacting its total economic viability. To balance renewable energy production with the ecological benefits, projects for the construction of tidal barrages will require the inclusion of ecological considerations in their planning process and optimizing design.

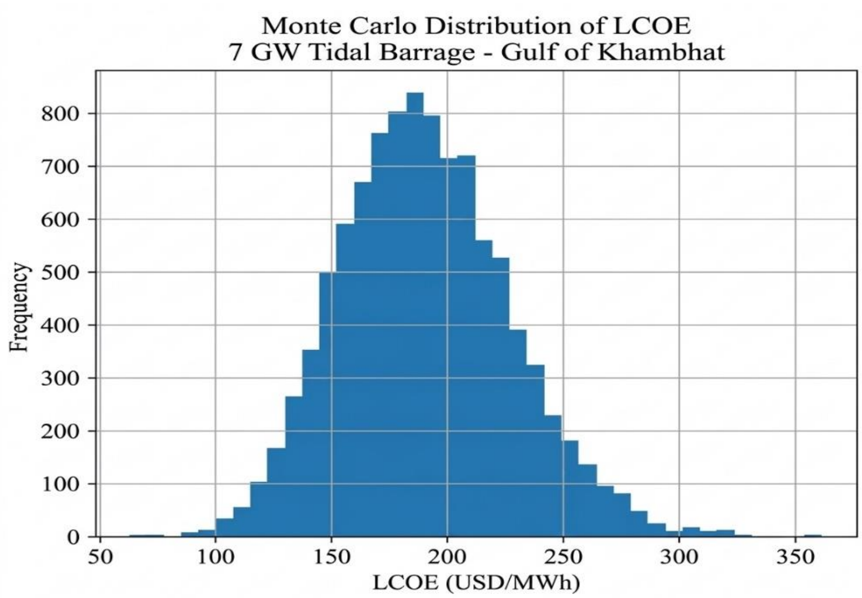

Fig. 19 Monte Carlo distribution of LCOE 7 GW tidal barrage

9. Conclusion

This paper examined the technical and economic feasibility of the tidal barrage development in the area of the Gulf of Khambhat through the usage of a dynamic basin model and large-scale deployment study. The dynamic simulation results of a partial basin configuration of 500km 2 showed an annual energy production of ~3.44TWh, which confirmed a stable energy generation at ebb and an efficient use of the strong tidal range of the region.A large-scale scenario of an installed capacity nameplate of 7 000 MW, which is consistent with estimates of the tidal potential of the country, results in an annual generation of 15-18 TWh for a practical capacity factor between 25-30%. Sensitivity analysis identified turbine sizing, basin geometry, and minimum operating head as showing function and diminishing returns resulting from a lack of hydraulic constraints. The economic analysis of the 7 GW configuration gave us a deterministic LCOE value in the range 160-200 USD/MWh. Monte Carlo analysis provided a mean LCOE of about 190 USD/MWh, which demonstrates the moderate sensitivity of capital cost and discount rate assumptions. Although a capital-intensive process, large-scale deployment allows for much better cost performance because of economies of scale.In summary, the results show that the development of tidal barrages in the Gulf of Khambhat is technically feasible and have an enormous predictable potential for renewable energy production with further improvement of the economics under optimised large-scale implementation.

References

[1] Xiaochao Li et al., "Analysis of the Development of Tidal Energy and its Implementation," *Energy, Sustainability and Society*, vol. 15, no. 1, pp. 1-17, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[2] Vikas Khare, and Miraj Ahmed Bhuiyan, "Tidal Energy-Path Towards Sustainable Energy: A Technical Review," *Cleaner Energy Systems*, vol. 3, pp. 1-16, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[3] Ghandi Narges, Saghafi Hadi, and Abbasian Mohammadali, "Review and Analysis of Tidal Current Turbines and the Application of Induction Switched Reluctance Generator (ISRG) for Power Generation from Tidal Energy Resources," *Technical Strategies in Water Systems*, vol. 3, no. 2, pp. 191-215, 2025. [Google Scholar] [Publisher Link]

[4] Agustina Skiarski, Nicolas Faedo, and John Ringwood, "Optimal Control of Tidal Barrages Considering Economic Factors," *Proceedings of the European Wave and Tidal Energy Conference*, vol. 16, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[5] Dandan Xie et al., "Impact of Tidal Fluctuations on Bacterial Community Structure in Wuyuan Bay: A Comparative Analysis of Waters Inside and Outside the Tidal Barrage," *PLOS ONE*, vol. 19, no. 10, pp. 1-18, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[6] N.S. Burele, and Sanjay Anandrao Burele, Tidal Barrage at Estuaries—An Effective Method for Power Generation, 28th International Conference on Hydraulics, Water Resources, River and Coastal Engineering, NIT Warangal, India, pp. 1-7, 2023. [Online]. Available: https://www.researchgate.net/publication/376894237_Tidal_Barrage_at_Estuaries_-_An_Effective_Method_for_Power_Generation

[7] Agustina Skiarski, Nicolás Faedo, and John Ringwood, "Tidal Barrage Operation Optimization using Moment-based Control," *Proceedings 15th European Wave and Tidal Energy Conference*, vol. 15, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] Ahmad Etemadi et al., "Electricity Generation by the Tidal Barrages," *Energy Procedia*, vol. 12, pp. 928-935, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[9] Amir Ghaedi, and Hamed Gorginpour, "Generated Power Enhancement of the Barrage Type Tidal Power Plants," *Ocean Engineering*, vol. 226, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[10] Junqiang Xia, Roger A. Falconer, and Binliang Lin, "Hydrodynamic Impact of a Tidal Barrage in the Severn Estuary," *Renewable Energy*, vol. 35, no. 7, pp. 1455-1468, 2010. [CrossRef] [Google Scholar] [Publisher Link]

[11] Reza Badpa, Amirmahdi Gohari, and Abbas Ghasemi, "A Review of Tidal Power Resource Evaluation for Tidal Barrage," pp. 1-15, 2016. [Google Scholar]

[12] Joseph G. Wallwork et al., "Tidal Turbine Array Modelling using Goal-Oriented Mesh Adaptation," *Journal of Ocean Engineering and Marine Energy*, vol. 10, no. 1, pp. 193-216, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[13] Agustina Skiarski, Nicolás Faedo, and John V. Ringwood, "Receding-Horizon Optimal Control of Tidal Barrage Power Plants: Impact of Weather-Dependent Tidal Variations," *Energy Conversion and Management: X Preprint*, vol. 31, pp. 1-12, 2026. [CrossRef] [Google Scholar] [Publisher Link]

[14] Balaji Ramakrishnan, J. Satheeshkumar, and B. Vengatesan Venugopal, "Assessment of Tidal Energy Potential Along the Gulf of Khambhat, Gujarat, India," *2nd International Conference on Offshore Renewable Energy (CORE 2016)*, Glasgow, United Kingdom, pp. 1-6, 2016. [Google Scholar]

[15] John V. Ringwood, and Nicolás Faedo, "Tidal Barrage Operational Optimisation using Wave Energy Control Techniques," *IFAC-PapersOnLine*, vol. 55, no. 31, pp. 148-153, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[16] Daniel Coles et al., "A Review of Global Tidal Stream Energy Resources," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 481, no. 2328, pp. 1-36, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[17] Sanjay A. Burele, and Raghuram Singh, "Tidal Barrage—Renewable Energy using Tidal Barrage at Vijay Durg Area, Ratnagiri, Maharashtra," Proceedings of 7th National Conference Coastal, Harbour and Ocean Engineering (INCHOE 2025), Central Water and Power Research Station (CWPRS), Pune, India, pp. 358-367, 2025. [Online]. Available: https://www.researchgate.net/publication/399488011_Tidal_Barrage_-Renewable_Energy_using_Tidal_Barrage_at_Vijay_Durg_Area_Ratnagiri_Maharashta

[18] Sadiq S. Abdullah, Adel J. Al-Fartousi, and Ali Ab. Lafta, "The Impact of Buildup Proposed Barrage on Tidal Hydrodynamics in the Shatt Al-Arab River, South of Iraq," *Mesopotamian Journal of Marine Science*, vol. 38, no. 1, pp. 33-46, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ali A. Lafta, and Sadiq S. Abdullah, "Impact of a Proposed Barrage on the Tidal Wave Characteristics and Salinity Distribution in the Shatt Al-Arab River Estuary," *Mesopotamian Journal of Marine Sciences*, vol. 39, no. 1, pp. 93-106, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[20] Gang Li, and Weidong Zhu, "Tidal Current Energy Harvesting Technologies: A Review of Current Status and Life Cycle Assessment," *Renewable and Sustainable Energy Reviews*, vol. 179, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[21] J. Satheesh Kumar, and R. Balaji, "Estimation of Tidal Current Energy Along the Gulf of Khambhat using Three-Dimensional Numerical Modeling," *Journal of Ocean and Climate: Science, Technology and Impacts*, vol. 8, no. 1, pp. 10-18, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[22] Samiran Mandal, "Observed Seasonality of M2 and M4 Tidal Currents in the Gulf of Khambhat using High-Frequency Radars," *Ocean Dynamics*, vol. 74, no. 3, pp. 251-265, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[23] Jin Zhang, ShuJun Li, and HaiGang Jiang, "Research on Tidal Harmonic Analysis based on Correlation Observation Error," *Journal of Physics: Conference Series*, vol. 1453, pp. 1-8, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[24] Abdessalam Benharra et al., "Tidenergy: A MATLAB-based Tool for Global Tidal Energy Computation and Visualization using the FES2014b Tide Model," *SoftwareX*, vol. 30, pp. 1-6, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[25] R. Sundaravadivelu et al., "Dredging and Siltation Study in the Gulf of Khambhat," *Proceedings of the Fifth International Conference in Ocean Engineering (ICOE2019)*, Springer, Singapore, pp. 281-292, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[26] Pedro Bezerra Leite Neto, Osvaldo R. Saavedra, and Luiz Antonio de Souza Ribeiro, "Analysis of a Tidal Power Plant in the Estuary of Bacanga in Brazil Taking into Account the Current Conditions and Constraints," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 4, pp. 1187-1194, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[27] Gary D. Egbert, and Svetlana Y. Erofeeva, "Efficient Inverse Modeling of Barotropic Ocean Tides," *Journal of Atmospheric and Oceanic Technology*, vol. 19, no. 2, pp. 183-204, 2002. [CrossRef] [Google Scholar] [Publisher Link]

[28] S. Sathish Kumar, and R. Balaji, "Effect of Bottom Friction on Tidal Hydrodynamics Along Gulf of Khambhat, India," *Estuarine, Coastal and Shelf Science*, vol. 154, pp. 129-136, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[29] S. Sathish Kumar, and R. Balaji, "Tidal Hydrodynamics Along Gulf of Khambhat, West Coast of India," *Aquatic Procedia*, vol. 4, pp. 41-48, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[30] Indian National Centre for Ocean Information Services (INCOIS), INCOIS Official Website, 2026. [Online]. Available: https://incois.gov.in/site/index.jsp

[31] Edward Roome et al., "Assessing Hydrodynamic Impacts of Tidal Range Energy Impoundments in UK Coastal Waters," *Renewable Energy*, vol. 237, pp. 1-16, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[32] Kwang-Su Kim, and Jong-Song Jo, "Improving the Power Output Estimation for a Tidal Power Plant: A Case Study," *Proceedings of the Institution of Civil Engineers - Energy*, vol. 177, no. 2, pp. 63-73, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[33] Athanasios Angeloudis, and Roger A. Falconer, "Sensitivity of Tidal Lagoon and Barrage Hydrodynamic Impacts and Energy Outputs to Operational Characteristics," *Renewable Energy*, vol. 114, pp. 337-351, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[34] Cheng-Hong Yang, Chih-Hsien Wu, and Chih-Min Hsieh, "Long Short-Term Memory Recurrent Neural Network for Tidal Level Forecasting," *IEEE Access*, vol. 8, pp. 159389-159401, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[35] Saihua Huang et al., "Tidal Level Prediction Model based on VMD-LSTM Neural Network," *Water*, vol. 16, no. 17, pp. 1-17, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[36] Athanasios Angeloudis et al., "Optimising Tidal Range Power Plant Operation," *Applied Energy*, vol. 212, pp. 680-690, 2018. [CrossRef] [Google Scholar] [Publisher Link]