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Research Article

Energy, Exergy and Environment Analysis of a Hydroelectric Power Plant

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ABSTRACT

This study presents a comprehensive energy, exergy, and sustainability assessment of a high-capacity hydroelectric power plant (HEPP). The analysis includes component-level performance evaluation, exergy destruction distribution, and sustainability indicators derived from monthly flow rate variations. The maximum available exergy released to the turbines was 529 MW, and the net exergy delivered from the switchyard was 481.67 MW. Among all components, the turbines exhibited the highest exergy destruction at 21.62 MW, mainly due to hydraulic friction, leakage losses, outlet flow losses, and mechanical friction in guide bearings and seals. Monthly analyses showed that both exergy efficiency and environmental performance varied with river flow rate. Higher flow conditions, particularly in April, increased exergy destruction and reduced sustainability indicators, whereas lower flow rates in August and September resulted in improved environmental benign indices and reduced environmental destruction indices. Sustainability parameters were also evaluated in detail. The HEPP demonstrated a loss-to-production ratio of 0.09, an exergy sustainability index of 9.282, an exergy stability factor of 0.91, an environmental benign index of 10.2, an environmental destruction coefficient of 1.1, and an exergy destruction factor of 0.089. Overall, the findings confirm that the HEPP operates as an environmentally compatible, thermodynamically efficient, and sustainable power generation facility. The results contribute to the understanding of performance optimization and long-term sustainability in hydraulic energy systems and provide a valuable framework for future improvement strategies.

Introduction

The fact that conventional energy resources are limited, rapidly depleting, and demand is increasing, allows countries to adopt renewable energy sources. As an established yet preferred power source, the Hydroelectric Power Plant (HEPP) is examined in this study. The HEPP is affected by seasonal changes and has been used to improve local energy security and to meet energy deficits and needs sustainably. Applying energy, exergy, and sustainability analyses to the HEPP is an essential tool to increase efficiency. Before presenting the analyses in detail, a brief review of related studies will be conducted to improve understanding and evaluation.

Oztop et al. [1] analysed the experimental and numerical efficiency of the Keban HEPP within the Elazig region, Turkey, using thermodynamic analysis. A good agreement between the experimental and numerical results is achieved. It was reported that thermodynamic analysis is an effective and straightforward method for determining turbine efficiency in HEPPs.

Kalinci et al. [2] developed the hybrid energy system conceptually, with a focus on hydrogen and electricity production. For this reason, Bozcaada was chosen, and the thermodynamic analysis of the system was presented using energy and exergy approaches. The hybrid system includes equipment such as photovoltaic panels, wind turbines, electrolyzers, and hydrogen tanks. Energy and exergy analyses were conducted to determine where and to what extent inefficiencies occur in the system.

Abuelnuor et al. [3] conducted a study to assess the potential for improvement in a hydroelectric power plant in Sudan by collecting empirical data. The exergetic efficiencies and exergetic destruction rates of each unit of the hydroelectric power plant were considered independently. The results indicated that the lowest energy yield during this period was 20.6 MW in August, whereas the highest exergetic destruction occurred in December, at 106.1 MW.

Kacar [4] investigated the thermodynamic modeling of a hydroelectric power plant that supplies the energy needs of a production facility that produces and stores hydrogen. He made the exergetic and sustainability analysis of the plant based on the 2nd law of thermodynamics. To conduct the thermodynamic evaluation of the hydroelectric power plant, an appropriate selection was made based on regional river-flow data and the plant's topographic conditions. It was estimated that the hydroelectric power plant should supply 200 kW to meet the hydrogen gas plant's electricity requirements.

Randriambahoaka and Rakotondramiarana [5] conducted energy production, exergetic, and sensitivity analyses of a hydroelectric power plant. In this study, they determined the exergy efficiency of the hydroelectric power plant and conducted a detailed analysis of the losses. In the study, it was also shown how exergy loss in equipment such as penstocks and turbines varies with flow rate.

Dal [6] has studied the feasibility and potential of a floating solar power plant in 10% of the lake basin of a hydroelectric power plant. It has been determined that the installed capacity of the floating solar power plant to be installed on the dam will be 576.4 MW, and the annual electricity production will be 802.4 GWh. It has also been determined that 378,336.3 tCO2 emissions can be avoided annually by producing 802.4 GWh of electricity.

Kafalı [7] compared the theoretical and current performance of the Gokcekaya Hydroelectric Power Plant. The plant's theoretical efficiency was 90.6%. At a unit flow rate of 99.8 m3/s and an adjustment vane opening of 89.37%, the turbine and unit efficiencies were 89.98% and 87.15%, respectively.

Demirdelen et al. [8] examined the role of hydroelectric power plants in the context of sustainable energy. It was found that Turkey's hydroelectric power generation is expected to increase to approximately 116 TWh. At this point, the potential energy generation that can be utilized on a small scale, based on Turkey's water basins, was evaluated to reduce dependence on fossil resources.

Haq et al. [9] conducted an exergetic assessment of power plants in Bangladesh to evaluate sustainability. They analyzed energy production and loss data for facilities such as coal, natural gas, and hydroelectric power plants between 2009 and 2019. Overall energy efficiency ranged from 34.55% to 36.1%, and exergy efficiency ranged from 35.07% to 36.59%. The energy efficiency of the hydroelectric power plant ranged from 84.19% to 85.55%, and the exergy efficiency ranged from 84.19% to 85.55% between 2009 and 2019.

In this study, comprehensive analyses of energy, exergy, and sustainability for an operating hydroelectric power plant in Türkiye are presented. Unlike many previous studies that focused solely on energy or exergy efficiency, this study provides a component-based assessment of exergy losses along the water pipeline, turbine, generator, transformer, and switchyard. Furthermore, sustainability indicators derived from the second law of thermodynamics are used to quantify the plant's environmental and sustainability performance. The results contribute to the efficient and sustainable operation of hydroelectric power plants by offering practical insights into loss distribution and potential for improvement.

Material and Method

The HEPP is located in eastern Turkey and started producing electricity in 2020. The HEPP body, which is composite, consists of a concrete dam with an asphalt core, compacted by a roller. A photo of the examined HEPP is shown in Fig. 1, and its technical specifications are shown in Table 1.

Figure 1. A photo from the examined HEPP [10]

Table 1 Technical specifications of HEPP [10]

Constant	Size	Unit
Local loss coefficient (k_{local})	0.5	-
Penstock roughness thickness ($k_{friction}$)	350	micron
Gross head (H_{gross})	88.49	m
Net head (H_{net})	87.55	m
Flow rate of water in the penstock (Q_1)	190	m^3/s
Flow rate of water in the penstock (Q_2)	40	m^3/s
Penstock diameter (D_1)	7.4	meter
Penstock diameter (D_2)	4.2	m
Angle of the penstock with the horizontal plane (θ)	0-45	deg
Length of penstock (L)	203.6	m
Dynamic viscosity of water (μ)(at 15^0C)	1.138×10^{-3}	kg/m s

The HEPP is considered an Open system with continuous flow. As shown in Fig. 2, as water accumulates in the dam, its potential energy increases. When the water in the dam reaches the operating water level, it is directed to the penstocks by opening the covers of the water intake structure. By conveying water through penstocks to the turbine, the turbine converts its potential energy into kinetic energy. In the turbine, this energy is transferred to the wheel through fixed and adjustable blades and converted into mechanical energy. From here, it is connected to the generator, and electrical energy is obtained. The electrical energy generated by the generator is first transferred to the transformers and then to the switchyard.

The HEPP has two power-generation systems: a 3-unit and a 1-unit system. Flow rates were determined based on average precipitation in the dam lake basin and seasonal conditions. The highest flow rate was 370 m^3/s in April, attributable to snowmelt, whereas the lowest was 110 m^3/s in August and September, with an annual average flow rate of 190 m^3/s.

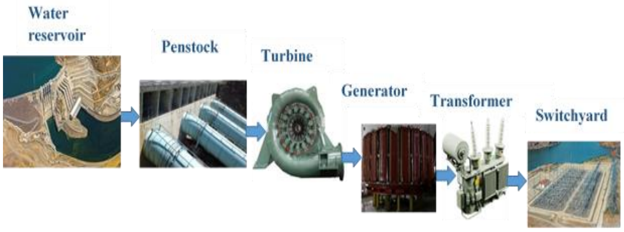

Figure 2. Flow diagram of the electricity production process at HEPP

Energy, Exergy, and Sustainability Analysis of HEPP

The term exergy is used to highlight the benefits of renewable and sustainable energy and to provide explanations in this context. The use of exergy has provided more valuable and reasonable information than energy for evaluating and improving energy systems, thereby improving understanding of the benefits of environmentally friendly energy [11]. At this point, the sustainability index has been developed to see the effect of exergy efficiency on development [12].

Today, the climate change problem that has emerged due to global warming has shown that the relationship between energy, exergy and sustainable development is an inseparable whole.

When the relationship among exergy, the environment, and sustainability is examined, the environmental impact approaches zero as a system's exergy efficiency approaches 100%, because exergy is converted from one form to another without being lost through waste emissions.

Energy Analysis

In the continuous flow energy equation, the mechanical energy entering is equal to the sum of the mechanical energy exiting and the mechanical loss. If the above equation is further clarified, the new equation is expressed as follows:

$$\dot{m}\left(\frac{P_1}{\rho_1}+\frac{V_1^2}{2}+gz_1\right)=\dot{m}\left(\frac{P_2}{\rho_2}+\frac{V_2^2}{2}+gz_2\right)+\dot{W}_{tur}+\dot{E}_{tot,l} \quad (1)$$

Where $\dot{W}_{tur}$ is the shaft power drawn by the turbine shaft, $\dot{E}_{tot,l}$ is defined as the total mechanical power loss. The energy entering the turbine is found by subtracting the loss from the penstocks from the total energy. The local and friction loss from the system are found by following equations:

$$h_{k,l}=\frac{k_l V^2}{2g} \quad (2)$$

$$\frac{1}{\sqrt{f}}=-2log\left[\frac{k_f}{3.7D}+\frac{2.51}{Re\sqrt{f}}\right] \quad (3)$$

Where k_f is the thickness of the porosity, D_l is the diameter of the penstock, Re is the Reynolds number based on hydraulic diameter, and f is the friction factor. The maximum power that the system can produce is:

$$\dot{W}_{max}=\rho QgH_{gr} \quad (4)$$

Then the efficiency of the penstock is calculated as follows:

$$\eta_{ps}=\left(1-\frac{\dot{E}_{tot,l}}{\dot{W}_{max}}\right) \quad (5)$$

The penstock mechanical total energy loss due to continuous and local losses is expressed:

$$\dot{E}_{p,l}=\rho\dot{Q}gh_L \quad (6)$$

Where h_L shows total loss in the system, ρ is the density of water, and $\dot{Q}$ is the flow rate of water in the penstock in m^3/s. When HEPP efficiency is calculated using gross head, it is defined as the ratio of the power plant's electric output to its maximum power, as shown in Eq. (7).

$$\eta_I=\frac{\dot{W}_E}{\dot{W}_{max}} \quad (7)$$

The total energy efficiency of the HEPP can also be expressed as the product of the efficiencies of the pressure pipes, turbine, generator, transformer, and switchyard as follows:

$$\eta_I=\eta_{ps}\eta_{tur}\eta_{gen}\eta_{tr}\eta_{sw} \quad (8)$$

Exergy Analysis

The valuable work potential of energy in a given state and quantity is defined as availability, or usable energy; in other words, exergy. Exergy is defined as the upper limit of the amount of work a system can do without violating any law of thermodynamics. The exergy method is a valuable tool, as it aims to use energy resources efficiently and to identify the points at which waste and losses occur, their types, and their magnitudes. Exergy analysis applies mass and energy conservation, together with the second law of thermodynamics, to analyze, design, and improve systems [13, 14].

Continuous losses due to frictional losses in the inner wall of the pipe caused by the water flowing through the line along the penstock line, local losses occurring in the straight parts of the penstock as well as in the parts such as inlet port, fitting, elbow, reduction, transmission and valve of the water intake structure, frictional losses in the cover of the water intake structure and the grid in the water intake structure constitute the exergy losses. The penstocks connected to the energy intake structure feed the power plant directly and operate independently of one another. If the water were delivered to the turbines via a penstock, it would have to be distributed through a branch pipe; thus, the losses in the branch would have to be accounted for. For detailed data, see [15].

Sustainability Assessment

Hydropower, a renewable energy source, is an essential component of sustainability owing to its contributions to economic development and its lower environmental impact relative to other energy sources. At this point, the sustainability of a system is assessed using parameters derived from the literature for sustainability analysis. Accordingly, the sustainability of the HEPP plant can be evaluated using the parameters presented below [12,15].

The exergy efficiency is expressed as the ratio of the valuable product exergy, i.e., the total output (electrical) exergy, to the maximum exergy entering the system as:

$$\eta_{II} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \quad (9)$$

The exergy destruction factor is a sustainability parameter that quantifies the extent to which the positive effect of HEPPs on exergy sustainability is reduced. The exergy destruction factor is expressed as the ratio of the total exergy destruction, which manifests itself as a loss in the system, to the total exergy entering the system, as below. To improve the plant's exergy-based sustainability, the exergy destruction factor should be close to zero [15].

$$f_{\text{edf}} = \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} \quad (10)$$

To demonstrate the positive impact of the environmental destruction coefficient on the exergy-based sustainability of HEPP, this coefficient should be evaluated within the framework of the 2nd Law of Thermodynamics. Therefore, the environmental destruction coefficient is related to exergy efficiency. The environmental destruction coefficient is expressed as the inverse of the exergy efficiency as in equation 2.50. For an environmentally compatible system, an environmental destruction coefficient close to 1[15].

$$\dot{E}_{edc} = \frac{1}{\eta_{ex}} \quad (11)$$

The environmental destruction index is a parameter used to evaluate the environmental hazard of the HEPP from a thermodynamic perspective. The environmental destruction index ranges from 1 to +∞ and is expressed as a function of exergy efficiency, defined as the ratio of non-reusable waste exergy [15].

$$\theta_{\text{edi}} = \frac{(r_{uwt}+f_{exd})}{\eta_{ex}} \quad (12)$$

Another sustainability parameter examined in the thermodynamic assessment is the environmental compatibility index, which enables evaluation of the HEPP's environmental compatibility from a thermodynamic perspective. The environmental compatibility index ranges from 0 to +∞. In order to improve the environmental adaptation index, the environmental benign index should be minimal and expressed as the inverse of the environmental destruction index as follow [15].

$$\theta_{\text{ebi}} = \frac{1}{\theta_{edi}} \quad (13)$$

To determine the exergy stability factor of a HEPP, the useful product exergy, i.e., the total output (electrical) exergy, and the total exergy destruction, which manifests itself as losses in the system, must be taken into account. The exergy stability factor ranges from 0 to 1 and should be close to 1 in practical application [15]. The exergy sustainability index is another vital sustainability parameter defined according to the 2nd Law of Thermodynamics; to determine this index, the environmental adaptation index and the exergy stability factor must be known. The lost generation rate of a HEPP is expressed as the ratio of the total exergy destruction, which manifests itself as losses in the system, to the useful product exergy, i.e., the total output (electricity) exergy.

Uncertainty and Error Analysis

In engineering analyses, uncertainties may arise from measurement limitations, variability in operational data, and assumptions regarding system efficiencies. In this study, uncertainties primarily occur from variations in flow rate, head measurements, and efficiency values for the turbine, generator, transformer, and switchyard, as obtained from operational records and manufacturer documentation.

Since the analyses are based on averaged operational data and well-established thermodynamic equations, the uncertainty propagation is limited and does not significantly affect the overall trends of the results. Minor deviations in input parameters may lead to slight variations in calculated energy and exergy values; however, these variations do not alter the relative distribution of losses among system components nor the overall conclusions regarding system performance and sustainability.

Similar qualitative uncertainty approaches have been widely adopted in energy and exergy analyses of large-scale power plants, where direct high-frequency measurement data are not available.

Results and Discussions

Energy analysis

In the energy analysis of the HEPP, separate calculations were made for the 3-unit and 1-unit lines. The calculation was first started by calculating the velocity of the water passing through the penstock, and then calculations such as local losses, continuous losses, mechanical energy losses, maximum power, penstock efficiency, turbine efficiency, specific speed calculations, generator, transformer, and switchyard efficiency, and power plant efficiency in the system have been made.

Penstock efficiency is calculated as 98%. To calculate the overall power plant efficiency, this section continues by determining the efficiency of the turbine and generator. To determine the turbine type using the specific-speed calculation, the turbine shaft power must first be calculated. In this calculation, the turbine efficiency must also be known. To facilitate verification later, the turbine efficiency of each turbine in 3 units is set to 0,96, and the turbine efficiency of the single-unit turbine is 0,94. The 1-unit turbine shaft power and the 3-unit turbine shaft power are calculated to be 155.973 kW and 32.152 kW, respectively. The specific speed of each turbine, which is 3

units, is calculated to be 1,48. The turbine type corresponding to the value 1,48 is a Francis turbine, and the turbine efficiency was determined to be 0,96, thereby ensuring turbine efficiency.
The turbine's specific speed, which is 1 unit, is calculated as 0.70. The turbine type corresponding to 0,70 is a Francis turbine, and the turbine efficiency was determined to be 0,94, thereby ensuring turbine efficiency.
Turbine loss is caused by water flow loss, hydraulic flow loss and internal loss caused by output loss, and external loss caused by friction losses in guide bearings and shaft seals. To minimize water flow loss due to leakage from the rotor rotation gap in turbines, the rotor rotation gap should be maintained within an optimal tolerance, accounting for the operating phase. To minimize flow loss due to boundary-layer effects in hydraulic flow, the areas through which the water passes should be leveled. Periodic maintenance is crucial to keep turbine power loss from wear, corrosion, and water leaks at low levels. The primary energy loss in turbines results from overload and underload operation; in this context, turbine operation should be performed at the optimal head and flow.

In addition to having very high generator efficiency, it is possible to determine where and to what extent generator losses occur [16]. In this context, the efficiency of a 3-unit generator was accepted as 98%, and the efficiency of a 1-unit generator was assumed as 97%. Table 2 presents the losses associated with the generator components.

Table 2 Percentage distribution of losses in the generator

Loss	Percentage (%)
Bearing friction loss	10
Air friction loss	15
Core loss	33
Armature coiling loss	14
Coil loss	15
Other losses	13

Losses in electrical systems can be attributed to the main power transformer (hysteresis loss, iron losses (fico), plate, core, boiler, and copper loss) and to the switchyard (breakers, disconnectors, transmission busbars, and insulator loss). Given that the losses in the transformer and switchyard are very low, their efficiency is assumed to be 99%.
The total turbine and total generator efficiencies in the HEPP are calculated. The total efficiency of the HEPP is calculated by multiplying the penstock efficiency, the total turbine efficiency, the total generator efficiency, the transformer efficiency, and the switchyard efficiency.

When the efficiency of the HEPP equipment is compared, the transformer and switchyard have the highest efficiency, whereas the turbines have the lowest. In Fig. 3, the equipment efficiencies in the HEPP are presented; accordingly, the equipment, turbine, and turbine components with the highest efficiency losses are identified.

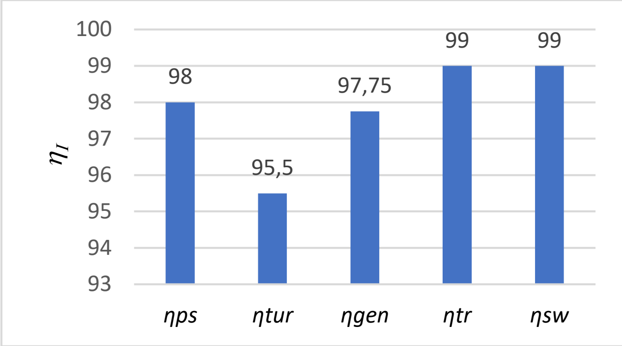

Figure 3. Energy efficiency of equipments in HEPP (%)

The HEPP's energy efficiency was 90% according to the above equation, and the plant's maximum power was calculated to be 529.056 kW. The electrical power generated by the HEPP was calculated to be 474,56 MW.

Exergy Analysis

In the exergy analysis of the HEPP, separate calculations were performed for the 3-unit and 1-unit lines. The analysis began by calculating the maximum exergy released to the hydraulic turbine, then proceeded to calculate the net exergy released to the hydraulic turbine and the exergy losses in the forced pipeline, hydraulic turbine, generator, transformer, and switchyard.

When the exergy losses of the HEPP equipment are compared, the turbine losses reach a maximum of 21.623,82 kW. The exergy loss, 4.86537 kW, occurred at the lowest switchyard compared with the others. The exergy losses of the equipment in the HEPP are presented in Table 3, and accordingly, the equipment, turbine and turbine components with the highest losses emerge.

Table 3 Exergy losses of equipment in HEPP

Exergy loss	Amount
$\dot{E}x_{ps}$	5.622 kW
$\dot{E}x_{tur}$	21.623,82 kW
$\dot{E}x_{gen}$	10.358,84 kW
$\dot{E}x_{tr}$	4.914,51 kW
$\dot{E}x_{sw}$	4.865,37 kW

The exergy efficiency of The hydroelectric power plant was calculated using the ratio of the exergy of the valuable product (the exergy of the generated electrical energy) to the maximum exergy entering the system. In this context, the total net exergy values for all equipment in the plant were determined separately. The average total net exergy value in the switchyard was 481.67 MW, and the total annual net exergy was 5,778 MW. Based on these results, the overall exergy efficiency of the hydroelectric power plant was determined to be 91%. Examining Fig. 4, which presents the monthly variation in the net exergy of the hydroelectric power plant, it is evident that the total net exergy varies significantly with seasonal conditions. The highest net exergy value was recorded in April at 938 MW, while in August and September, this value dropped to a minimum of 280 MW. These findings clearly demonstrate the sensitivity of the plant's performance to hydrometric conditions.

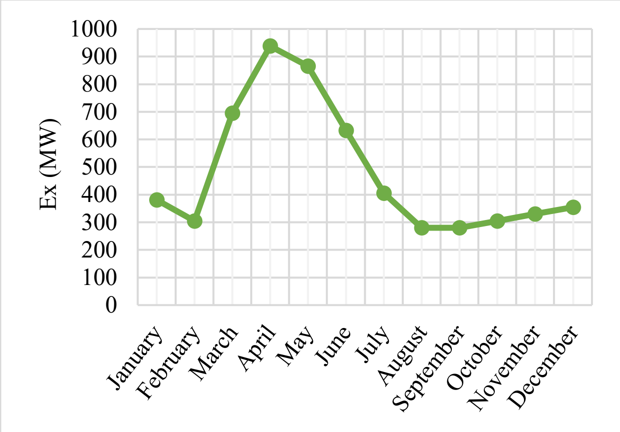

Figure 4. Change of net exergy of HEPP by months

The HEPP is equipped with four vertical-axis Francis turbines. The efficiencies of the three identical units were determined to be 96%, operating at an annual average flow rate of 190 m³/s. The remaining single unit operates at 94% efficiency, with an annual average flow rate of 40 m³/s. Exergy losses in the turbines arise from hydraulic friction, friction at the seals and guide bearings, and leakage through the runner clearance gap. The average total exergy loss for the three-unit group was calculated as 19 MW, corresponding to an annual total loss of 230 MW. For the single turbine unit, the average total exergy loss was 2 MW, corresponding to an annual total loss of 15 MW.

Fig. 5 illustrates the monthly variation of the HEPP's exergy efficiency as a function of the available water flow rate. The highest flow rate delivered to the plant occurred in April, during which the exergy efficiency was calculated as 88%. Conversely, the lowest flow rates were recorded in August and September, and the exergy efficiency in these months increased to 94%. These findings indicate that the exergy efficiency of the HEPP decreases as the available flow rate increases, primarily due to increased hydraulic and mechanical irreversibilities under higher load conditions.

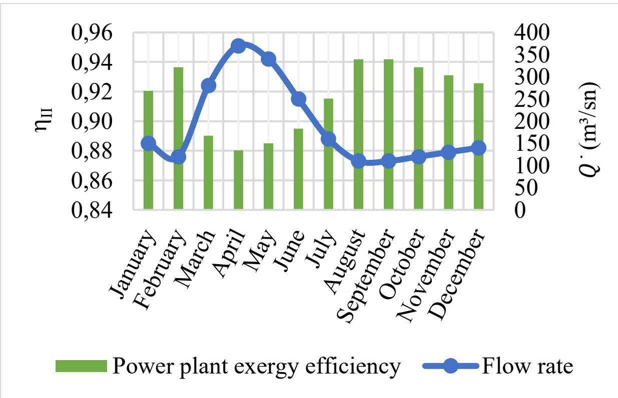

Figure 5. Variation of exergy efficiency of HEPP

Sustainability Analysis

In the sustainability assessment of the HEPP, several thermodynamic and environmental performance indicators were evaluated, including exergy efficiency, exergy destruction factor, environmental destruction coefficient, environmental destruction index, environmental compliance (benign) index, exergy stability factor, exergy sustainability index, and loss production rates.

Fig. 6 presents the sustainability parameters of the HEPP. According to the results, the loss production rate of the power plant was calculated as 0.09, the exergy sustainability index as 9.282, the exergy stability factor as 0.91, the environmental benign index as 10.2, the environmental destruction index as 0.098, the environmental destruction coefficient as 1.1, the exergy destruction factor as 0.089, and the overall exergy efficiency of the power plant as 91%.

For an energy facility to be classified as environmentally compatible, economically viable, and sustainable, the sustainability parameters are expected to fall within specific ranges. In this context, the exergy destruction factor should approach zero, the environmental destruction coefficient should be close to one, and the exergy stability factor should also be near unity. The results obtained in this study demonstrate that the HEPP satisfies these criteria, thereby confirming that the facility operates as an environmentally friendly, sustainable, and economically beneficial energy system with a significant contribution to regional and national development.

The environmental destruction index of the HEPP is defined as a function of the exergy destruction factor, the non-reusable waste exergy ratio, and the environmental destruction coefficient. Based on the analysis, the average index value was 0.098. Fig. 7 illustrates the monthly variation of the environmental destruction index as a function of the water flow delivered to the HEPP.

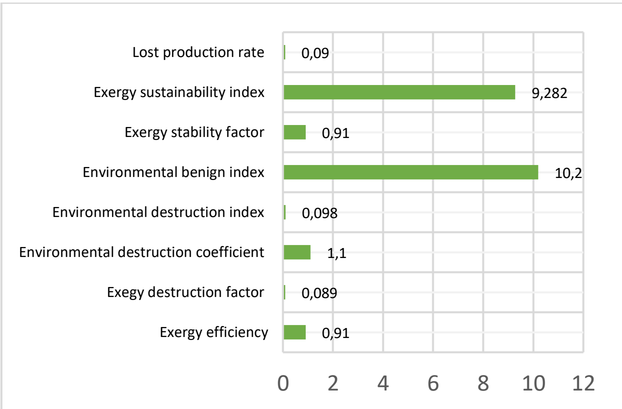

Figure 6. Sustainability parameters of the HEPP

The highest flow rate supplied to the plant occurred in April, during which the environmental destruction index reached its maximum value of 0.099. In contrast, the lowest flow rates were observed in August and September, and the corresponding environmental destruction index decreased to 0.092. These results indicate that the environmental destruction index increases with increasing flow rate, primarily due to increased exergy destruction and non-reusable waste exergy under higher load conditions.

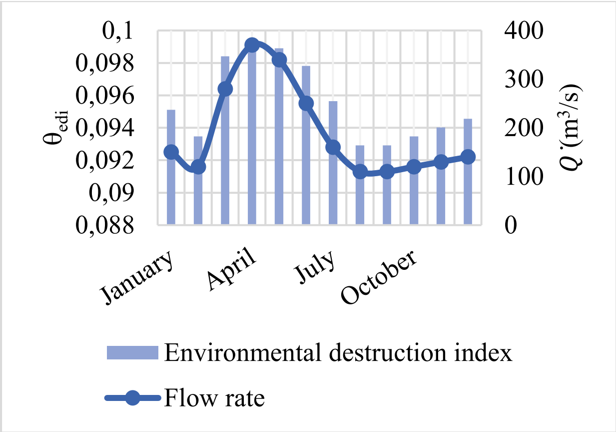

Figure 7. Variation of environmental destruction index

The environmental benign index, which is used to assess the thermodynamic compatibility of the HEPP with the environment, is conceptually the inverse of the environmental destruction index. The average value of this index was calculated as 10.2. Fig. 8 presents the monthly variation of the environmental benign index as a function of the water flow supplied to the HEPP. The highest flow rate delivered to the plant occurred in April, during which the environmental benign index reached 10.05. In contrast, the lowest flow rates were observed in August and September, corresponding to an increase in the environmental benign index of 10.76. These findings indicate that the environmental benign index decreases with increasing flow rate, consistent with the rise in thermodynamic irreversibilities under higher load conditions.

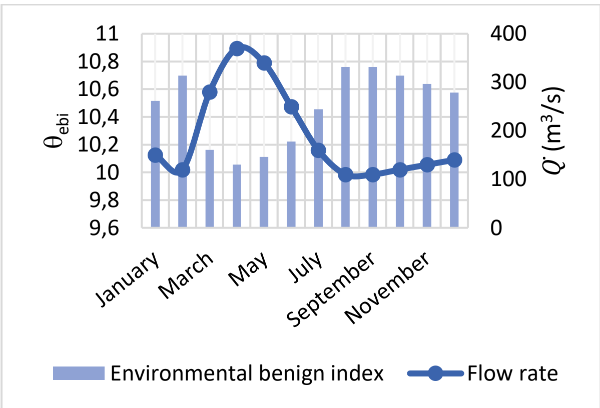

Figure 8. Variation of environmental benign index

The exergy sustainability index of the HEPP varies with the environmental compatibility index and the exergy stability factor, with an average of 9,282. In Fig. 9, the variation of the HEPP's exergy sustainability index with flow rate and month is shown. Accordingly, the maximum flow available to the HEPP occurred in April, and the power plant's exergy sustainability index was 9,17. The lowest flow to the HEPP occurred in August and September, and the power plant's exergy sustainability index was 9,81. As a result, as the flow rate supplied to the HEPP increases, the power plant's exergy sustainability index decreases.$\dot{Q}$

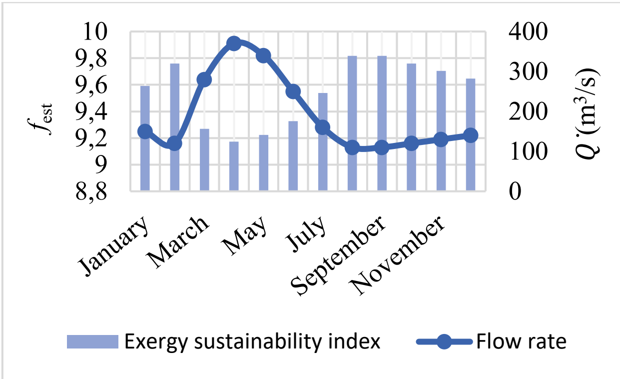

Figure 9. Variation of exergy sustainability index

Conclusions

This study presents a comprehensive assessment of the energy, exergy, and sustainability of an operating hydroelectric power plant, using real operational and design data. Beyond quantifying efficiencies and losses, the results provide important insights into how energy conversion processes affect the overall performance and sustainability of large-scale hydropower systems.

The findings demonstrate that although the overall efficiency and exergy efficiency of the plant are relatively high, the dominant energy and exergy losses occur in the hydraulic turbines. This highlights the critical role of turbine operating conditions, maintenance practices, and hydraulic design in improving plant performance. Identifying turbines as the primary source of losses provides practical guidance for prioritizing efficiency improvement efforts in existing hydropower plants.

The sustainability indicators derived from exergy analysis further show that the examined power plant operates within environmentally favorable limits. The calculated exergy sustainability index and related parameters indicate that hydropower plants, when operated under appropriate conditions, can contribute significantly to sustainable energy production with minimal environmental impact. These results emphasize the importance of exergy-based indicators as effective tools for evaluating not only efficiency but also environmental and sustainability performance.

Overall, this study contributes to the literature by integrating energy, exergy, and sustainability analyses at the component level for a real hydroelectric power plant. The methodology and findings can support decisionmakers and plant operators in identifying loss mechanisms, improving operational strategies, and enhancing the sustainable utilization of hydropower resources.

- The hydroelectric power plant shows high overall performance, with an energy efficiency of 90% and an exergy efficiency of 91%.
- The highest exergy destruction occurs in the turbines (21,623.82 kW), mainly due to hydraulic irreversibilities, leakage losses, and mechanical friction. This indicates that turbine-related improvements offer the greatest potential for performance enhancement.
- The maximum instantaneous power output of the plant is 529 MW, while the net exergy delivered from the switchyard is 481.67 MW, confirming effective energy conversion across electrical components. Exergy-based sustainability indicators demonstrate favorable environmental performance, with an exergy sustainability index of 9.282 and a low loss-to-production ratio of 0.09, confirming that the HEPP operates as a sustainable and environmentally compatible energy system.

Ethics committee approval

There is no need to obtain permission from the ethics committee for the article prepared.

Conflict of Interest

There is no conflict of interest with any person / institution in the article prepared.

Abbreviations

HEPP: Hydroelectric Power Plant

EBI: Environmental Benign Index

EDI: Environmental Destruction Index

EDC: Environmental Destruction Coefficient

ESI: Exergy Sustainability Index

ESF: Exergy Stability Factor

Subscripts

tur: turbine

gen: generator

ps: penstock

tr: transformer

sw: switchyard

l: loss

max: maximum

min: minimum

References

[1] H. F. Oztop, G. Kahraman, and H. L. Yucel, “Evaluation of energy efficiency using thermodynamics analysis in a hydropower plant: A case study,” *Renew. Energy*, vol. 34, no. 6, pp. 1458–1465, 2009, doi: 10.1016/j.renene.2008.10.030.

[2] Y. Kalinci, I. Dincer, and A. Hepbasli, “Energy and exergy analyses of a hybrid hydrogen energy system: A case study for Bozcaada,” *Int. J. Hydrogen Energy*, vol. 42, no. 4, pp. 2492–2503, 2017, doi: 10.1016/j.ijhydene.2016.02.048.

[3] A. A. A. Abuelnuor, K. Ahmed, K. M. Saqr, Y. A. M. Nogoud, and M. E. A. M. Babiker, “Exergy analysis of large and impounded hydropower plants: Case study El Roseires Dam (280 MW),” *Environ. Prog. Sustain. Energy*, vol. 39, no. 3, 2019, doi: 10.1002/ep.13362.

[4] O. Kacar, “Thermodynamic modelling of power generation in a run-of-river hydroelectric power plant,” M.S. thesis, Inst. Nat. Appl. Sci., Niğde Univ., Niğde, Türkiye, 2009.

[5] N. Randriambahoaka and H. T. Rakotondramiarana, “Investigation of a pico-hydropower plant performance by combining exergy analysis and global sensitivity analysis: A case study of Andriantseboka Analamanga Madagascar,” *J. Multidiscip. Eng. Sci. Stud.*, vol. 3, no. 1, pp. 1296–1302, 2017.

[6] A. R. Dal, “Investigation of the potential of using lakes and dams as solar power plants: The case of Yamula Dam,” *Gazi Univ. J. Sci. Part C: Des. Technol.*, vol. 9, no. 4, pp. 726–738, 2021, doi: 10.29109/gujsc.1002791.

[7] K. Kafalı, “Comparison of theoretical and actual performance of a hydroelectric power plant,” M.S. thesis, Inst. Sci., Osmaniye Korkut Ata Univ., Osmaniye, Türkiye, 2020.

[8] T. Demirdelen, M. Bilgili, A. Ozbek, H. Bilirgen, and F. Ekinci, “The role of hydropower installations for sustainable energy development in Turkey and the world,” *Renew. Energy*, vol. 126, pp. 755–764, 2018, doi: 10.1016/j.renene.2018.03.089.

[9] M. A. U. Haq, A. A. Mansur, A. S. M. Shihavuddin, M. H. Maruf, R. H. Ashique, M. T. Islam, M. Rabbani, and M. K. Nipun, “Exergy-based evaluation of power plants for sustainability and economic performance identification,” *Case Stud. Therm. Eng.*, vol. 28, Art. no. 101393, 2021, doi: 10.1016/j.csite.2021.101393.

[10] Kalehan Energy, “Asagi Kalekoy Dam and HEPP Project.” [Online]. Available: https://kalehan.com.tr/projeler/asagi-kalekoy-baraji-ve-hes/. Accessed: Nov. 20, 2025.

[11] S. Kapan, N. Celik, U. Camdali, and A. Taskiran, “Energy and exergy analyses of a submerged arc furnace used for ferrochrome production,” *Int. J. Exergy*, pp. 89–106, 2024, doi: 10.1504/IJEX.2024.139223.

[12] M. Kanoglu, I. Dincer, and M. A. Rosen, “Role of exergy in increasing efficiency and sustainability and reducing environmental impact,” *Energy Policy*, vol. 36, no. 1, pp. 128–137, 2008, doi: 10.1016/j.enpol.2007.09.006.

[13] I. Dincer and M. A. Rosen, *Exergy: Energy, Environment and Sustainable Development*. Amsterdam, Netherlands: Elsevier, 2021, doi: 10.1016/B978-0-12-824372-5.00001-4.

[14] A. S. Joshi, I. Dincer, and B. V. Reddy, "Thermodynamic assessment of photovoltaic systems," *Sol. Energy*, vol. 83, no. 8, pp. 1139–1149, 2009, doi: 10.1016/j.solener.2009.01.011.

[15] E. Bozoglan, A. Midilli, and A. Hepbasli, "Sustainable assessment of solar hydrogen production techniques," *Energy*, vol. 46, no. 1, pp. 85–93, 2012, doi: 10.1016/j.energy.2012.07.013.

[16] K. Ajiro, T. Inoue, and S. Sato, "Improvement of generator efficiency," *Fuji Electr. Rev.*, vol. 28, no. 2, pp. 52–58, 1982.