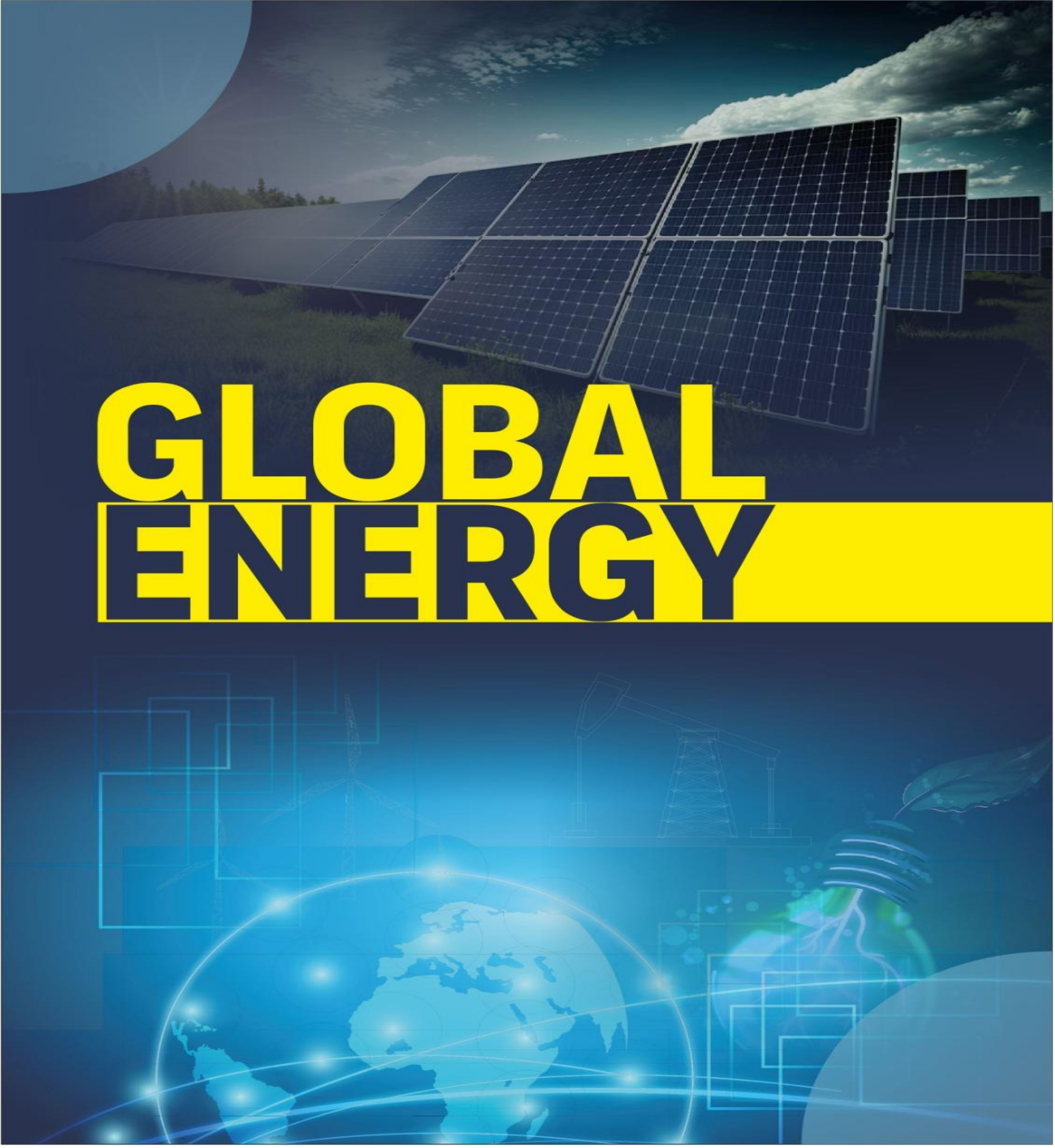


GLOBAL ENERGY (GEN)

2024 - Volume: 1 Issue: 2

Global Energy 1;2 (2024)

Global Energy

1;2 (2024) 3-10

Energy Recovery in Wastewater Treatment Plants Through Micro Hydroelectric Systems: A Feasibility Assessment

[a,b]İbrahim Halil Demirel, [c]Hakan Enes İzgi

[a]Batman University, Kozluk Vocational School, Department of Construction, 72400, BATMAN/TURKEY

[b]Batman University, Energy Coordinatorship, Vice Coordinator, 72060, BATMAN/TURKEY

[c]Batman University, Graduate Education Institute, Department of Energy Management, 72060, BATMAN/TURKEY

[a] ihalil.demirel@batman.edu.tr, ibrahimhdemirel@gmail.com

ARTICLE INFO

Article history:
Received 30 November 2024
Revised 11 December 2024
Accepted 13 December 2024
Available online 18 December 2024
Presented in International Energy Summit 2024

Key words:
WWTP
M-HES
Renewable energy
Energy recovery

* Corresponding author.
E-mail address:
ihalil.demirel@batman.edu.tr

ABSTRACT

This study aims to evaluate the energy production potential of micro-hydroelectric power plant (M-HES) applications at the Batman Wastewater Treatment Plant (WWTP). The energy production potential was calculated by considering different flow types and hydraulic head heights. The results indicate that M-HES applications could provide an annual energy production of 142,939.5 kWh to 188,879.3 kWh, meeting approximately 15.06% to 19.89% of the plant's total energy consumption. The findings demonstrate that M-HES systems offer a viable solution not only for the Batman WWTP but also for other wastewater treatment plants with similar infrastructures, serving as a guide for future engineering projects.

1. Introduction

Wastewater treatment plants (WWTP) are fundamental infrastructure elements of modern societies, operating to protect water resources, ensure public health, and promote environmental sustainability. These facilities effectively treat domestic and industrial wastewater, contributing to both the preservation of ecosystems and the reuse of water resources. However, wastewater treatment processes often require significant energy consumption. This energy demand constitutes a substantial portion of operational costs and, due to greenhouse gas emissions generated during energy production, poses challenges to achieving environmental sustainability goals. Therefore, developing strategies to improve the energy efficiency of wastewater treatment plants has become a critical necessity to reduce economic costs and minimize environmental impacts.

Water and energy are two critical resources for the sustainability of modern societies, offering significant opportunities for environmental protection and economic benefits through their integrated management. Traditionally, water supply and energy production systems have been designed independently, yet there exists a strong interdependence known as the “Water-Energy Nexus” [1,2]. While energy production requires water for processes such as cooling and steam generation, the collection, treatment, and distribution of water are energy-intensive activities. This interrelation underscores the critical importance of integrated management of water and energy systems in reducing costs, lowering greenhouse gas emissions, and ensuring the sustainable use of resources. In particular, energy efficiency applications in water and wastewater treatment plants hold great potential for improving economic performance and contributing to environmental sustainability. Innovative technologies and strategies play a pivotal role in achieving these objectives and are essential for meeting the United Nations' 2030 Sustainable Development Goals.

The water sector faces multifaceted challenges, including the adverse impacts of climate change on water resource availability, rapid population growth, industrialization, and infrastructural issues. Climate change introduces unpredictable shifts in water regimes, threatening both water supply and quality, while population growth and industrialization place increasing pressure on existing resources. These pressures are further compounded by operational issues such as aging infrastructure, leaks, and deteriorating water quality. Additionally, rising energy costs present another critical challenge, as water provision and usage often involve energy-intensive processes. These factors not only increase the financial burden on the sector but also complicate efforts to achieve sustainability goals [3,4]. Addressing these issues requires integrated and innovative strategies to balance resource demands, ensure water security, and align with broader environmental and economic objectives.

Furthermore, the lack of effective coordination among stakeholders such as water authorities, regulators, and political entities exacerbates pressing socio-economic, environmental, and resilience challenges in water management. Addressing these issues requires holistic approaches that encompass efficient resource management, modernization of infrastructure, and enhanced collaboration among stakeholders. Such strategies are not only essential for ensuring the sustainability of the water sector but also hold significant potential to contribute to societal well-being and environmental protection. By fostering integrated and cooperative efforts, these approaches can help mitigate current challenges and align water management practices with long-term sustainability goals.

To enhance energy production and efficiency in wastewater treatment plants, modifications involving the integration of renewable energy sources, alongside methane production, offer significant potential. Incorporating renewable energy systems such as solar and wind power provides sustainable and environmentally friendly solutions to meet the energy demands of these facilities. For instance, photovoltaic panels installed within the facility premises can generate electricity from solar energy, while wind turbines can be utilized in suitable areas around the plant to harness wind energy effectively. Additionally, micro-hydroelectric power systems (M-HES) represent an innovative modification, particularly suited for low-flow and low-head conditions at water flow points or discharge outlets of the treatment plants. These solutions not only diversify the energy portfolio of wastewater treatment facilities but also contribute to reducing their carbon footprint and operational costs, aligning with broader sustainability objectives.

Hydroelectric systems are renewable energy technologies that generate electricity by utilizing the flow of water to drive turbines. A subtype of these systems, M-HES, stands out as an innovative and sustainable energy source [5,6]. One of the most significant advantages of M-HES is that they do not require the construction of large dams or reservoirs, as is the case with large-scale hydroelectric systems, thereby minimizing environmental impacts. Recognized as an environmentally friendly alternative in renewable energy production, M-HES systems are particularly suited for water sources with low flow rates and low hydraulic head differences. Their adaptability and minimal ecological footprint make them a viable option for sustainable energy solutions, especially in regions where traditional hydroelectric systems may not be feasible.

The applicability of M-HES for energy production in wastewater treatment plants has been evaluated in various studies. Erkan et al. [7] conducted theoretical calculations based on the hydraulic head differences between the outlet and discharge points at the Van-Edremit, Elâzığ-Sivrice, and Tunceli central treatment plants, determining energy recovery rates of 20%, 9.5%, and 6.6%, respectively. Baran [8] highlighted that the Marmara Region has the highest electricity generation potential, whereas the Eastern Anatolia Region has the lowest. The study also predicted a significant increase of up to 138.58% in the Black Sea Region's energy production potential due to rising flow rates between 2018 and 2025. Kayıkçı et al. [9] analyzed the energy production potential in three different wastewater treatment plants in Istanbul, leveraging hydraulic head differences between units. Their findings indicated that M-HES systems could achieve up to 10% energy savings with payback periods ranging from 0.5 to 0.9 years. The turbine power potentials were calculated as 93.34 kW/h, 90.21 kW/h, and 36.85 kW/h. These studies collectively demonstrate that M-HES offers an environmentally friendly and economically viable energy solution, with significant potential for integration into wastewater treatment systems.

This study examines the feasibility and energy recovery potential of micro-hydroelectric power plants (M-HES) in the Batman Wastewater Treatment Plant (WWTP). The analysis evaluates the impacts of M-HES design models on energy production, energy efficiency, and the plant's annual energy consumption. Based on the plant's current potential, the contribution of energy recovery to the facility's energy consumption and the resulting economic savings were analyzed. These findings have been compared with the results of similar studies in the literature to provide a comprehensive evaluation..

2. Material and Method

2.1 Study Area

In the city center of Batman, a wastewater treatment plant (WWTP) operated by the Batman Municipality serves the region. The Batman Municipality WWTP processes approximately 61,000 m^3 of wastewater daily through physical treatment methods before discharging it into the Batman River. Although the facility does not include biological or advanced treatment processes, it provides physical treatment capacity for an area of 85 km^2, serving a population of approximately 477,456 [10]. The location of the WWTP, along with the Batman River and its basin, is shown in Figure 1. Daily wastewater inflow data for the Batman WWTP have been analyzed for the years 2011–2022 (excluding 2018). To estimate potential flow rates, the average daily wastewater values were categorized into rainy and dry periods for each calendar year. The average flow values for the plant are presented in Table 1.

Figure 1. Study area

Within the scope of this study, the geographical, demographic, and technical characteristics of the Batman Municipality WWTP were analyzed to assess its potential for energy efficiency and the integration of renewable energy sources. The data obtained from the facility aim to contribute to the development of sustainable approaches to wastewater management in the region.

Table 1. Wastewater inlet flows for Batman WWTP (m^3/d)

Year	***ADF***[a]	***MDF***[b]	***ADDF***[c]	***MDDF***[d]	***ADRF***[e]	***MADRF***[f]
2011	46.556	73.352	46.291	66.244	49.154	73.552
2012	46.404	75.778	46.323	61.542	46.660	75.778
2013	49.767	63.465	50.041	63.465	48.342	63.099
2014	47.544	63.043	47.745	63.043	46.683	54.099
2015	53.130	63.372	54.040	63.372	49.999	60.952
2016	49.631	62.094	49.641	60.442	49.571	62.094
2017	49.922	61.609	49.686	61.609	51.021	60.904
2019	53.543	61.708	53.614	61.708	53.256	61.151
2020	56.198	62.187	56.769	62.187	53.870	61.566
2021	41.368	61.132	40.920	61.132	44.704	61.105
2022	33.149	48.566	33.000	48.566	33.694	46.767
Average	47.93	63.30	48.01	61.21	47.90	61.92

[a] Average daily wastewater flow
[b] Maximum daily wastewater flow
[c] Average daily dry wastewater flow
[d] Maximum daily dry wastewater flow
[e] Average daily rainy wastewater flow
[f] Maximum daily rainy wastewater flow

2.2 Energy Recovery in Wastewater Treatment Plants: M-HES

Energy recovery in wastewater treatment plants (WWTPs) holds significant potential for both environmental sustainability and economic savings. Optimizing the energy-intensive processes involved in water treatment and integrating renewable energy systems reduce energy consumption and minimize the carbon footprint. Innovative applications, such as micro-hydroelectric power plants (M-HES), enable energy recovery by harnessing the movement of wastewater.

In WWTPs, treated wastewater can be utilized for electricity generation in M-HES before being discharged into receiving environments after disinfection. M-HES provides an environmentally friendly, reliable, and stable alternative for renewable energy production in wastewater treatment plants. These systems are particularly advantageous due to their minimal environmental impact and ability to operate without requiring dam construction, large land areas, or causing significant ecological disruption. The energy production potential of treated wastewater can be calculated by considering flow fluctuations during summer and winter seasons as well as day and night cycles. Power output can also be estimated based on varying flow rates and hydraulic head heights. The use of impulse turbines, in particular, enhances flow velocity, increases the dissolved oxygen concentration in the discharge water, and positively impacts water quality [11,12]. Thus, M-HES applications play a dual role by not only contributing to renewable energy generation but also improving water quality, demonstrating their critical importance in the sustainable management of wastewater treatment facilities.

Hydroelectric power plants convert the potential energy of water into electricity, with production capacities ranging from a few kilowatts to thousands of megawatts. These systems are highly versatile and can be implemented in any location with sufficient flowing water, from small-scale applications to large infrastructure projects. Micro-hydroelectric power plants (M-HES) refer to plants with a production capacity of less than 100 kW, standing out as cost-effective and environmentally friendly energy solutions [13]. If a WWTP has suitable hydraulic head and flow conditions, renewable energy production can be achieved using M-HES technology. However, several key criteria must be considered for such investments:

- **Treated wastewater flow rate**: The continuity of adequate flow is critical for energy production.
- **Hydraulic head height**: The elevation difference is a decisive parameter affecting energy conversion efficiency.
- **Turbine type**: Selecting the most appropriate turbine for the specific flow rate and head height is essential.
- **Investment cost**: Initial installation costs, payback periods, and long-term economic benefits should be evaluated.
- **Electricity price**: Regional energy prices significantly influence the investment's return on investment (ROI).

When these parameters are carefully considered, the installation of M-HES in WWTPs offers an effective solution for both energy production and environmental sustainability, contributing to operational efficiency and reduced carbon emissions.

2.3 Design Approach for Micro HEPP

Micro-hydroelectric power plants (M-HES) are systems that do not require a reservoir, unlike large dams, and provide sustainable energy production with minimal environmental impact. In these systems, only a portion of the flowing water is utilized for energy production, and the system is typically installed between units within a wastewater treatment plant or between the plant's outlet and discharge point. To calculate the actual power output (P) in M-HES, factors such as friction losses in penstocks and turbine/generator efficiency must be considered. While modern turbine technologies can achieve efficiencies exceeding 90%, the overall system efficiency generally ranges from 60% to 80%, depending on the hydraulic head and flow rate.

The energy production in M-HES is determined using the following formula:

$$P = Q * H * g * \eta \tag{1}$$

Here;
P; Electrical energy power (kW)
Q; Wastewater flow rate (m^3/s)
H: Net hydraulic drop, (m)
g; Gravitational acceleration, 9.81, (m/s^2)
ρ: Density of treated wastewater (kg/m^3)
η; Efficiency of microturbine, (dimensionless)

This formula allows for the theoretical estimation of energy production potential, enabling the assessment of M-HES applicability in wastewater treatment plants, particularly for sites with suitable flow rates and head heights**.**

In this study, the flow rate data for the Batman WWTP were analyzed based on the categories outlined in Table 1. The flow rates were classified into average daily wastewater flow, maximum daily wastewater flow, average and maximum daily dry-season flow, and average and maximum daily rainy-season flow. Using a theoretical approach, the energy production potential for each flow rate was calculated using Equation 1. For these calculations, the density of treated wastewater was assumed to be 1000 kg/m^3, and the efficiency factor of the microturbine was taken as 0.75. The hydraulic head data for the M-HES were determined using Google Earth software, which identified the elevations at the plant’s outlet and discharge points. Based on these findings, the hydraulic head for the proposed M-HES was assumed to be 4 meters. Analyses conducted under various flow scenarios allowed for an assessment of energy production capacity during both dry and rainy periods. This approach aimed to evaluate the system's performance under varying climatic and flow conditions and to optimize the energy recovery potential of the facility, contributing to the development of a more sustainable and efficient wastewater management system.

3. Results and Discussion

In this study conducted for the Batman Wastewater Treatment Plant (WWTP), the energy production potential of micro-hydroelectric power plant (M-HES) applications was evaluated using daily average flow rates. Based on calculations assuming a hydraulic head of 4 meters, the energy production potential for different flow types ranged between 16.31 kW and 21.56 kW (Table 2). These results align with similar studies in the literature [7-9], demonstrating that M-HES can make a significant contribution to renewable energy production in wastewater treatment plants.

Table 2. Potential for generating electrical energy for Batman WWTP

Flow ype	***ADF***[a]	***MDF***[b]	***ADDF***[c]	***MDDF***[d]	***ADRF***[e]	***MADRF***[f]
P (kW)	16.32	21.56	16.35	20.84	16.31	21.08
P(kWh/y)	143011.2	188879.3	143243.9	182643	142939.5	184746.6

Domestic water consumption and the resulting wastewater production tend to peak at specific times of the day, with these peak periods typically occurring during the early morning hours, prior to the start of the workday, and in the evening, following post-work activities. These fluctuations in wastewater production are influenced not only by the time of day but also by seasonal variations. During summer months, increased water usage driven by factors such as irrigation and cooling leads to higher peak values, whereas these values tend to decrease during the winter months. Such dynamics play a critical role in the energy consumption and capacity management of wastewater treatment plants. Therefore, it is essential to optimize system designs to accommodate these daily and seasonal variations, ensuring efficient and sustainable operation of the facilities.

The energy recovery rates were calculated by comparing the energy generated by the proposed M-HES with the energy consumption of the facility (Table 3). Based on the current flow and hydraulic head characteristics of the plant, the annual energy production capacity was determined to range between 142,939.5 kWh and 188,879.3 kWh (Table 2). When compared to the total energy consumption of 949,310 kWh in 2023, the M-HES applications could meet approximately 15.06% to 19.89% of the facility's energy needs. This contribution is significant for reducing energy consumption and enhancing environmental sustainability in energy-intensive wastewater treatment plants.The obtained results align with findings from the literature. For instance, Erkan et al. [7] reported energy recovery rates ranging from 6.6% to 20% in studies conducted on wastewater treatment plants in Van-Edremit, Elâzığ-Sivrice, and Tunceli. Similarly, Kayıkçı et al. [9] highlighted that M-HES systems in wastewater treatment plants in Istanbul could achieve energy savings of up to 10% with payback periods of 0.5 to 0.9 years. These findings demonstrate the significant potential of the Batman WWTP to contribute to energy efficiency and sustainability goals through the implementation of M-HES. By leveraging its existing flow and hydraulic head potential, the facility could play a vital role in advancing renewable energy integration and reducing its operational carbon footprint.

The primary advantages of M-HES systems lie in their environmentally friendly design, low investment costs, and broad range of applications. The energy production values calculated in this study demonstrate that the implementation of M-HES at the Batman WWTP can significantly reduce the facility's energy consumption while providing long-term economic benefits. However, advancing energy efficiency in wastewater treatment plants will require the development of more sophisticated engineering solutions and optimized designs. Such improvements will play a critical role in achieving regional energy goals.

Furthermore, a detailed analysis of the effects of flow fluctuations during dry and rainy periods on energy production is essential to enhance the efficiency and effectiveness of these applications. Addressing these factors will ensure that M-HES systems not only meet energy demands but also contribute to broader sustainability objectives.

Table 3. Batman WWTP electricity consumption quantity

Date	T1 (07:00-18:00)	T2 (18:00-23:00)	T3 (23:00-07:00)	Active (kWh)
31/08/2023	36,421	17,157	27,543	81,122
04/09/2023	961	84	589	1,634
30/09/2023	2,020	1,030	1,687	4,736
31/10/2023	40,843	20,806	33,678	95,328
30/11/2023	16,669	8,921	14,673	40,263
31/12/2023	50,519	26,820	40,878	118,217
31/01/2024	13,921	6,991	11,389	32,300
29/02/2024	38,576	19,433	30,555	88,564
31/03/2024	46,638	23,979	38,502	109,119
30/04/2024	21,278	10,169	17,017	48,465
31/05/2024	42,245	20,399	33,446	96,091
30/06/2024	33,475	15,521	25,336	74,332
31/07/2024	16,276	7,669	12,675	36,619
31/08/2024	55,593	25,685	41,242	122,520
Total	**415,435**	**204,664**	**329,210**	**949,310**

4. Conclusion

This study comprehensively evaluated the energy production potential of micro-hydroelectric power plant (M-HES) applications at the Batman Wastewater Treatment Plant (WWTP). The analyses revealed that M-HES systems could meet approximately 15.06% to 19.89% of the plant's annual energy consumption, which is 949,310 kWh. These results demonstrate the significant contribution of M-HES systems in enhancing energy efficiency and promoting the use of renewable energy sources in wastewater treatment plants.

The findings of this study are not only relevant for the Batman WWTP but also serve as a guide for other wastewater treatment facilities with similar infrastructures. Moving forward, it is recommended to optimize M-HES designs to accommodate flow fluctuations, select turbines to maximize efficiency, and conduct a more detailed analysis of seasonal variations.

In conclusion, M-HES applications have the potential to transform wastewater treatment plants from energy-consuming infrastructures into energy-generating systems, thereby contributing significantly to the development of sustainable energy policies and practices.

References

[1] Hamiche, A. M., Stambouli, A. B., & Flazi, S. (2016). A review of the water-energy nexus. Renewable and Sustainable Energy Reviews, 65, 319-331. https://doi.org/10.1016/j.rser.2016.07.020

[2] Gjorgiev, B., & Sansavini, G. (2017). Water-energy nexus: Impact on electrical energy conversion and mitigation by smart water resources management. Energy Conversion and Management, 148, 1114-1126. https://doi.org/10.1016/j.enconman.2017.06.053

[3] Helmbrecht, J., Pastor, J., & Moya, C. (2017). Smart solution to improve water-energy nexus for water supply systems. Procedia Engineering, 186, 101-109. https://doi.org/10.1016/j.proeng.2017.03.215

[4] Luna, T., Ribau, J., Figueiredo, D., & Alves, R. (2019). Improving energy efficiency in water supply systems with pump scheduling optimization. Journal of Cleaner Production, 213, 342-356. https://doi.org/10.1016/j.jclepro.2018.12.190

[5] Dalcalı, A., Çelik, E., & Arslan, S. (2012). Mikro ve mini hidroelektrik santralleri için mikrodenetleyici tabanlı governor sisteminin tasarımı. Erciyes Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 28(2), 130-135.

[6] Llácer-Iglesias, R. M., López-Jiménez, P. A., & Pérez-Sánchez, M. (2021). Hydropower technology for sustainable energy generation in wastewater systems: Learning from the experience. Water, 13(22), 3259. https://doi.org/

[7] Erkan, D., Yılmaz, T., Yücel, A., Yılmaz, A., Tel, A., & Uçar, D. (2018). Atıksu arıtma tesislerinde enerji kazanımı için mikro ölçekte hidroelektrik santrallerin uygulanabilirliği. Harran Üniversitesi Mühendislik Dergisi, 1, 1-6.

[8] Baran, B. (2021). Usage of wastewater treatment plants hydroelectric energy for urban lighting energy: The case of Turkey. Uluslararası Mühendislik Araştırma ve Geliştirme Dergisi, 13(2), 750-762.

[9] Kayıkçı, Z., Akarsu, C., Sönmez, V. Z., & Sivri, N. (2023). Atıksu arıtma tesislerinde sürdürülebilir enerji üretimi için mikro hidroelektrik teknolojisi kullanımı: İstanbul örneği. Anadolu Çevre ve Hayvancılık Dergisi, 8(2), 162-168. https://doi.org/10.35229/jaes.1241476

[10] Çevre, Şehircilik ve İklim Değişikliği Bakanlığı. (2024). Batman İli 2023 Yılı Çevre Durum Raporu. Batman, Türkiye.

[11] Demirel, I. H., & Ozkan, F. (2022). An experimental study of air-demand ratio in free-surface gated circular conduits. Water Supply, 22(6), 5933-5946.

[12] Ozkan, F., Demirel, I. H., Tuna, M. C., & Baylar, A. (2015). The effect of length of free-surface gated circular conduit on air-demand ratio and aeration efficiency. Water Science and Technology: Water Supply, 15(6), 1187-1192.

[13] Amran, M., Radzi, M., Lqbal, M., & Hakim, A. (2004). Basic design aspects of micro hydro power plant and its potential development in Malaysia. PECon 2004. Proceedings. National Power Energy Conference 2004, 220–223.

Global Energy

1;2 (2024) 11-15

Evaluation of EDMS Usage in Terms of Environmental Sustainability

[a]Murat Ekin, [b]Yavuz Elitok

[a]Batman University, Institute of Graduate Studies BATMAN/TURKEY

[b]Batman University, Faculty of Economics and Administrative Sciences, Department of Business Administration BATMAN/TURKEY

[a] murat.ekin@batman.edu.tr,

ARTICLE INFO

Article history:
Received 30 November 2024
Revised 11 December 2024
Accepted 13 December 2024
Available online 18 December 2024
Presented in International Energy Summit 2024

Key words:
EDMS
Sustainability
Environment

* Corresponding author.
E-mail address:
murat.ekin@batman.edu.tr

ABSTRACT

Innovation in information technologies have led to the rapid spread of electronic applications and brought a new dimension to document management processes. Document management systems, which are used by digitizing traditional printed documents, have gradually been replaced by Electronic Document Management System (EDMS). EDMS is of strategic importance for organizations, not only increasing operational efficiency but also saving costs and energy. In addition, the contribution of EDMS to sustainability goals is also noteworthy, as it minimizes environmental impacts by reducing paper use and contributes to a greener future. Although there have been various studies on EDMS in Turkey, the energy saving and sustainability aspects of the subject have not been emphasized enough. The aim of this study is to reveal the cost and energy savings, operational efficiency and sustainability contributions of EDMS in universities. In addition, it is aimed to create a resource that will provide guidance to institutions that have switched to EDMS or are in the process of transition. In this context, the savings and sustainability advantages of EDMS in universities are analyzed. As a result of the data obtained regarding the environmental impacts of the use of EDMS at Batman University, it was seen that 113 trees were saved and 572 tons of water were saved in 2023. In addition, 32.4 tons of CO2 emissions and 2.3 tons of waste were reduced.

1. Introduction

Electronic Document Management Systems (EDMS) are one of the fundamental components of digital transformation processes, providing organizations with advanced technology to manage their documents in digital environments. By eliminating the complexity and slow pace of traditional paper-based processes, they enable faster, more secure, and more efficient document management. Moreover, EDMS is not limited to accelerating business processes or reducing costs; it also offers significant advantages in terms of environmental sustainability. These benefits can be considered a vital tool in achieving sustainable development goals today. Environmental sustainability refers to an approach aimed at reducing the impact of human activities on natural ecosystems and safeguarding natural resources for future generations [1]. EDMS contributes significantly to this area, particularly by minimizing paper consumption, supporting the preservation of forest resources, reducing carbon footprints, and decreasing waste production. The environmental costs associated with traditional paper use, such as energy consumption, water waste, and greenhouse gas emissions are significantly reduced through the processing of digital documents. For instance, considering that the production of one sheet of paper results in approximately 600 ml of water, 34 grams of CO2, and 2.4 grams of waste, widespread use of EDMS can yield substantial resource savings on a large scale [1, 2].

This study, conducted at Batman University, demonstrates the environmental impact of EDMS with concrete data. The system implemented within the university has not only increased the speed of business processes but has also led to significant reductions in energy efficiency and carbon emissions through annual paper savings. For instance, the savings observed during a specific period were associated with tangible benefits, such as the preservation of hundreds of trees and the prevention of the release of tons of carbon dioxide. These types of gains provide an important model not only for Batman University but also for the implementation of similar systems in other institutions and organizations. In this context, electronic document management is viewed not only as an operational innovation but also as a strategic tool that facilitates achieving environmental sustainability goals. The widespread adoption of EDMS will contribute to increased environmental awareness both locally and globally, enabling more efficient resource use. Thus, digital transformation processes will be integrated with sustainability, allowing institutions to adopt a more responsible structure in both economic and ecological terms. The environmental impacts of EDMS are not limited to short-term gains; they also ensure the widespread adoption of environmentally conscious policies in the long term and leave a more livable world for future generations. Research that further highlights the benefits of such systems will increase awareness in both the academic and institutional worlds and will create significant gains for a sustainable digital transformation [1, 3, 4].

2. The Impact of EDMS on Environment

The environmental impacts of paper production are generally prepared using average values and aim to demonstrate the environmental costs of the paper production process. This type of assessment may suggest a correct approach, but precise figures can vary depending on the production processes, raw materials used, and energy sources. It is estimated that approximately 10,000 to 20,000 liters of water are required to produce one ton of paper. The use of recycled paper can reduce water consumption. Various sources report differing values for water consumption in the production of a single A4 sheet. According to TÜBİTAK data, 13 liters of water can be used to produce one A4 sheet of paper. Other sources state that CO2 emissions for the production of one A4 sheet range from 13 to 35 grams. Waste produced during paper production is a result of the cellulose and chemical processes, and the amount of waste varies depending on the production process [5].

It is evident that energy, water consumption, and waste quantities during paper production have an impact on environmental sustainability. Particularly, chemicals and intensive processes used in cellulose production increase the environmental costs. Negative effects have even been observed in common methods such as Kraft (sulfate) due to chemical use. The importance of recycling paper production is emphasized here. For example, recycled paper production consumes 64% less energy and uses less water compared to virgin cellulose-based paper production. Additionally, one ton of paper produced through recycling saves 26 tons of water. Recycled paper products significantly reduce the environmental impact by decreasing waste quantities and energy consumption. For institutions, reducing paper consumption and encouraging recycling are critical measures. The widespread adoption of digital solutions such as Electronic Document Management Systems can make significant contributions to environmental sustainability goals [6].

2.1 PExample of Batman University

Since 2014, Batman University has been using EDMS to digitize all its documents. The environmental impacts of the system implemented at Batman University were examined in 2023 based on the following values for producing one A4 sheet of paper: 600 ml of water, 34 g of CO2, and 2.4 g of waste.[1]

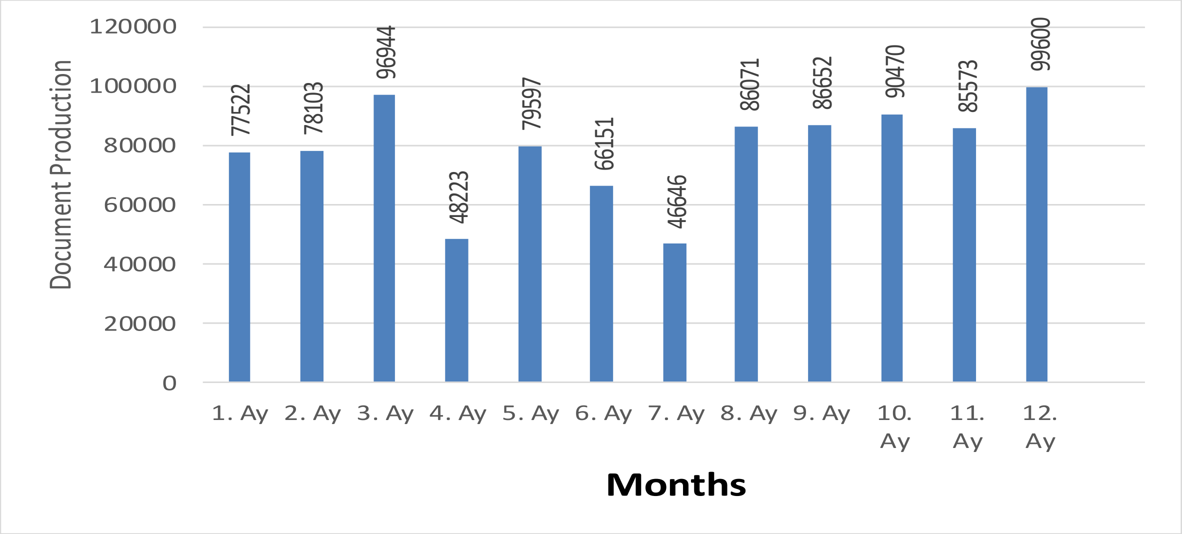


Figure 1 Electronic Document Production at Batman University in 2023

In 2023, the monthly production of electronic documents ranged from a low of 46,646 in July to a high of 99,600 in December. The peak production in March (96,944 documents) and December indicates busy work periods, while the decrease in months like April (48,223 documents) and July may be due to holidays or seasonal slowdowns. A total of approximately 950,000 documents were produced throughout the year, significantly reducing paper use and contributing to environmental sustainability. The positive impacts on water, carbon emissions, and waste due to paper savings for each electronic document highlight the critical role of digitalization in both economic and environmental dimensions.

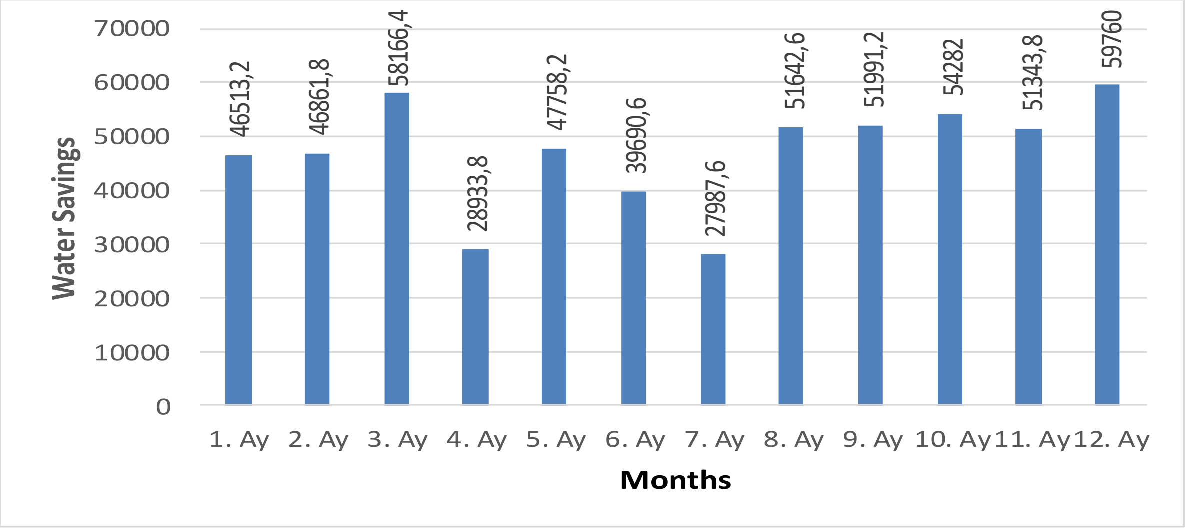


Figure 2 Water Savings from EDMS Use at Batman University in 2023

---

[1] It was calculated using the formula found in the Batman University Electronic Document Management System Environment Module.

According to the graph data, varying amounts of water savings were achieved throughout the year, with the highest savings (59,760 liters) occurring in December. By not using paper in 2023, Batman University saved 572 tons of water.

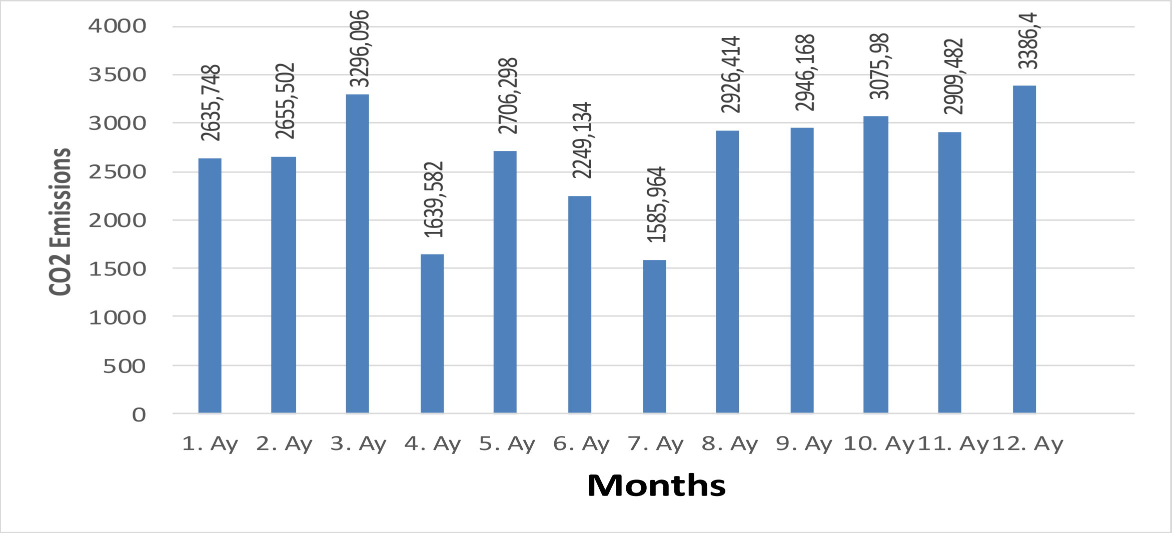


Figure 3 Reduction in CO2 Emissions Due to EDMS Use at Batman University in 2023

This figure clearly illustrates the impact of the Electronic Document Management System (EDMS) on reducing carbon emissions. A regular decrease in carbon emissions throughout the year was observed with the use of EDMS, contributing significantly to environmental sustainability. Notably, in March and December, the system's impact peaked with a reduction of approximately 3,500 kg. EDMS use resulted in a decrease of 32.4 tons of carbon emissions in 2023.

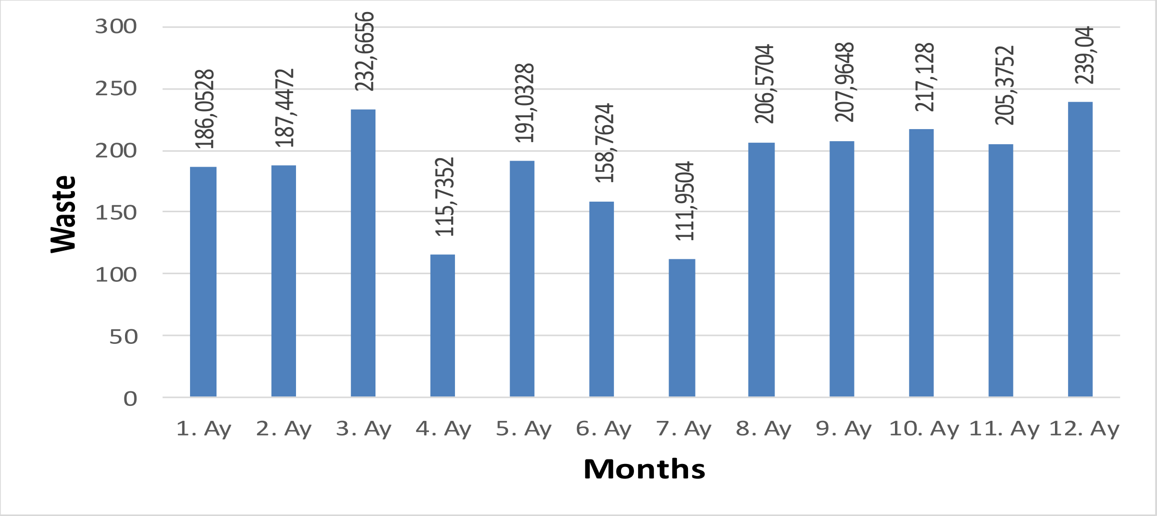


Figure 4 Waste Prevention Due to EDMS Use at Batman University in 2023

The environmental benefits of EDMS are highlighted through the amount of waste prevented. Monthly data show that waste prevention ranged from 150 to 250 kg. Especially in March and December, the amount of waste prevented peaked, and a total of 2.3 tons of waste was prevented in 2023. This contribution not only reduces institutional waste management costs but also minimizes environmental impacts. This reduction in waste production is a significant step in protecting natural resources and easing the burden on waste storage areas.

3. Conclusion

The example of Batman University highlights the contributions of Electronic Document Management Systems (EDMS) to environmental sustainability. The study reveals that EDMS reduced paper usage, preventing the cutting of 113 trees in 2023, saving 572 tons of water, and reducing CO2 emissions by 32.4 tons. Additionally, 2.3 tons of waste were prevented. It was determined that the system offers significant benefits not only in terms of environmental impact but also in energy and cost savings. The research demonstrates that EDMS is a vital tool for achieving sustainability goals and can guide other institutions. The findings confirm that digitalization plays a critical role in both environmental and economic terms.

References

[1] S. Solhan, "Fizikselden Elektroniğe; Belge Yönetim ve ArÇivleme Sürecinin Sürdürülebilirliği," KURUMSAL BELLEKLERİN GELECEĞİ, p. 49, 2016.

[2] B. Yalçınkaya, "Elektronik belge yönetim sistemi EBYS uygulamalarında başarı faktörü ve fayda analizi," AJIT-e: Academic Journal of Information Technology, vol. 7, no. 23, pp. 67-96, 2016.

[3] F. ÖZDEMGRCG, "Bütünleşik e-kurum sistemleri ve kurumsal yapılanmalara yansıması: Ankara Üniversitesi e-BEYAS uygulaması ve kurumsal yapılanma," KURUMSAL BELLEKLERİN GELECEĞİ, p. 35, 2016.

[4] M. O. Cibaroğlu and A. H. Turan, "Elektronik belge yönetim sistemlerinin genişletilmiş teknoloji kabul modeli temelinde kullanımı: Ampirik bir değerlendirme," Adnan Menderes Üniversitesi Sosyal Bilimler Enstitüsü Dergisi, vol. 5, no. 2, pp. 204-217, 2018.

[5] https://bilimgenc.tubitak.gov.tr/bunu-biliyor-muydunuz/kagit-geri-donusumu-ile-su-tasarrufu, 2019

[6] https://donusumdernegi.org/kagit-uretimi-ve-geri-donusum/, 2015

Global Energy

1;2 (2024) 16-22

Green Hydrogen and its Potential in Turkey

[a]Can Ekim, [b]Ahmet Gündoğdu

[a,b]Batman University, Faculty of Enginering , Department of Electrical and Electronics Engineering, 72000, BATMAN/TURKEY

[a] can.ekim@batman.edu.tr, ahmet.gundoğdu@batman.edu.tr

ARTICLE INFO

Article history:
Received 30 November 2024
Revised 11 December 2024
Accepted 13 December 2024
Available online 18 December 2024
Presented in International Energy Summit 2024

Key words:
Green Hydrogen
Renewable Energy
Carbon Footprint

* Corresponding author.
E-mail address:
can.ekim@batman.edu.tr

ABSTRACT

Green hydrogen is a clean and sustainable energy carrier that plays a critical role in the global energy transition and achieving decarbonization goals. This article addresses multifaceted topics such as the cost analysis of green hydrogen production and its potential in Turkey. Produced through the electrolysis of water using renewable energy sources green hydrogen unlike grey blue and brown hydrogen derived from fossil fuels does not involve carbon emissions. This characteristic makes green hydrogen a crucial tool in combating climate change. Factors affecting the production cost of green hydrogen include electricity costs electrolyzer technology and capacity factor. The decreasing costs of renewable energy and technological advancements are increasing the competitiveness of green hydrogen and supporting its widespread adoption. Turkey with its rich renewable energy potential and strategic location has a significant advantage in green hydrogen production. The National Hydrogen Strategy and private sector investments demonstrate Turkey's determination to progress in this field. Green hydrogen can be applied in various sectors such as energy transportation industry and buildings and can provide numerous benefits such as increasing energy independence economic development and sustainability. In conclusion green hydrogen will play a crucial role in the energy systems of the future and Turkey can achieve significant gains by taking an active role in this transformation.

1. Introductıon

Today, the need for energy is increasing. Due to the decreasing lifespan of fossil fuels and their effects on the environment, the use of renewable energy sources has become widespread. One of these energy sources is hydrogen energy. Hydrogen energy is environmentally friendly and has high energy density. Hydrogen is named according to different production methods. These are gray hydrogen, blue hydrogen and green hydrogen. Gray hydrogen is produced from fossil fuels. Blue hydrogen is produced with carbon capture technologies. Green hydrogen stands out from other hydrogens as a zero-carbon emission and clean energy carrier. Green hydrogen produced using renewable energy sources has the potential to create innovation in our energy system and offers an important opportunity for countries such as Turkey that are dependent on energy imports. Turkey is located in a very suitable geography for green hydrogen production with its solar and wind energy potential. Our country aims to increase both energy security and contribute to environmental sustainability by investing in green hydrogen technologies in line with its energy transformation goals. In this article, the importance of green hydrogen, current policies, projects and future goals in Turkey will be examined in detail.

2. Green Hydrogen

Green hydrogen is the hydrogen that results from the electrolysis of water using renewable energy in the process of which an electric current separates water molecules into hydrogen and oxygen rather than the more traditional methods of producing hydrogen. Unlike conventional techniques for producing hydrogen, the method of green hydrogen production does not entail any release of carbon dioxide to the air hence no other greenhouse gases. This makes green hydrogen an energy carrier with low carbon content and friendly to the environment[1].

2.1. Advantages of Green Hydrogen

Green hydrogen is in the spotlight as a clean and sustainable fuel, which can have a much more important impact in changing the global energy game. This renewable source of energy holds the potential for driving faster abandonment of fossil fuel reliance and reversing the impacts of global warming. This new green hydrogen does not do anything at all to contribute to global warming due to no greenhouse gas being emitted during production. Current mainstream green hydrogen production, gray hydrogen, comes from natural gas, with a high foul release of carbon dioxides dumped into the air from the process. Blue hydrogen is made in much the same way as gray from natural gas, but carbon capture and storage technology are applied to cut carbon emissions. Despite this improvement, blue hydrogen remains reliant on fossil fuels, and the carbon capture process is costly and energy intensive. Brown hydrogen, specifically, has the undesirable distinction of being the dirtiest fuel, as it carries with it the highest carbon footprint and it’s derived from coal – hence, brown, gray, blue hydrogen all contribute to greenhouse gas emissions which drive climate change[2]. The types of hydrogen are compared in Table 1.

Table 1. Comparison of Hydrogen Types

Feature	Green Hydrogen	Gray Hydrogen	Blue Hydrogen	Brown Hydrogen
Carbon Emission	None	High	Low (with CCS)	Very High
Sustainability	High	Low	Medium	Low
Environmental Impact	Minimal	High	Medium	Very High
Energy Source	Renewable Energy	Natural Gas	Natural Gas	Coal
Cost	High	Low	Medium	Low

Generation of green hydrogen entails no emission of greenhouse gases at the production source. This is achieved through electrolysis of water into hydrogen and oxygen using electricity obtained from renewable sources like solar, wind, and hydro. It’s made in a very sustainable way without any harmful gases being emitted into the atmosphere in this way. The other importance of green hydrogen is in energy storage. Often, because alternative sources produce energy intermittently, the energy produced may not meet the demanded energy. Hence, green hydrogen is a marvellous solution to accumulate the extra energy and use it when required. Thus, security in the supply of energy could be done while raising the efficiency of alternative sources of energy[3][4].

2.2.Production of Green Hydrogen

The base of green hydrogen production is, in fact, the process of electrolyzing water to separate hydrogen and oxygen from the water using electricity, renewable electricity again achieved using solar, wind, and hydropower. It is therefore renewable electricity that will have carried out the electrolysis as mentioned in Figure 1.

- Renewable energy production: The very first step in this process is energy production through a renewable source, which can be solar panels, winds mills/turbines or power house working on hydro power[5].
- Electrolysis: Electricity is led to a set of electrolyzers, where water molecules are split into hydrogen and oxygen using electrical current[6].
- Hydrogen Collection and Storage: Collected hydrogen gas is stored after separation by different methods.
- Distribution: The stored hydrogen is distributed by pipelines or tankers to the required places.

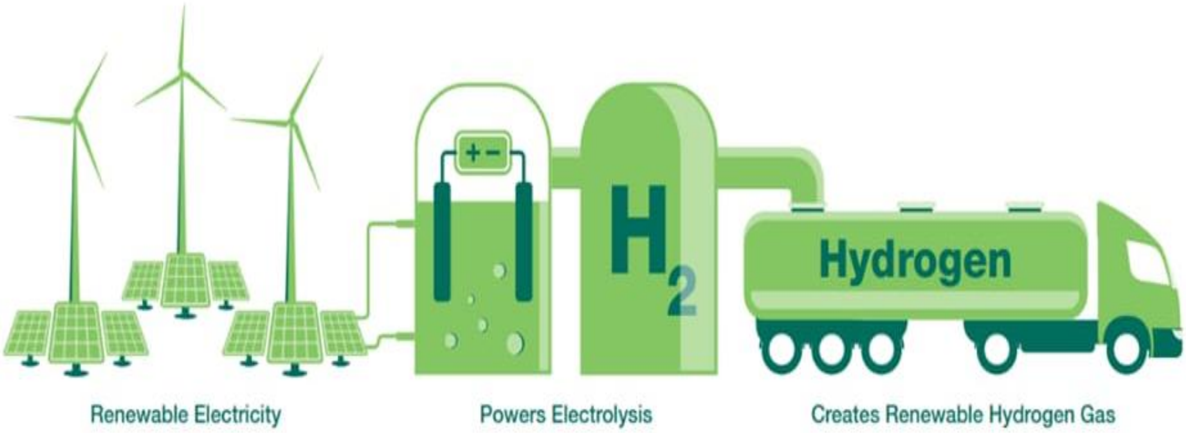


Figure 1. Production of Green Hydrogen

The green hydrogen production cost here comes up impacted by several factors like the cost of electricity, efficiency of the electrolyzer, and also the capacity factor. Renewable sources, particularly those like solar and wind energies, underwent sharp cost declines over the past years and are forecasted for continuation in forthcoming years. Another factor for costs is associated with the technology of the electrolyzer that is used. By using efficient and durable electrolyzers, one can reduce costs. The capacity factor of renewable energy sources decreases the costs of these, while operating maintenance, as well as the costs of storage and distribution all add up to the total costs. This will then optimize all such factors, which will then eventually make green hydrogen become more economically and more commonly used. Such an act would then enhance the competitiveness of green hydrogen and would speed up such a transition into a much more sustainable energy system[7][8].

3. Green Hydrogen in Turkey

It is with this situation that Turkish green hydrogen may become a more substantive matter with the favorable geographical position and the renewable energy potential of the country. Further investments in solar and wind energy will both enhance the prospect of competitiveness through lowering the costs associated with manufacturing green hydrogen and increase Turkey’s capacity to extract hydrogen profitably. In this sense, the strategies and policies of Turkey with regard to the production and utilization of green hydrogen will be vital for energy transition as a country and attaining goals on decarbonization[9][10].

3.1.Green Hydrogen Potential and Benefits in Turkey

Green hydrogen potential in Turkey is quite high, due to several aspects:

- High Renewable Energy Resource Potential: Turkey stands as quite a sunny and windy place on the geographic map. The International Energy Agency (IEA) mentioned that Turkey's technically available solar energy reaches 380 GW. On the other hand, its available wind energy hits 48 GW. Taking advantage of this would lead to the minimization of the costs related to producing green hydrogen and boost its sustainable nature.
- Strategic Geographical Location: Acting as a bridge between Europe and Asia, Turkey holds appreciable merit when it comes to the export of green hydrogen. This country is poised with the potential to meet the growing demand for green hydrogen in Europe. Further, strong trade relations with Middle Eastern and North African countries might help the country export green hydrogen to these places[11].
- Suitable Infrastructure for the Production and Application of Green Hydrogen Technologies: Advanced industrial infrastructure in Turkey offers a ground most suitable for the production and application of green hydrogen technologies. Especially, in the automotive, chemicals, iron and steel,

cement and refinery sectors, etc., there would be big potentials to be the leading sectors not only demanding green hydrogen but also developing and applying green hydrogen technologies[12].

- Green hydrogen is a field where Turkey is drawing attention with increasing investments and political support. It is the national strategy and action plan, the YEKA tenders, R&D incentives, and international collaborations that support the development of the green hydrogen ecosystem.

Figure 2. Places with High Hydrogen Potential in Turkey[11]

Turkey meets a major portion of its energy needs through imported ‘fossil fuels and this poses risks in terms of energy security as well as the current account deficit. The special thing about green hydrogen is that it is produced from renewable resources and therefore, helps a country improve its energy dependency as well as avoid valuable foreign exchange going for energy imports. Furthermore, the application of green hydrogen will contribute significantly to the mitigation of and adaptation to climate change. The road to the Turkish target for 2053 net zero emissions and its nationally determined contribution under the Paris Agreement runs critically through the adoption of green hydrogen.

3.2.Green Hydrogen Developments in Turkey

Green hydrogen is one of the subjects in which Turkey has made huge steps in recent years, establishing ambitious targets in this area. Rounds of developments in the field receive endorsement with public sector policies and incentives, as well as growing private investments.

- National Hydrogen Strategy and Roadmap: This strategy document from Ministry of Energy and Natural Resources will be published in January 2023 and outlines Turkey’s vision and targets for green hydrogen. The strategy intends to achieve an electrolyzer capacity of 2 GW by 2030, 5 GW by 2035, and 70GW by 2053 and intends to make Turkey a key player in the worldwide green hydrogen economy[13].
- Ace for aligning with the Green Deal: The Action Plan is prepared to align with the overall Green Deal framework of the European Union, thereby underpinning the critical operation of the green hydrogen in meeting the decarbonization targets. The policy sets forth various measures and support systems to promote the production and use of green hydrogen. The YEKA tenders will be commonly perceived to cut the cost of renewable electricity required in green hydrogen production through investment stimulation in solar and wind energy resources. These tenders represent an encouragement to indigenous manufacturing and technology development. Hydrogen Valley is established in Balikesir, and the Hydrogen Valley Project represents an attempt to render Turkey a

significant center with respect to green hydrogen production (Figure 3)[14]. As for the project's goals, a minimum of 500 tons of green hydrogen is planned to be produced per year within the ambit thereof, whereas said green hydrogen shall find applications within the industry, transportation as well as energy sectors. Private sector investments and public-private cooperation shall be how this project comes to be executed.

- Pilot Green Hydrogen Production Facilities: To the Bandırma district of Balıkesir in Turkey, a pilot green hydrogen facility will be established by Enerjisa, making them the pioneer in such an endeavor in the country. This marks a crucial step towards testing as well as technology optimization for green hydrogen production. Eti Mine Enterprises; and TC Ministry of Industry and Technology jointly developed a Domestic Production Type Pem Electrolyzer and Enerjisa Üretim aims to place it in Bandırma Energy Base[14].
- Tüpraş: Tüpraş will produce green hydrogen with its refineries it will establish and is targeting the front rank in non-carbon electricity production[15].
- Sectoral Collaborations and Investments: Joint ventures between companies in automotive, chemistry, iron and steel, energy sectors are being contemplated for the purpose of evaluating the potential and investments on green hydrogen. These collaborations are intended to diffuse green hydrogen to other sectors and fast track technological advancements.

Figure 3. Enerjisa Hydrogen Valley[14]

4. Conclusions

The micro-fossil world deposits accumulated over millions of years by the activity of bacteria Laser trimming modifies their structure and nature to liberate small quantities of versatile hydrogen filled with sustainability features. The sustainability of using green hydrogen, which does not emit harmful or greenhouse gases under the production process, and while being consumed, will be a great leap towards renewable energy and a carbon-free economy. At present, the total production cost of green hydrogen is higher than fossil fuel-based hydrogen. But as renewable electricity costs come down while technology progress and economies of scale in electrolyzers develop further, these tendencies will turn it into a more affordable form of energy in the future. The geographical and industrial properties could combine to make Turkey a big player in green hydrogen. Turkey's plentiful renewable energy sources, strategic location, and well-developed industrial base give the country a potential high standing in the coming green hydrogen scenario. Sectoral policies implemented together with private sector investments and various R&D activities may facilitate the actualization of this possibility. Unlike some other alternatives of renewable energy, green hydrogen may not merely remain confined to specific applications or sectors, but extend to a wide range of applicabilities, such as the transportation system and building complexes wherein they would enable several strategic advantages to be accrued, including enhanced energy independence, the ushering in of new economic prospects, reduction in GHG emissions, and forestalling technological stagnancy; thus, the future must be green. There is indeed a need for nations like Turkey to take on a catalytic role in this energy revolution through the realization of the greening potential of hydrogen. Creating hydrogen R&D investment conditions promoting national technology development encouraging pilot projects in green hydrogen technologies, and all other related investments guarantee the development and broad application of green hydrogen technologies. Effective feeding of this new energy into the system with new “fuel lines” to “tap” it must be developed. International collaboration information sharing, and technology transfer will have to play a crucial role in it. The last one is qualified workforce training and social awareness-raising activities that will give support to society in adopting green hydrogen and development of the sector.

References

[1] G. Squadrito, G. Maggio, and A. Nicita, “The green hydrogen revolution,” *Renew Energy*, vol. 216, p. 119041, Nov. 2023, doi: 10.1016/j.renene.2023.119041.

[2] G. Bilgiç Tüzmen, “Türkiye Hidrojen Enerjisi Stratejilerinin ve Geliştirilen Politikaların Araştırılması,” *Duzce University Journal of Technical Sciences*, vol. 2, no. 1, pp. 70–79, 2024, [Online]. Available: https://dergipark.org.tr/tr/pub/duted

[3] S. Ö. Aydin, “TÜRKİYE’NİN ENERJİ ARZ GÜVENLİĞİNDE YEŞİL HİDROJEN POTANSİYELİ,” Master Thesis, Institute of Social Sciences, İstanbul, 2023.

[4] A. M. Oliveira, R. R. Beswick, and Y. Yan, “A green hydrogen economy for a renewable energy society,” *Curr Opin Chem Eng*, vol. 33, p. 100701, Sep. 2021, doi: 10.1016/j.coche.2021.100701.

[5] A. Alzoubi, “Renewable Green hydrogen energy impact on sustainability performance,” *International Journal of Computations, Information and Manufacturing (IJCIM)*, vol. 1, no. 1, Dec. 2021, doi: 10.54489/ijcim.v1i1.46.

[6] S. G. Nnabuife, A. K. Hamzat, J. Whidborne, B. Kuang, and K. W. Jenkins, “Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production,” *Int J Hydrogen Energy*, Jul. 2024, doi: 10.1016/j.ijhydene.2024.06.342.

[7] N. Ma, W. Zhao, W. Wang, X. Li, and H. Zhou, “Large scale of green hydrogen storage: Opportunities and challenges,” Jan. 02, 2024, *Elsevier Ltd*. doi: 10.1016/j.ijhydene.2023.09.021.

[8] Q. Hassan, S. Algburi, A. Z. Sameen, H. M. Salman, and M. Jaszczur, “Green hydrogen: A pathway to a sustainable energy future,” *Int J Hydrogen Energy*, vol. 50, pp. 310–333, Jan. 2024, doi: 10.1016/j.ijhydene.2023.08.321.

[9] G. K. Karayel, N. Javani, and I. Dincer, “Green hydrogen production potential for Turkey with solar energy,” *Int J Hydrogen Energy*, vol. 47, no. 45, pp. 19354–19364, May 2022, doi: 10.1016/j.ijhydene.2021.10.240.

[10] A. E. Yıldırım, E. B. Kaplan, and A. Khanayev, “HİDROJEN TEMELLİ ENERJİ VE TÜRKİYE HYDROGEN-BASED ENERGY AND TURKEY,” *INTERNATIONAL JOURNAL OF AFRO-EURASIAN RESEARCH (IJAR)*, vol. 8, no. 15, pp. 29–47, 2023.

[11] E. Çolak and H. Aksoy, “Türkiye’nin yeşil hidrojen üretim ve ihracat potansiyelinin teknik ve ekonomik açıdan değerlendirilmesi Enerji Politikaları Araştırma Merkezi,” İstanbul, 2021. [Online]. Available: www.shura.org.tr

[12] Gizem ERSOY, “GELECEĞİN ENERJİ KAYNAĞI: YEŞİL HİDROJEN EKONOMİSİ ,” in *V. ULUSLARARASI KAHRAMANMARAŞ YÖNETİM, EKONOMİ VE SİYASET KONGRESİ*, Bursa, 2022, pp. 84–98.

[13] T.C. Enerji ve Tabii Kaynaklar Bakanlığı, “Türkiye Hidrojen Teknolojileri Stratejisi ve Yol Haritası,” Ankara, 2023.

[14] “Türkiye’nin İlk Hidrojen Vadisi Enerjisa Üretim Bünyesinde Kuruluyor,” https://www.enerjisauretim.com.tr/blog/.

[15] “Stratejik Dönüşüm,” https://www.tupras.com.tr/tr/.

Global Energy

1;2 (2024) 23-28

Prediction of Crude Oil Production Using Random Artificial Neural Networks

[a] Ömer Faruk ERTUĞRUL, [b] Ülkü KARDAŞ

[a] Batman University/Faculty of Engineering and Architecture/Department of Electrical and Electronics Engineering Batman, Turkey

[a] omerfaruk.ertugrul@batman.edu.tr

[b] mertzeynepkardas@gmail.com

ARTICLE INFO

Article history:
Received 30 November 2024
Revised 11 December 2024
Accepted 13 December 2024
Available online 18 December 2024
Presented in International Energy Summit 2024

Key words:
Oil Production
Artificial Neural Networks
Prediction Models
RNN
ELM
RVFL

* Corresponding author.
E-mail address:
mertzeynepkardas@gmail.com

ABSTRACT

Oil is one of the cornerstones of the global energy sector, and oil production holds vital importance for countries in terms of economic development and energy security. Accurately predicting production levels in oilfield wells plays a critical role in enhancing operational efficiency and optimizing costs. However, traditional forecasting methods fail to adequately address the complexities of production processes and environmental variations. Today, artificial intelligence techniques, such as Artificial Neural Networks (ANNs), have the potential to provide higher accuracy and efficiency in oil production forecasting.

This study aims to compare the predictive performance of models like RNN, ELM, and RVFL by utilizing real production data from the Çakıllı Field in the Batman Region and to contribute to AI-based applications in the energy sector. Furthermore, another significant aspect of this study is its emphasis on how accurate predictions not only yield economic benefits but also pave the way for developing strategies that support environmental sustainability. In this context, the potential of AI-based models in the energy sector is evaluated.

If you have further requests or would like me to continue building the paper, let me know!

1. Introduction

Oil, as one of the most essential resources in the global energy system, lies at the foundation of economic development, energy security, and industrial processes. Oil production has served as the driving force behind growth and infrastructure development, particularly in emerging economies. Effectively managing and accurately forecasting oil production processes has a direct impact not only on operational efficiency but also on the global energy supply-demand balance.

History of Oil Production Processes

Research on oil production forecasts dates back to the early 20th century, coinciding with the rapid growth of the energy sector. Early forecasting methods relied on simple mathematical models and linear extrapolation of historical data. These methods, limited by the technological capabilities of the time, utilized basic statistical tools and were insufficient for thoroughly analyzing production data from the fields.

The 1970s and 1980s marked a period when the widespread adoption of computers in the energy sector enabled the use of more sophisticated forecasting models. During these years, time series analyses, regression models, and nonlinear statistical methods came to the forefront. Simulation models, aimed at improving field productivity, allowed for a broader analysis of oil production. However, these methods struggled to account for complex environmental variables and uncertainties.

Weaknesses of Traditional Methods

Although traditional forecasting methods offer certain advantages in understanding and predicting oil production processes, they fall short of meeting the requirements of today's complex production and environmental systems. The main weaknesses of these methods can be summarized as follows:

1. **Linear Assumptions:** Most traditional statistical models assume linear relationships between variables. However, oil production processes often involve complex and nonlinear dynamics.
2. **Limited Data Usage:** Most models consider only historical production data and a few environmental variables. Ignoring geological, environmental, and operational factors reduces the accuracy of predictions.
3. **Dynamic and Uncertain Conditions:** In oil production, the conditions of fields, well characteristics, and environmental effects change over time. Traditional methods are limited in adapting to such dynamic conditions.
4. **Incompatibility with Large Datasets:** Modern oil fields generate massive amounts of data through sensors and digital monitoring tools. Traditional methods are inadequate for processing and analyzing these large datasets.

Modern Approaches and Artificial Neural Networks

In recent years, the use of artificial intelligence (AI) and machine learning (ML) techniques in oil production forecasting has gained significant attention. Artificial Neural Networks (ANNs) have revolutionized this field with their ability to learn patterns in complex data structures and model nonlinear relationships. Modern neural network models such as RNN, ELM, and RVFL have demonstrated high performance on dynamic datasets. These models provide effective solutions by analyzing historical production data to forecast future production volumes. Additionally, the adaptive and scalable nature of artificial neural networks makes them capable of handling large datasets.

This study evaluates the advantages of artificial neural networks in oil production forecasting and their superiority over traditional methods. The objective is to test the performance of RNN, ELM, and RVFL models on production data from the Çakıllı Field and derive concrete results applicable to the energy sector.

2. Conceptual Framework

Predicting oil production holds strategic importance for the energy sector, and various methods have been developed over time to advance this process. The conceptual framework aims to explain the theoretical foundation of this study, the models used, and the principles on which these models are based. Forecasting models used in oil production processes have historically evolved from simple mathematical methods to modern artificial intelligence-based algorithms.

2.1. Traditional Forecasting Models

Traditional forecasting methods are generally based on linear statistical models and linear extrapolation of historical data. These models aim to predict energy production volumes over a specific period under fixed assumptions. However, the linear assumptions and limited data utilization capacities of such models fail to fully reflect the dynamic and nonlinear nature of modern production processes. Moreover, complex factors such as environmental variables and site-specific characteristics cannot be effectively modeled using these approaches.

2.2. Artificial Intelligence and Machine Learning Approaches

Artificial intelligence and machine learning techniques offer significant advantages over traditional methods due to their ability to learn nonlinear relationships and make predictions from large datasets. Specifically, artificial neural networks (ANNs) emerge as a powerful tool for modeling complex interactions in production processes. ANN models can work with data-intensive oil fields, leveraging data collected from sensors and digital monitoring systems, and adapt to continuously changing environmental conditions.

2.3. Models Used: RNN, ELM, and RVFL

The models used in this study include recurrent neural networks (RNN), which are notable for their ability to analyze time-dependent relationships in dynamic datasets. Extreme learning machines (ELM) and random vector functional links (RVFL) stand out as effective methods for oil production forecasting due to their rapid training processes and capabilities to handle nonlinear and complex data. These models not only analyze historical production data but also consider operational and environmental variables to provide highly accurate forecasts.

This conceptual framework serves as a fundamental guide for understanding how oil production processes can be more effectively analyzed using modern methods. The focus of this study is to overcome the limitations of traditional methods and highlight the potential contributions of artificial neural networks to the energy sector.

2. Objective of The Study

The primary objective of this study is to leverage the advantages of artificial neural networks (ANNs), which have become widely used with technological advancements, to predict oil production processes and to demonstrate the superiority and success of ANNs compared to traditional methods currently in use. Specifically, the study focuses on evaluating and comparing the performance of models such as Recurrent Neural Networks (RNN), Extreme Learning Machines (ELM), and Random Vector Functional Links (RVFL) using production data from the Çakıllı Field, particularly in analyzing nonlinear and dynamic datasets.

Another aim of this research is to highlight the potential of AI-based forecasting models, either already in use or under consideration in the energy sector, through concrete examples. In this context, analyzing environmental and geological factors affecting oil production processes will shed light on the development of new methods that enhance prediction accuracy. This will contribute to more efficient resource management in the energy sector and enable the development of more reliable forecasting models for the global energy supply-demand balance.

This study not only aims to improve prediction accuracy but also seeks to provide a scientific foundation for the applicability of AI methods in the energy sector. The findings are expected to contribute to innovative approaches in oil production forecasting and drive advancements in the field.

4. Method

In this study, an experimental method was employed to evaluate the performance of artificial neural network (ANN) models used in oil production forecasting. The study involved analyzing historical production data from the Çakıllı Field in the Batman Region and applying RNN (Recurrent Neural Networks), ELM (Extreme Learning Machines), and RVFL (Random Vector Functional Links) models to this data. The methodological framework of the study consists of the following steps:

4.1. Data Collection and Preprocessing

The data used in this study includes historical production information, environmental variables, and operational parameters obtained from the Çakıllı Field. A detailed preprocessing process was conducted to clean the data of any missing or erroneous values and make it suitable for analysis. First, incomplete or inaccurate data from the Çakıllı Field was cleaned. Then, the data was normalized to make it suitable for artificial neural networks.

4.2. Model Selection and Configuration

The study focused on RNN, ELM, and RVFL algorithms, which have strong capabilities for modeling nonlinear data relationships. During the configuration of these models, hyperparameter optimization was performed, and the optimal parameters for each model were determined. The data was split into training and testing sets in an 80% training and 20% testing ratio.

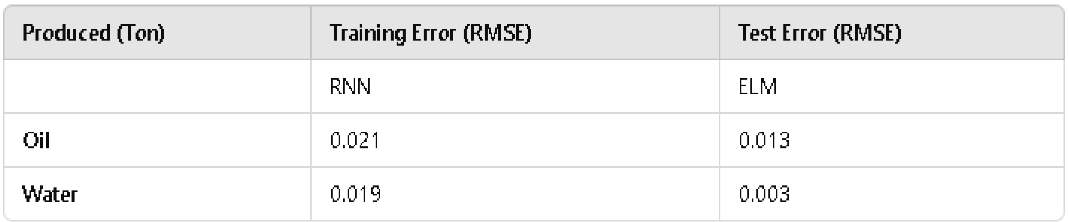
4.3. Model Training and Testing

The models were trained using the training dataset, and their prediction accuracy was evaluated on the test dataset. Statistical metrics such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2) were used as performance measures. Prediction results on both training and test datasets were compared to assess the effectiveness of each model in forecasting oil production. These methods ensured the processing of appropriate data for accurate predictions, demonstrating the effectiveness of ANNs in the field.

4.4. Evaluation and Comparison of Results

The results were evaluated by comparing them with traditional forecasting methods. Monthly production data from the Çakıllı Field was used to predict the amounts of produced oil and water. The number of wells and the average API gravity of the produced oil were used to estimate the amounts of oil and water. Using RNN, ELM, and RVFL models with five-fold cross-validation, the training and test RMSE errors for each model are presented in Table 1. The results indicate that random artificial neural networks can be effectively applied to oil production forecasting.

Table 1. Training and Test Error Rates (RMSE)



Produced (Ton)	Training Error (RMSE)	Test Error (RMSE)
	RNN	ELM
Oil	0.021	0.013
Water	0.019	0.003

This methodological approach provides a robust foundation for evaluating the effectiveness and applicability of artificial neural networks in oil production forecasting. Additionally, it serves as a guide for similar studies on large datasets and dynamic systems in the energy sector.

5. Findings

In this study, an analysis was conducted to predict oil and water production using monthly production data from the Çakıllı Field. Variables such as the number of wells and the average API gravity of the produced oil were considered, and predictions were made using Random Neural Networks (RNN), Extreme Learning Machines (ELM), and Random Vector Functional Links (RVFL). The performance of the models was evaluated using a 5-fold cross-validation method, and the training and test error rates are presented in Table 1.

Training and Test Error Rates

- **Oil Prediction:** In oil production, the RNN model exhibited a training error of 0.021 RMSE and a test error of 0.358 RMSE, while the ELM model showed the best performance with a training error of 0.013 RMSE and a test error of 0.088 RMSE. The RVFL model, on the other hand, showed moderate performance compared to other models, with a training error of 0.084 RMSE and a test error of 0.048 RMSE.
- **Water Prediction:** In water production, the ELM model achieved the lowest training error of 0.003 RMSE. For test errors, the RVFL model exhibited the lowest value at 0.040 RMSE. The RNN and ELM models had test errors of 0.077 RMSE and 0.075 RMSE, respectively.

Evaluation

- **RNN:** While the RNN model demonstrated the ability to model time-dependent relationships in dynamic datasets, it showed higher error rates during the testing phase compared to other models. This indicates the need for further parameter optimization, especially for large datasets.
- **ELM:** The ELM model stood out with its fast training process and low training errors. It delivered generally successful results in both training and testing phases for oil and water predictions.
- **RVFL:** The RVFL model showed effective results in terms of prediction accuracy with low error rates during the testing phase. Although it lagged behind other models in training errors, a significant improvement in test performance was observed.

General Findings

The results indicate that artificial neural networks (ANNs) are effective tools for predicting oil and water production. In particular, the ELM and RVFL models demonstrated higher accuracy and better adaptability to dynamic conditions compared to traditional methods. While RNN models show potential for understanding complex data relationships, it was noted that more comprehensive optimization processes are needed to improve their performance.

These findings suggest that artificial neural networks could have a wide range of applications in the energy sector and provide more precise and reliable predictions for oil production processes. Furthermore, the study’s results highlight that AI methods for processing large datasets will guide future research and enhance operational efficiency in the industry.

6. Conclusion and Recommendations

This study evaluated the potential of artificial neural networks (ANNs) for predicting oil and water production and compared the performance of RNN, ELM, and RVFL models using production data from the Çakıllı Field. The findings demonstrated that ANNs offer significant advantages in overcoming the limitations of traditional forecasting methods.

The conclusions are summarized as follows:

1. **Superiority of ELM and RVFL Models:** ELM and RVFL models provided more accurate predictions in oil and water production with lower RMSE values. ELM, in particular, stood out due to its rapid adaptation during the training process and low error rates.
2. **Potential of RNN in Dynamic Data:** While RNN models have the capacity to model time-dependent relationships, they require hyperparameter optimization to improve their performance.
3. **Advantage Over Traditional Methods:** ANN models demonstrated higher accuracy than traditional methods by effectively modeling nonlinear relationships and dynamic environmental variables.

Recommendations

Based on the results of this study, the following recommendations are proposed:

1. **Use of Larger Datasets:** To evaluate the performance of ANNs more comprehensively, studies should be conducted with larger and more diverse datasets from different oil fields.
2. **Inclusion of Environmental Factors:** Incorporating environmental variables and geological characteristics into the models can enhance prediction accuracy. Special attention should be given to variables such as seasonal effects and operational conditions.
3. **Integration of Models:** Hybrid approaches combining different ANN models could yield more robust prediction results. For instance, integrating the low test error of RVFL with the fast training capacity of ELM could be considered.
4. **Application in the Energy Sector:** The findings can be translated into practical applications to support decision-making processes in the energy sector. Pilot projects should be developed to implement ANN-based forecasting systems in field management and resource planning.

Future Work

While this study highlights the applicability of ANNs in oil production forecasting, it also serves as a significant starting point for future research. The effectiveness of these methods can be expanded by focusing on more complex datasets and different fields. Furthermore, advancements in artificial intelligence technologies, such as deep learning and reinforcement learning, can be integrated into this area.

These results strengthen the contribution of ANNs to the energy sector for oil production forecasting and provide a valuable roadmap for more efficient resource utilization in operational processes.

References

[1] Akdöl, R.Ş. (2018). "Yapay Sinir Ağları Yöntemi ile Petrol Fiyatları Tahmini." KLU İktisadi ve İdari Bilimler Fakültesi Dergisi, 7(2), 1-15

[2] Çam, S., Ballı, E., & Sigeze, Ç. (2017). "Petrol Fiyatlarındaki Oynaklığın ARCH/GARCH Modelleri ve Yapay Sinir Ağları Algoritması ile Tahmini." Uluslararası Yönetim İktisat ve İşletme Dergisi, ICMEB17 Özel Sayısı, 588-597.

[3] Gümrah, F. (2002). "Azalan Üretim Eğrileri, Yapay Sinir Ağları ve Birleştirilmiş Oto Regresif Hareketli Ortalamalar Yöntemi ile Petrol Kuyusu Üretim Azalım Verilerinin Analizi." Yüksek Lisans Tezi, Orta Doğu Teknik Üniversitesi.

[4] Kavas, H.G. (2019). "Dünya Enerji Görünümü ve Yapay Sinir Ağları ile Türkiye Talebinin Gelecek Tahmini (Feed Forward/Bi-LSTM)."

[5] Oran, Y. (2019). "Derin Öğrenmenin Temel Yapı Taşları: ANN, RNN ve CNN'in Çalışma Prensipleri ve Uygulamaları." Medium.

[6]https://www.ultralytics.com/tr/blog/ai-in-oil-and-gas-refining-innovation#:~:text=Petrol%20ve%20gaz%20end%C3%BCstrisini%20olu%C5%9Fturmak,7%20milyar%20dolara%20ula%C5%9Fmas%C4%B1%20bekleniyor.

[7] https://botekotomasyon.com/yapay-zekanin-petrol-ve-gaz-endustrisindeki-artan-rolu/

[8] https://www.endustri40.com/petrol-ve-gaz-endustrisinde-yapay-zeka-ve-robotik/

Global Energy
1;2 (2024) 29-36

The Importance of Rare Earth Elements (REEs) for Energy Transition

[a,b] Nilufer Kursunoglu, [c]Sait Kursunoglu

[a] Faculty of Engineering and Architecture, Department of Petroleum and Natural Gas Engineering, 72400, BATMAN/TURKEY

[c] Faculty of Engineering and Architecture, Department of Petroleum and Natural Gas Engineering, 72400, BATMAN/TURKEY

[b] nilufer.kursunoglu@batman.edu.tr, https://orcid.org/0000-0003-1765-9015

ARTICLE INFO

Article history:
Received 30 November 2024
Revised 11 December 2024
Accepted 13 December 2024
Available online 18 December 2024
Presented in International Energy Summit 2024

Key words:
Rare Earth Elements
Clean Energy Technologies
Energy Transition

* Corresponding author.
E-mail address:
nilufer.kursunoglu@batman.edu.tr

ABSTRACT

Rare Earth Elements (REEs) have emerged as essential materials in the global shift towards a low-carbon economy, playing a pivotal role in clean energy technologies such as wind turbines, electric vehicles (EVs), and energy-efficient lighting systems. Their unique magnetic, luminescent, and electrochemical properties make them indispensable for the development of permanent magnets, batteries, and other key components of renewable energy infrastructure. This paper explores the importance of REEs in the energy transition, focusing on their application in renewable energy generation, electric transportation, and energy storage systems. Through an analysis of current trends, future projections, and ongoing research efforts, this paper highlights the key role REEs will play in enabling the world to meet its climate goals. It also underscores the importance of global cooperation and innovation in ensuring that REE production aligns with sustainability goals and supports the broader clean energy transition. The findings suggest that while REEs are indispensable for a low-carbon future, addressing the associated environmental, economic, and political challenges is critical for realizing their full potential in the energy transition.

1. Introduction

The global shift towards a low-carbon economy has become one of the most pressing issues of the 21st century, driven by the urgent need to mitigate climate change, reduce greenhouse gas emissions, and transition away from fossil fuels. As the effects of global warming become more apparent, with rising sea levels, extreme weather events, and widespread biodiversity loss, governments, industries, and societies around the world are seeking new pathways to achieve carbon neutrality and build a sustainable future. Central to this energy transition is the adoption of clean energy technologies such as wind, solar, and hydropower, as well as the electrification of transportation through electric vehicles (EVs). However, what is often overlooked in discussions about renewable energy and electric vehicles is the critical role played by Rare Earth Elements (REEs).

REEs, a group of 17 chemically similar elements including neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and lanthanum (La), are integral to the technologies that enable the transition to a low-carbon future. While their name might suggest rarity, REEs are actually relatively abundant in the Earth's crust; however, they are rarely found in economically viable concentrations. What makes REEs truly "rare" is the difficulty in extracting and processing them in an environmentally friendly and cost-effective manner. Despite these challenges, their unique properties make them indispensable for a wide range of high-tech applications, especially in the clean energy sector [1]. The importance of REEs for renewable energy systems and electrification cannot be overstated. They are essential in the manufacture of permanent magnets, which are used in the motors of electric vehicles and in the generators of wind turbines. For instance, neodymium and praseodymium are critical in the production of neodymium-iron-boron (NdFeB) magnets, which are known for their exceptional strength and efficiency. These magnets enable electric motors to operate with greater power density, reducing both size and weight while enhancing performance. Similarly, wind turbines, particularly those with direct-drive systems, rely on NdFeB magnets to improve efficiency, reduce maintenance costs, and generate electricity even at lower wind speeds [2].

In addition to their use in clean energy generation and electric vehicles, REEs play a crucial role in a variety of other technologies that are vital for the energy transition. For instance, REEs are used in energy-efficient lighting technologies, such as LEDs and compact fluorescent lamps (CFLs), which help reduce electricity consumption in homes, businesses, and public spaces. Phosphors made from REEs like europium (Eu) and terbium (Tb) are used to produce the bright, energy-efficient light emitted by these technologies. Moreover, REEs are key components in advanced battery technologies that are essential for energy storage systems. As renewable energy sources such as solar and wind are inherently intermittent—meaning they do not provide continuous power throughout the day—energy storage systems are crucial for ensuring a reliable and stable supply of electricity to the grid. REEs like lanthanum and cerium are used in some nickel-metal hydride (NiMH) and solid oxide fuel cells (SOFCs), helping improve energy density and longevity [3].

The demand for REEs has already begun to skyrocket as industries ramp up production of clean energy technologies. According to the International Energy Agency (IEA), achieving the goals of the Paris Agreement—limiting global warming to well below 2°C—will require a massive increase in the deployment of renewable energy systems, electric vehicles, and energy-efficient technologies, all of which are heavily reliant on REEs [4]. For example, the number of electric vehicles on the road is expected to increase from 11 million in 2020 to as many as 230 million by 2030, while wind energy capacity will need to quadruple in the same timeframe. This dramatic expansion highlights the growing dependence on REEs to support the energy transition, positioning these elements as essential materials in the global push towards a sustainable future. However, the growing reliance on REEs has also raised significant concerns about the security of supply. The global supply chain for REEs is highly concentrated, with China accounting for over 60% of global production and more than 85% of refining capacity. This concentration poses a strategic vulnerability for countries and industries that rely on a steady supply of these materials. In the past, geopolitical tensions and trade disputes have resulted in disruptions to the REE supply chain, leading to price spikes and uncertainty for manufacturers of clean energy technologies [5]. The potential for future supply disruptions has prompted countries like the United States, Australia, and members of the European Union to invest in diversifying their REE supply chains through domestic mining, processing facilities, and international partnerships.

Environmental sustainability is another critical issue tied to the future of REEs. The extraction and processing of REEs are resource-intensive and often result in significant environmental damage, including habitat destruction, water contamination, and the generation of hazardous waste, including radioactive materials [6]. These environmental risks present a paradox: the very materials essential for building a clean energy future could themselves cause harm to ecosystems and communities if not managed responsibly. Addressing these sustainability challenges is a key priority for policymakers, industries, and researchers who are working to develop more environmentally friendly extraction techniques, as well as recycling technologies that can recover REEs from end-of-life products [7].

This paper aims to explore the importance of REEs in the clean energy transition, focusing on their critical role in renewable energy technologies, electric vehicles, and energy-efficient systems. It will also examine the challenges associated with REE supply chains, environmental sustainability, and technological innovation, offering insights into the future of these vital materials in a rapidly changing world. Through a comprehensive analysis of the opportunities and risks posed by the increasing reliance on REEs, this paper seeks to provide a roadmap for how REEs can contribute to a more sustainable and equitable energy future.

7. The Role Of REEs In Clean Energy Technologies

2.1. Wind Turbines

Wind energy is one of the most promising renewable energy sources in the fight against climate change. Wind turbines, particularly the larger and more efficient offshore models, rely heavily on Rare Earth Elements (REEs) to improve performance and reduce operational costs. The most important REEs in this context are neodymium (Nd), praseodymium (Pr), and dysprosium (Dy), which are used to produce high-strength neodymium-iron-boron (NdFeB) permanent magnets. These magnets are integral to the function of wind turbines, especially in their generators. Traditional wind turbines use gearboxes to generate electricity, but turbines with direct-drive systems that incorporate NdFeB magnets are far more efficient. They eliminate the need for gearboxes, reducing maintenance and mechanical losses. This innovation has contributed to longer-lasting, more reliable turbines that can operate efficiently even in low-wind conditions, further increasing the viability of wind energy as a dominant player in the global renewable energy mix [8].

2.2. Electric Vehicles (EVs)

The automotive industry is undergoing a seismic shift towards electrification, with electric vehicles (EVs) at the forefront of efforts to reduce greenhouse gas emissions from transportation. Electric vehicles rely on REEs, particularly in their electric motors, where similar NdFeB magnets are used. These magnets are vital for producing lightweight, powerful motors that are essential for maximizing the energy efficiency and range of EVs. Neodymium-based magnets offer high energy density, enabling more compact and efficient motors compared to traditional induction motors. Dysprosium (Dy) is often added to neodymium magnets to improve their thermal stability, making them more suitable for the high operating temperatures of EV motors. This allows for improved vehicle performance and longer battery life, both of which are key selling points for the mass adoption of electric cars [8]. Fig. 1 highlights the greater reliance of electric vehicles on critical minerals. Fig. 2 illustrates the substantial difference in mineral requirements between clean energy technologies compared to other power generation sources.

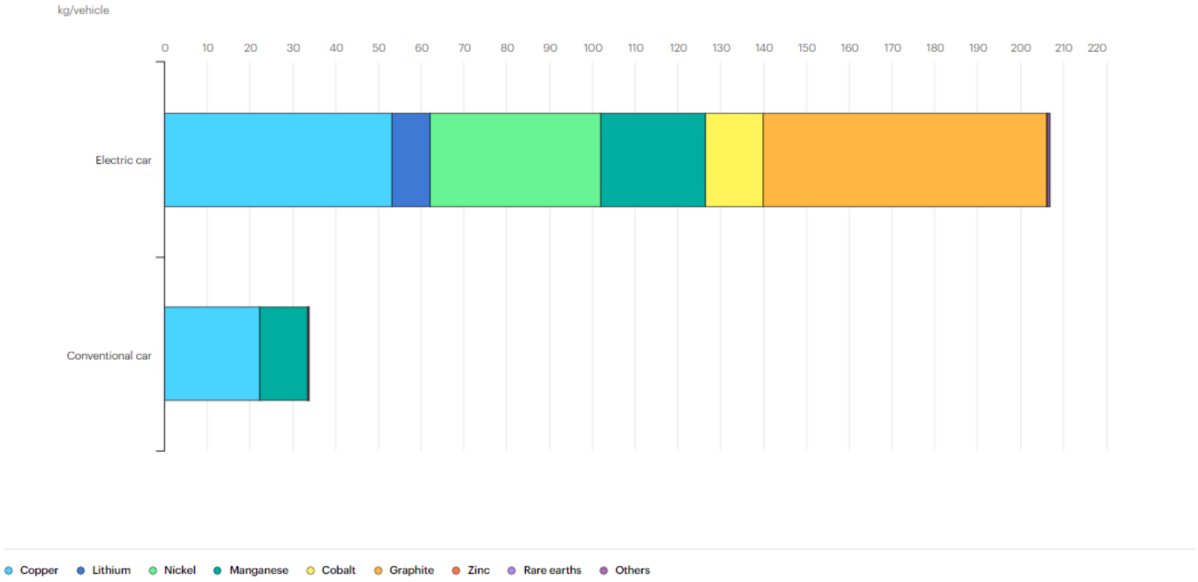


Fig. 1. Minerals used in electric cars compared to conventional cars [4]

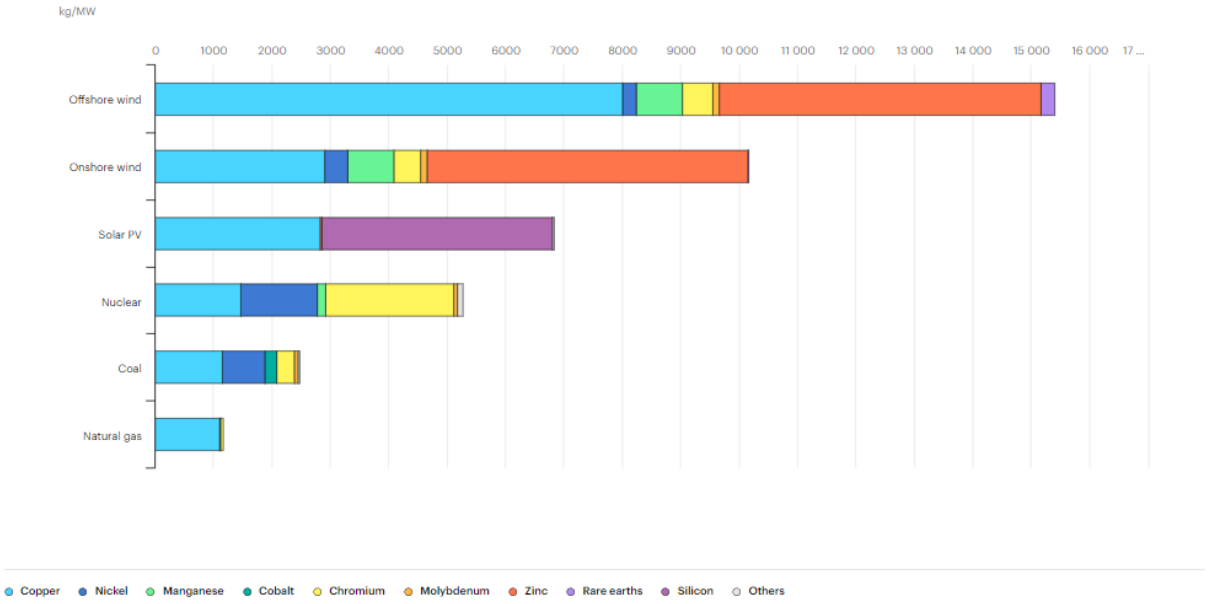


Fig. 2. Minerals used in clean energy technologies compared to other power generation sources [4]

2.3. Energy Storage Systems

Energy storage systems are indispensable for balancing the intermittent nature of renewable energy sources like solar and wind. As renewable energy generation fluctuates depending on weather conditions and time of day, advanced storage systems are needed to ensure a consistent and reliable supply of electricity. REEs contribute to both the materials science and technological advances driving innovation in this space [8].

2.4. Phosphors and Energy-Efficient Lighting

Rare Earth Elements also play a critical role in energy-efficient lighting technologies, particularly phosphors used in light-emitting diodes (LEDs) and compact fluorescent lamps (CFLs). REEs like yttrium (Y), europium (Eu), and terbium (Tb) are used to create the white light that is emitted from these lighting sources. LEDs and CFLs are much more energy-efficient compared to traditional incandescent bulbs, using a fraction of the electricity and having much longer lifespans. As global energy consumption for lighting accounts for a significant portion of electricity use, improvements in lighting efficiency directly contribute to energy conservation and the reduction of carbon emissions [9].

2.5. Other High-Tech Applications Supporting Energy Transition

Beyond direct energy applications, REEs are indispensable in other high-tech areas that indirectly support the energy transition. For instance, catalysts containing REEs are used in petroleum refining to reduce emissions and increase efficiency in the production of cleaner fuels. Cerium oxide is a critical component in catalytic converters, which reduce harmful emissions from internal combustion engines in vehicles, particularly as the world transitions away from fossil fuels [8].

8. The Future of REEs In A Low-Carbon Economy

As the world continues to transition towards a low-carbon economy, the demand for Rare Earth Elements (REEs) is expected to rise dramatically. This surge in demand stems from the need for cleaner, more sustainable energy sources and technologies (International Energy Agency [4]. However, the future of REEs in the context of this energy transition is shaped by several key factors, including supply chain security, resource availability, technological innovation, and sustainability concerns.

3.1. Rising Demand for REEs in Renewable Energy and Electric Vehicles

One of the primary drivers of increased REE demand is the rapid growth of renewable energy technologies, particularly wind power and electric vehicles (EVs). According to various industry projections, the global demand for key REEs such as neodymium, praseodymium, and dysprosium could increase by several hundred percent by 2050 [10]. This demand is largely fueled by the expanding markets for offshore wind turbines and electric motors for EVs, both of which rely heavily on permanent magnets made from NdFeB (neodymium-iron-boron) alloys.

For instance, the IEA predicts that wind energy capacity could more than triple by 2040, with offshore wind playing a significant role in this expansion [4]. Similarly, electric vehicles are expected to dominate the global automotive market by mid-century, with some estimates suggesting that up to 50 million EVs could be sold annually by 2040 [8]. The motors in these EVs require REE-based magnets to achieve the high efficiency and performance needed for longer driving ranges and reduced energy consumption. Fig. 3 shows the share of clean energy technologies in total demand for selected minerals.

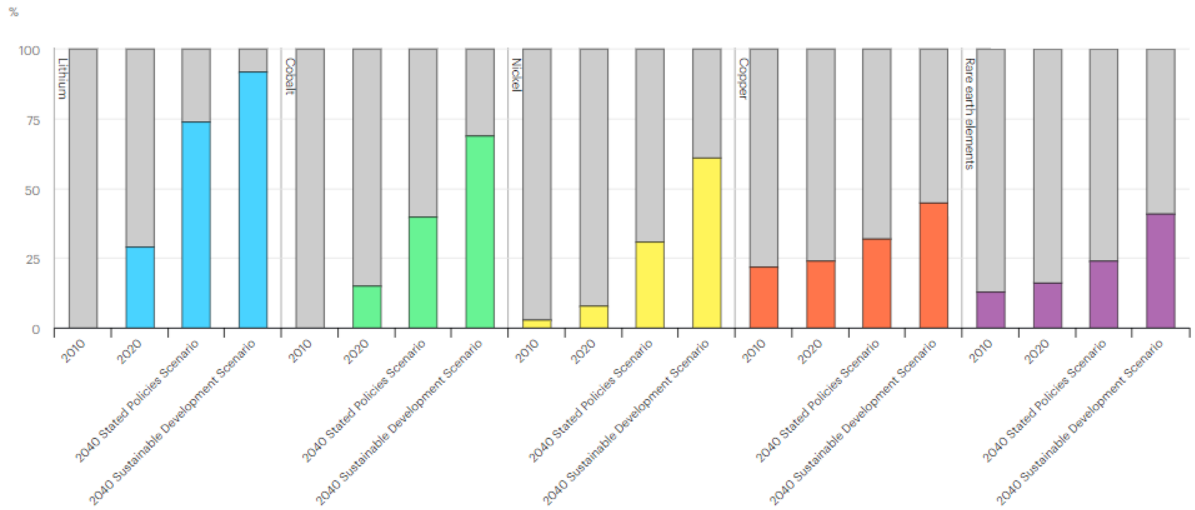


Fig. 3. Share of clean energy technologies in total demand for selected minerals by scenario, 2010-2040 [4]

3.2. Supply Chain Vulnerabilities and Geopolitical Considerations

A critical issue for the future of REEs in a low-carbon economy is the concentration of REE production in a few countries, most notably China, which currently controls over 60% of global REE output and 85% of refining capacity [11]. This dominance has led to concerns about supply chain security, particularly in light of trade tensions and geopolitical uncertainties. In the past, export restrictions and other policies from China have caused disruptions in the global supply of REEs, leading to price spikes and concerns about access to these vital materials [12]. Fig. 4 illustrates the total mineral demand for clean energy technologies. Fig. 5 shows the growth in demand for selected minerals from clean energy technologies.

3.3. Sustainability and Environmental Concerns

The environmental impact of REE mining and processing is a growing concern as the demand for these elements rises. Traditional REE extraction methods involve the use of large amounts of chemicals, water, and energy, leading to significant environmental degradation. Waste from REE processing can contain radioactive materials, which poses long-term environmental and health risks [6]. This creates a paradox where the materials critical for clean energy technologies could themselves contribute to environmental harm if not managed responsibly.

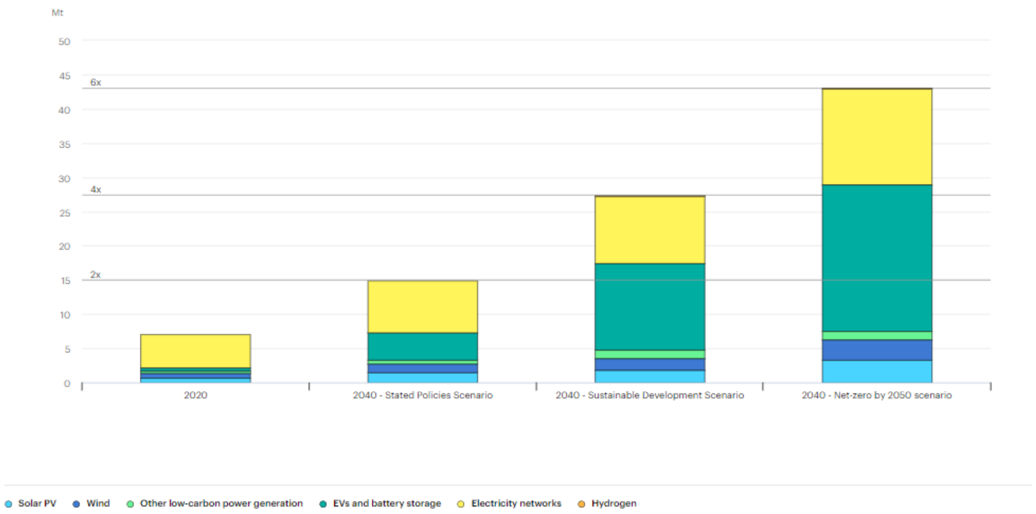


Fig. 4. Total mineral demand for clean energy technologies by scenario, 2020 compared to 2040 [4]

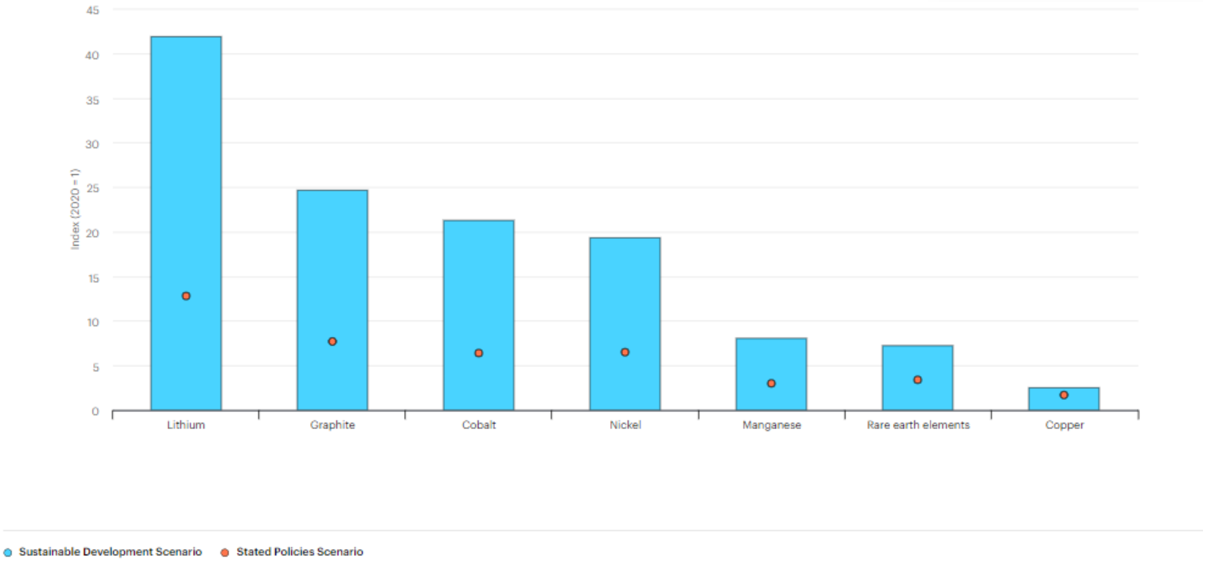


Fig. 5. Growth in demand for selected minerals from clean energy technologies by scenario, 2040 relative to 2020 [4]

To address these issues, there is a growing push towards sustainable mining practices and the development of environmentally friendly extraction technologies. Research is being conducted into methods such as bioleaching and in-situ leaching, which use biological or chemical processes to extract REEs with less environmental impact compared to traditional mining techniques [12]. These innovations aim to reduce the ecological footprint of REE production while ensuring a steady supply of materials for the clean energy transition.

3.4. Technological Innovations and Material Substitution

In addition to improving the sustainability of REE supply chains, technological innovation will be crucial for reducing dependence on these critical materials. One area of focus is material substitution, where researchers are seeking to develop alternative materials that can replace or reduce the use of REEs in key applications. For example, significant efforts are being made to develop rare-earth-free magnets for use in electric motors and wind turbines [3]. Although these alternatives have yet to reach the same level of performance as REE-based magnets, progress in this area could help mitigate future supply risks. Other innovations include advancements in nanotechnology, material efficiency, and magnet recycling. For instance, 3D printing and additive manufacturing are being explored as methods to reduce the amount of REEs needed for certain applications by producing more precise and efficient components [11].

3.5. Policy and Global Cooperation

Governments and international organizations play a key role in shaping the future of REEs in the low-carbon economy. Policymakers are increasingly aware of the strategic importance of REEs for energy security and economic development, and many countries are developing national strategies to ensure a stable and sustainable supply of these materials. For example, the European Union has launched initiatives such as the European Raw Materials Alliance (ERMA) to diversify supply chains and promote sustainable mining practices within Europe [13].

9. Conclusions

Rare Earth Elements (REEs) are at the heart of the global energy transition, acting as critical materials for technologies that are essential to achieving a low-carbon economy. Their unique properties make them indispensable for the production of high-efficiency electric motors, powerful wind turbines, advanced batteries, and other clean energy technologies. As the world seeks to drastically reduce greenhouse gas emissions, the demand for these elements is set to soar, especially as renewable energy systems like wind and solar, along with electric vehicles (EVs), become more prevalent.

However, the future of REEs in a low-carbon economy is fraught with challenges that extend beyond mere availability. While the demand for REEs grows, several critical issues must be addressed to ensure that their extraction, production, and recycling align with the principles of sustainability and equity. Chief among these challenges is the supply chain dependency on a small number of countries, particularly China, which dominates the production and processing of REEs. This concentration poses significant risks to the stability and security of the global REE supply, especially in the face of geopolitical tensions or export restrictions.

Environmental sustainability is another critical issue. The extraction and processing of REEs are often associated with significant ecological impacts, including habitat destruction, water contamination, and the generation of radioactive waste. As demand for REEs grows, these environmental risks must be carefully managed to avoid creating a new form of ecological degradation in the pursuit of clean energy. Sustainable mining practices, such as bioleaching and in-situ leaching, hold promise for reducing the environmental footprint of REE production, but these technologies are still in the early stages of development.

Technological innovation plays a crucial role in ensuring that the future of REEs is both sustainable and secure. Researchers are exploring a range of alternative materials that could replace or reduce the use of REEs in key applications, such as electric motors and magnets. While many of these alternatives are still in the experimental phase, their development could help mitigate the risks associated with REE supply shortages. Furthermore, advancements in battery technologies, including the potential shift from lithium-ion to solid-state or sodium-ion batteries, may reduce the dependency on REEs in the energy storage sector.

In conclusion, Rare Earth Elements will continue to play a pivotal role in the decarbonization of the global economy, acting as a backbone for key clean energy technologies. However, the future of these elements will depend on the world’s ability to innovate, collaborate, and adopt sustainable practices that mitigate the environmental and geopolitical risks inherent in their production. A thoughtful, coordinated approach to managing REEs will be essential for ensuring that the energy transition is not only technologically advanced but also ecologically and socially responsible. By investing in new technologies, diversifying supply sources, and improving recycling capabilities, we can harness the full potential of REEs to build a cleaner, more sustainable future for all.

References

[1] H. M. King, “Rare Earth Elements: The Materials Behind Emerging Technologies,” *Geology.com*, [Online]. Available: https://geology.com/articles/rare-earth-elements/. Accessed: October 18, 2024.

[2] E. Alonso, A. M. Sherman, T. J. Wallington, M. P. Everson, F. R. Field, R. Roth, R. E. Kirchain, “Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies,” *Environmental Science & Technology*, vol. 46, no. 6, pp. 3406-3414, 2012. doi: 10.1021/es203518d.

[3] K. Habib, H. Wenzel, “Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling,” *Journal of Cleaner Production*, vol. 84, pp. 348-359, 2014. doi: 10.1016/j.jclepro.2014.04.035.

[4] International Energy Agency, “The Role of Critical Minerals in Clean Energy Transitions,” IEA Publications, [Online]. Available: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions. Accessed: October 18, 2024.

[5] European Commission, “Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability,” European Commission Publications, [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0474. Accessed: October 18, 2024.

[6] T. E. Graedel, J. Allwood, J. P. Birat, B. K. Reck, S. F. Sibley, G. Sonnemann, M. Buchert, “What Do We Know About Metal Recycling Rates?,” *Journal of Industrial Ecology*, vol. 15, no. 3, pp. 355-366, 2011. doi: 10.1111/j.1530-9290.2011.00342.x.

[7] S. M. Jowitt, T. T. Werner, Z. Weng, G. M. Mudd, “Recycling of the rare earth elements,” *Current Opinion in Green and Sustainable Chemistry*, vol. 13, pp. 1-7, 2018. doi: 10.1016/j.cogsc.2018.02.008.

[8] U.S. Department of Energy, “Critical Materials Assessment,” [Online]. Available: https://www.energy.gov/sites/default/files/2023-05/2023-critical-materials-assessment.pdf. Accessed: October 10, 2024.

[9] N. S. Satpute, S. Dhoble, “Role of rare-earth ions for energy-saving LED lighting devices,” *Elsevier eBooks*, pp. 407-444, 2021. doi: 10.1016/b978-0-12-823710-6.00018-2.

[10] K. A. Gschneidner, J. Jensen, “Rare Earth Elements: Materials, Properties, and Applications,” in *Handbook on the Physics and Chemistry of Rare Earths*, vol. 37, pp. 1-93, 2007. doi: 10.1016/S0168-1273(07)37001-1.

[11] K. Binnemans, P. T. Jones, B. Blanpain, T. V. Gerven, Y. Pontikes, “Towards zero-waste valorisation of rare-earth-containing industrial process residues: a critical review,” *Journal of Cleaner Production*, vol. 99, pp. 17-38, 2015.

[12] V. Balaram, “Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact,” *Geoscience Frontiers*, vol. 10, no. 4, pp. 1285-1303, 2019.

[13] European Commission, “Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability,” European Union, [Online]. Available: https://ec.europa.eu/docsroom/documents/42849. Accessed: September 10, 2024.