Petroleum Cities' Carbon-neutral Pathway Collaborative Assessment and Coupling Strategies for Traditional-new Energy Integration

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Abstract

This study positions itself within the strategic framework of carbon peak and carbon neutrality, focusing on energy transition dynamics in petroleum-based cities, with Dongying serving as a paradigmatic case. Through investigating the coordinated development of conventional and renewable energy systems, the research elucidates pathways for synergistic advancement between established and emerging energy sectors. Such coordination proves instrumental in accelerating Dongying's transformation into a national demonstration zone for modern energy economy while ensuring energy security. Our methodological approach integrates three key dimensions. Four-pillar safeguard mechanisms are proposed: technological innovation ecosystems for cross-sector integration, Policy mechanisms and institutional frameworks, market-oriented reform strategies, professional capacity building programs. These findings provide actionable insights for resource-dependent cities navigating the dual imperatives of energy security assurance and carbon neutrality achievement.

Keywords

Coupling coordination, Collaborative assessment, Traditional energy, New energy, Oil city, System development degree model

Introduction

At present, the research direction at home and abroad is inclined to combine the development of traditional energy enterprises with a low-carbon economy, the green and low-carbon transformation of resource cities, the replacement transaction of conventional energy and new energy power generation rights, the clean utilization of fossil energy and the utilization of renewable energy [1]. At the international level, European Union (EU) member states have formulated renewable energy targets and adopted a series of policy measures [2]. The US government and enterprises are also increasing investment and research in renewable energy [3]. However, there are few research documents on the coordinated development of traditional energy and new energy. This paper studies the coordination level measurement of traditional energy and new energy in China's oil cities under the two-carbon target [4]. As a typical oil city, Dongying is rich in oil, coal, and other traditional resources, and is a prefecture-level city with a strong oil production capacity in China. It has a superior geographical position and has natural resources such as wind energy, electric energy, and solar energy. It is of typical significance to study the coordinated development of its traditional energy and new energy [5].

Development status of traditional energy and new energy in oil city

Analysis of current situation

There are 262 resource-based cities in China, with wide distribution and great historical contributions. 26 cities include petroleum cities, including Daqing, Yulin, Dongying Puyang, Songyuan, Panjin, and Qingyang. Dongying is a typical oil and gas city and traditional energy market, as the victory oilfield producing location. Dongying was built for "oil", after years of development, formed the petrochemical industry, rubber tires, oil equipment, non-ferrous metals industrial cluster, energy structure of coal, industrial structure focus on economic development characteristics is very prominent. At the same time, Dongying is also a large city of new energy and clean energy, rich in wind, light, geothermal, and other resources. Crude oil processing capacity and refined oil supply capacity are the country's largest, solar annual radiation of 5,253 megajiao / square meters, can develop geothermal resources distribution area of 5,655 square kilometers. Solar energy, wind energy, geothermal energy, biomass energy development conditions are good, but there are still high production costs, low output, small application scope, the reason is that the core technology holding rate is low, science and technology research and development investment is not enough [6]. Traditional competitive industries need more internal impetus, which is the most reliable support for Dongying to promote the conversion of old and new growth drivers. It can also become a new "tuyere" to promote the coordinated development of traditional energy and new energy and develop towards a green, circular, safe, efficient, and sustainable direction [7].

Opportunities and challenges

The following will mainly analyze the opportunities and challenges in the aspects of policy, resources, power consumption, carbon reduction effect, and development and utilization.

(1) Development opportunity

a) In terms of policy, Dongying adheres to the new development concept of "innovation, coordination, green, openness and sharing" as the leader. It proposes to build the largest million-ton Carbon Capture, Utilization and Storage (CCUS) whole industry chain demonstration base, deepen the transformation of old and new kinetic energies. Promoting the green and low-carbon transformation of the economy, industry, energy system and way of life in Dongying. Striving to build a demonstration zone for ecological protection and high-quality development in the Dajiang-Dahe River Delta, create a benchmark case for Dongying in the provincial green, low-carbon and high-quality development pilot area, and ensure carbon peaking is achieved as scheduled.

b) In terms of resources, it will give full play to the advantages of resource endowment. Promoting the diversified utilization of hydrogen energy, geothermal energy and biomass energy. Laying out and building "three bases and one demonstration area" for large-scale centralized photovoltaic power generation projects. Pusing forward the construction of offshore wind power bases with high quality, cultivating the integration of "wind power generation + hydrogen reserve" application mode, and actively carry out research and demonstration on the utilization of ocean energy.

c) In terms of power consumption, it has accelerated the construction of a new type of power system with a gradually increasing proportion of new energy. Enhancing the ability to consume clean energy power, improved the power system's regulating capacity. Moderately developing natural gas peaking power stations, actively exploring the new mode of "renewable energy + energy storage + distributed regulator", and enhancing the controllability of renewable energy generating units' power output [8].

d) In terms of the effectiveness of emission reduction, efforts will be made to promote energy conservation and carbon reduction in coal power, focus on energy efficiency improvement, comprehensively enhance energy conservation management capacity. Implementing key projects for energy conservation and carbon reduction, establishing an incentive and constraint mechanism guided by energy efficiency. Phasing out and updating old equipment, introducing advanced production lines, comprehensively enhancing energy efficiency standards. Optimizing the energy use structure, adopting distributed energy storage, "PV+storage optimizes the energy consumption structure, adopting distributed energy storage, "photovoltaic + energy storage" and other modes, and increasing the proportion of non-fossil energy consumption. Promoting green and low-carbon upgrading and transformation, and accelerating the construction of green data centers [9].

e) In terms of development and utilization, Dongying accelerates the development and utilization of clean energy, vigorously developing solar, wind, hydrogen, geothermal, biomass and other new energy sources. Promoting the clean and efficient development of oil and gas resources, and supporting the application of green low-carbon technologies in exploration and development of Shengli Oilfield. Promoting synergistic development of traditional and new energy resources, and striving to build a national demonstration zone for modern energy economy [10].

(2) Challenges

a) China is currently in the primary stage of the energy transition. Although the Dongying Municipal

Government has rolled out a series of policies to support and drive the development of traditional and new energy and advance energy transition, relevant departments must always adhere to the concept of coordinated development in energy planning and policy implementation. Finding the right balance between the development of traditional energy sources and new energy sources, and the concept of change is the first step to promote the synergistic development of traditional energy sources and new energy sources [11].

b) Underutilized production capacity, a substantial crude oil supply gap, and prominent oil supply-demand contradictions persist. Insufficient crude oil supply and inadequate storage, and transportation infrastructure hinder the development of local refining enterprises, while the limited crude oil logistics capacity in the Dongying Port Development Zone further restricts industrial progress [12].

c) The use of energy is highly dependent on oil, coal, and other traditional energy sources. The energy system is still to be perfected, clean energy power generation has gained significant development, but the situation of traditional thermal power generation has not changed, and the pressure of green transformation of the energy industry is greater [13].

d) Coal consumption dominates thermal power generation with a high reliance level, and energy-related environmental pollution exposes China to mounting international pressure, thereby constraining the development of traditional energy sources. Against this backdrop, it is imperative to explore pathways for synergistic development between traditional and new energy sources [14].

e) The energy structure of Dongying is focused on the chemical industry. To promote the coordinated development of traditional energy and new energy, it is necessary to master the key core technologies, but the unbalanced development of energy science and technology will also become a restrictive factor.

Research method

Model construction

(1) System development degree model

a) Normalization process

To eliminate the difference in dimensions between the indicators, normalize the data corresponding to each indicator:

Positive indicators are defined as shown in Equation (1):

$$r_{ij} = (r_{ij}^0 - \min_{1\le j\le n}(r_{ij}^0))/(\max_{1\le j\le n}(r_{ij}^0) - \min_{1\le j\le n}(r_{ij}^0)) \quad (1)$$

Negative indicators are defined as shown in Equation (2):

$$r_{ij} = (\max_{1\le j\le n}(r_{ij}^0) - r_{ij}^0)/(\max_{1\le j\le n}(r_{ij}^0) - \min_{1\le j\le n}(r_{ij}^0)) \quad (2)$$

Where: r_{ij}^0 is the value of the i indicator for the j year (i=1, 2, ..., n), the above two values represent respectively the maximum and minimum sample values of the first indicator, and r_{ij} refers to the normalized value of the i indicator in the j year.

When the entropy value method is used for the calculation of indicator weights, the entropy value e_i calculation of each indicator is carried out first:

$$e_i = -k \times \sum p_{ij} \times \ln(p_{ij}) \quad (3)$$

In formula: k=1/ln(m), i=1, 2, …, n.

$$p_{ij} = \frac{r_{ij} * 0.99 + 0.01}{\sum r_{ij} * 0.99 + 0.01} \quad (4)$$

To overcome the problem of zero value after the normalization process, this paper multiplies the indicators by 0.99 and then adds 0.01.

b) Determination of the differentiation coefficient

In this paper, after calculating the entropy value e_i, it is necessary to determine the differentiation coefficient g_i corresponding to this indicator:

$$g_i = 1 - e_i \quad (5)$$

c) Determination of the index weight

The formula for calculating the w_i-weight of the indicator i:

$$w_i = \frac{g_i}{\sum_{i=1}^{m} g_i} \quad (6)$$

Special attention should be paid to the fact that if $g_i = 0$, then $w_i = g_i = 0$, i.e., the differentiation factor is 0 and the weight is 0.

d) The effect of comprehensive development

$$X_1^j = \sum w_i \times r_{ij} \quad (7)$$

Where: X_1^j represents the combined developmental efficacy of the system 1 in a year X_1^j.

e) System development degree

$$T_j = \alpha X_1^j + \beta X_2^j \quad (8)$$

Where: T_j denotes the degree of development of the two systems in a year j. α and β are the weights of the two systems, respectively, $\alpha = 0.5$ and $\beta = 0.5$ are of equal importance to the two systems in this paper.

(2) System coordination model

Assuming that the system development efficacy values of the two systems are X_1 and X_2, the corresponding coefficients of divergence for the two are:

$$C_V = \frac{\sqrt{\frac{(X_1 - X_2)^2}{2}}}{\frac{(X_1 + X_2)}{2}} \tag{9}$$

Further derivation of Eq. is obtained:

$$C_V = \sqrt{2 \times \left[1 - X_1X_2 / \left(\frac{X_1 + X_2}{2}\right)^2\right]} = \sqrt{2 \times (1 - C)} \tag{10}$$

Where C_V is the degree of coordination between X_1 and X_2, where:

$$C = X_1X_2 / \left(\frac{X_1 + X_2}{2}\right)^2 \tag{11}$$

When C_V=0, $X_1 = X_2$ denotes a line with slope 1 from the origin, and the optimal coordination of any point on it is 1. This line is the optimal coordination line in the usual sense.

When $C_V \neq 0$, it represents that the line deviates from the origin and will produce an intercept on the horizontal and vertical axes, representing that the coordination is not optimal at this point.

C_V Smaller is equivalent to a larger C. Since C takes values between 0 and 1, C is used to calculate the degree of coordination on behalf of C_V comparability and intuition.

(3) Coupling coordination model

It has been described earlier that the coupled coordination degree is a centralized reflection of the joint functioning of the two aspects of coordination and development, and if expressed graphically, the coupled coordination degree is the position of the intersection of the two straight lines of the coordination line and the development line. It is characterized by: First, any point of the optimal coordination line is the optimal point of coordination, the same degree of coordination, in the development of the line at a higher position on the intersection of the higher level of coupled coordination. Second, the system development level is the same, in the coordination of the higher point position, the higher the level of coupled coordination. Third, the coupling coordination understanding, on the one hand, emphasizes coordinated development, while pursuing a higher level of development. Based on the above views, the coupled coordination model can be expressed as:

$$D_j = C_j \times T_j \tag{12}$$

Where: D is the system coupling coordination degree.

Indicator design

Figure 1 illustrates the integration pathways between the three-segment oil industry chain and new energy sectors. Upstream, midstream and downstream oil sectors jointly facilitate the development of wind, solar, hydrogen, geothermal and biomass energy via diverse technical and operational modes.

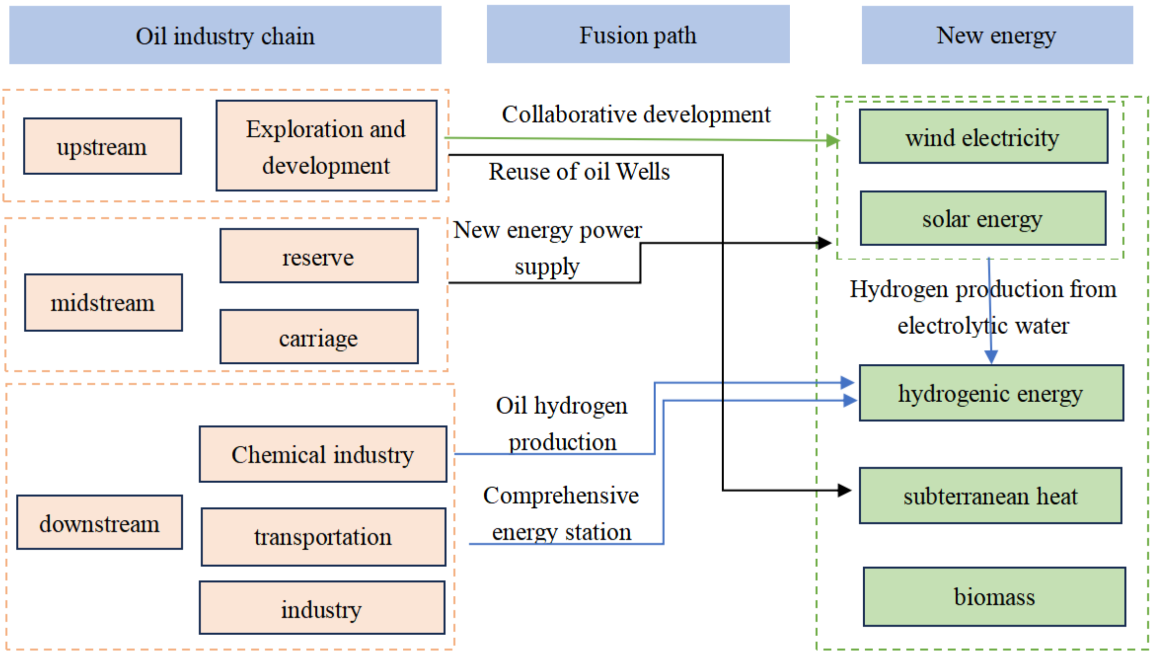

Figure 1. Deep coupling utilization path of oil and new energy.

By analyzing the main meanings of traditional energy and new energy systems, drawing on the reference to existing research results, and taking scientific, dynamic, operable, and hierarchical as the principle, the index system involved in this paper is constructed, as shown in Table 1.

Table 1. Indicator system for conventional and new energy systems.

Subsystems	Indicator name	Efficacy type
Traditional energy X_1	Crude oil production X_{11}	+
	Natural gas production X_{12}	+
	Mining industry investment in fixed assets X_{13}	+
	Oil consumption X_{14}	+
	Natural gas consumption X_{15}	+
	Coal consumption X_{16}	-
	Carbon emission intensity X_{17}	-
New energy X_2	Installed renewable energy capacity X_{21}	+
	Renewable energy generation capacity X_{22}	+

Sources of data

The research data in this paper are all from the Dongying Statistical Yearbook (2018-2021), and some of the data are from the official website of Dongying.

Empirical analysis

Research results

The coupling between traditional energy source and new energy source systems is calculated according to the formula of development degree, coordination degree, and coupling coordination degree, as Shown in Table 2.

The development degree of traditional energy and new energy is generally on the steady rise, with a large growth rate and fast growth rate in 2020-2021, and a slight decline in 2019-2020.The coordination degree of traditional energy and new energy has been on the continuous rise, and the growth rate is fast and large in 2018-2020, while the growth rate is relatively slow in 2020-2021. The coupling coordination degree of traditional energy and new energy is generally on the gradual rise, and the growth rate is slow from 2018 to 2020, and the growth rate is greatly increased significantly from 2020 to 2021.

Table2. Coupling situation of traditional energy and new energy system.

Year	Development degree	Coordination degree	Coupling coordination degree
2018	0.263	0.075	0.020
2019	0.318	0.499	0.159
2020	0.289	0.828	0.239
2021	0.809	0.944	0.764

Result analysis

(1) The degree of development

In 2019, China took firm steps to cut overcapacity and advance structural adjustment in the coal sector. Dongying also optimized its energy structure and phased out outdated production capacity. Affected by falling efficiency in Shengli Oilfield and population outflow, the city's GDP dropped markedly and maintained sluggish growth from 2019 to 2020. The overall development benefits of traditional energy weakened, resulting in a lower coupling level between the two systems.

(2) In terms of coordination degree

On January 3rd, 2018, The State Council officially approved the "Overall Plan for the Construction of Shandong New and Old Kinetic Energy Conversion Comprehensive Pilot Area", agreeing to set up Shandong's new and old kinetic energy conversion comprehensive pilot area.

Dongying, under the "three-core leadership and multi-point breakthrough" strategy, serves as a demonstration base for the green and circular high-end petrochemical industry and a pilot area for the transformation and development of oil resource-based cities. The planning of the Lubei high-end petrochemical industry base offers a critical opportunity for the transformation and upgrading of growth drivers in Dongying, prompting the city to prioritize the coordinated development of traditional and new energy sources and formulate corresponding development plans. This initiative further enables Dongying to leverage its resource advantages to advance economic transformation.

(3) Coupling coordination degree

Under the national policy plans such as the Implementation Plan of the Major Project of the Transformation of Old and New Energy Sources in Shandong Province and the Development Plan of the New Energy Industry in Shandong Province (2018-2028), the development of traditional energy and new energy in Dongying is advancing together. To protect China’s energy security and effectively implement the “two-carbon” policy, Dongying will be more accurate and effective in the development of traditional energy and new energy. According to the development trend, traditional energy and new energy not only work together in development, but also the relationship between the two is complementary, and the coupling coordination degree of traditional energy and new energy will continue to increase.

Strategy analysis

Drawing on an analysis of collaborative development pathways for traditional and new energy in Dongying City and their economic implications, this study puts forward targeted safeguard measures. They are proposing from the aspects of strengthening scientific and technological innovation, improving the policy service system, deepening the reform of “discharge management service”, focusing on talent training, and practicing green and low-carbon.

Strengthening scientific and technological innovation

First, efforts should be made to build a complete industry-university-research alliance, build a national new energy laboratory and its related Research and Development (R&D) platform, constantly strengthen the research of basic theories, and timely tracking of the most advanced technologies. Actively investing resources to research smart manufacturing and digital transformation, and introducing corresponding policies and measures to promote the sustainable development of the smart photovoltaic industry. Focusing on investing resources to research and develop new solar cells, wind power equipment, and more advanced basic materials, equipment, and parts with greater reliability. We will continue to promote the application of new energy and multi-energy complementary technologies. Opening up more emerging industries and build a complete, sustainable, and green development model. Scientific and technological innovation is the key. Strengthening scientific and technological innovation is an important measure to ensure the safety of the industrial chain and supply chain and enhance the competitiveness of the entire industry.

Improving the service policy system

To promote the healthy development of new energy such as the photovoltaic industry, we should improve the relevant standards, improve the protection of intellectual property rights, establish a sound regulatory body, and improve the new energy public service system. It is necessary to conduct in-depth research on new energy, establish a complete information database, and publish the research results on the platform to improve the ecological environment of the entire new energy industry. Actively promoting relevant technological improvements, and vigorously develop public services, such as providing a high level of new energy equipment standards, testing and certification, and supervision of key products.

Deepening the reform of “delegating supervision and management services”

The purpose of the reform of streamlining regulations and providing services is to improve the business environment and promote economic development. We will deepen the reform of delegating power, delegating regulation, and providing services in the new energy sector, and continue to improve the efficiency of project approval. We will improve the investment approval system for new energy projects, build a chain supervision model, and ensure supervision in all areas before, during, and after events. We rely on the national online supervision and approval platform for investment projects to realize centralized approval of new energy projects. Green approval channels will be set up to boost processing efficiency, alongside formulated project access negative lists and corporate commitment lists to advance the commitment-based approval system for enterprise investment projects. No unreasonable costs shall be imposed on new energy enterprises under any pretext.We should strengthen the comprehensive reform of the economic system, establish a sound and perfect market mechanism, policy system, and supervision system, eliminate all forms of barriers, and provide a good space for the development of excellent enterprises.

Paying attention to personnel training

Talent is the first resource. The focus of “double carbon” is to change the traditional “double carbon” talent training model, making it more targeted and practical value. To attract more outstanding talent, we should establish a fair and effective recruitment mechanism and provide excellent training resources. To promote the cross-border exchange of “double carbon”, we should actively explore the ideas, methods, and technologies of “double carbon” to better meet the needs of society for innovators with multiple capabilities.

Practice green and low-carbon

The concept is the forerunner of action. Since the 18th CPC National Congress, China has been continuously promoting the new concept of green and low-carbon economic development. The sustainable development of the energy sector and the sustainable utilization of the petroleum and petrochemical industry will become the core tasks. We shall actively and steadily advance the goals of carbon peaking and carbon neutrality, and firmly pursue green and low-carbon development strategies. We will develop low-carbon, zero-carbon and negative-carbon technologies covering energy conservation, energy storage, hydrogen energy, electrification, carbon capture and carbon utilization. Efforts will be made to explore the integrated development of traditional fossil energy and biomass energy, and advance the construction of energy conservation and carbon emission control systems. We will expand businesses related to new energy and new materials, and drive the coordinated development of traditional and emerging energy industries. We will continue to promote bilateral and multilateral cooperation in the energy sector, optimize the strategic layout of resource imports and overseas oil and gas resources, and achieve breakthroughs in inventory optimization and increase.

Conclusion

The coordinated development of traditional energy and new energy can reduce carbon emissions, save energy, and help achieve carbon neutrality. It is also conducive to ensuring China’s energy security and is of great significance to China’s high-quality development. Dongying is a typical resource-based petroleum city in China, with prominent resource endowment advantages of renewable energy, resource advantages, policy inclines, and broad prospects for the coordinated development of traditional energy and new energy in Dongying. Guided by energy resource security and underpinned by stable industrial and supply chains, Dongying shall advance coordinated energy development. It needs to boost technological innovation, refine policy frameworks, advance market-oriented reforms and cultivate comprehensive talents to build a national demonstration zone for modern energy economy. These measures can safeguard regional energy security and offer practical experience for energy transformation of other oil-based cities nationwide. To promote China to achieve peak carbon neutrality as soon as possible.

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Conflicts of Interest

The author declares no conflict of interest.

References

[1] Yang, X., Guo, Y., Liu, Q., Zhang, D. (2022) Dynamic Co-evolution analysis of low-carbon technology innovation compound system of new energy enterprise based on the perspective of sustainable development. *Journal of Cleaner Production*, 349, 131330.

[2] Musiał, W., Zioło, M., Luty, L., Musiał, K. (2021) Energy policy of European Union member states in the context of renewable energy sources development. *Energies*, 14(10), 2864.

[3] Brodny, J., Tutak, M., Bindzár, P. (2021) Assessing the level of renewable energy development in the European Union member states. A 10-year perspective. *Energies*, 14(13), 3765.

[4] Rabbi, M. F., Popp, J., Máté, D., Kovács, S. (2022) Energy security and energy transition to achieve carbon neutrality. *Energies*, 15(21), 8126.

[5] Yang, Z., Liu, J., Xing, Q. (2022) Evaluation of synergy between low-carbon development and socio-economic development based on a composite system: a case study of Anhui Province (China). *Scientific Reports*, 12(1), 20294.

[6] Bourek, Y., Ammari, C., Pesyridis, A. (2024) The integration of solar-hydrogen hybrid renewable energy systems in oil and gas industries for energy efficiency: optimal sizing using Fick's Law optimisation Algorithm. *Energy Conversion and Management*, 308, 118372.

[7] Strojny, J., Krakowiak-Bal, A., Knaga, J., Kacorzyk, P. (2023) Energy security: a conceptual overview. *Energies*, 16(13), 5042.

[8] Che, S., Wang, J., Chen, H. (2023) Can China's decentralized energy governance reduce carbon emissions? Evidence from new energy demonstration cities. *Energy*, 284, 128665.

[9] Ding, Y., Bi, C., Qi, Y., Han, D. (2024) Coordinated governance of energy transition policy and pollution and carbon reduction: a quasi-natural experiment based on new energy demonstration city policy. *Energy Strategy Reviews*, 53, 101395.

[10] Fu, D., Zhang, L. (2024) How can low-carbon help high-quality urban development? - Empirical evidence from low-carbon city pilot policies. *PLOS One*, 19(5), e0302683.

[11] Mahmoud, M., Ramadan, M., Naher, S., Pullen, K., Abdelkareem, M. A., Olabi, A. G. (2021) A review of geothermal energy-driven hydrogen production systems. *Thermal Science and Engineering Progress*, 22, 100854.

[12] Shah, M., Prajapati, M., Yadav, K., Sircar, A. (2022) A review of the geothermal integrated hydrogen production system as a sustainable way of solving potential fuel shortages. *Journal of Cleaner Production*, 380, 135001.

[13] Li, Z., Zhang, W., Zhang, R., Sun, H. (2020) Development of renewable energy multi-energy complementary hydrogen energy system (a case study in China): a review. *Energy Exploration & Exploitation*, 38(6), 2099-2127.

[14] Solanki, D., Shah, M., Prajapati, M. (2025) The role of geothermal and wind energy in hydrogen production: towards a carbon-free future. *Carbon Neutral Systems*, 1(1), 9.