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OPINION
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Global Monitoring of the Development of Digital Energetics Based on the Technologies of Industry 4.0: IoT, Blockchain, Robots, and Artificial Intelligence

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INTRODUCTION

The transition to Industry 4.0 contributed to the formation of digital energy, which is characterized by the active use of high technologies in various economic processes of the energy economy. Industry 4.0 technologies are defined in different ways in the national programs and strategies of the same name. For example, in Germany, which was the first to adopt a national strategy referred to as “Industrie 4.0,” Industry 4.0 technologies shall be understood to mean the entirety of technologies that form cyber-physical systems and make Germany a leader in terms of technology (European Commission, 2022).

In the United Kingdom, Industry 4.0 technologies shall be understood to mean “eight great technologies” (Government of UK, 2022). The most general (universal, international) list of Industry 4.0 technologies can be found in UNCTAD records (2022), where they are referred to as “Frontier technologies” and include Artificial Intelligence (AI), Internet of Things (IoT), Big Data, Blockchain, 5G, 3D printing, robots, drones, Gene Editing, nanotechnologies, and Solar Photovoltaic (Solar PV).

The studies by Haddouche and Ilinca (2022), Kanoun et al. (2021), Maggiore et al. (2021), Matsunaga et al. (2022), Morelli et al. (2022), Otoum et al. (2022), Wachnik et al. (2022) refer to IoT, Blockchain, robots, and AI as the most advanced and most common technologies of Industry 4.0 in the energy economy. The problem lies in the fact that despite the advantages of digital energetics disclosed in detail in the existing literature (Popkova, 2022), there is still much uncertainty as to whether these advantages are achieved in practice and how to maximize them.

Due to this problem, the development of digital energetics occurs spontaneously. The lack of scientific and methodological support prevents achieving full growth potential to increase the effectiveness of advanced technologies of Industry 4.0 in the energy economy. In the context of global competition in the field of high technologies, energy economies aim to strengthen their digital competitive advantages.

The disadvantage of the current approach to the development of the energy economy based on Industry 4.0 technologies is that its digital competitiveness is an objective in itself. This approach does not guarantee benefits in the form of energy sustainability, providing only its innovation and high-tech. This causes the low effectiveness of this approach due to limited results at high costs (investments in high technologies) and risks (relating to innovations). The hypothesis of this article is that, with the current approach, there is a weak connection between digitalization and energy sustainability.

TABLE 1 | Global monitoring of the development of digital energy based on Industry 4.0 technologies in 2021.

Country category	Country	Energy Trilemma index, scores 0–100	The readiness for frontier technologies index		Government AI readiness index, scores 0–100	Digital Competitiveness, scores 0–100	Efficiency of digital energy
			Scores 0–1	Scores 0–100			
		ETI	-	RFT	AIR	DCEE	DEEF
Top countries by GDP per unit of energy use	Irish	76.8	0.92	92.0	72.80	80.53	0.93
	Switzerland	83.8	0.97	97.0	68.56	83.12	1.01
	Colombia	69.0	0.44	44.0	58.91	57.30	1.34
	Denmark	83.0	0.92	92.0	76.96	83.99	0.98
Top countries by energy imports, net	Singapore	69.3	0.95	95.0	82.46	82.25	0.78
	South Korea	70.1	0.93	93.0	76.55	79.88	0.83
	Belgium	76.3	0.90	90.0	60.07	75.46	1.02
	Portugal	75.6	0.71	71.0	64.31	70.30	1.12
Top countries by fuel exports (merchandise exports)	Qatar	70.3	0.46	46.0	67.18	61.16	1.24
	UAE	69.5	0.63	63.0	71.60	68.03	1.03
	Saudi Arabia	67.5	0.57	57.0	63.42	62.64	1.12
	Kazakhstan	67.7	0.50	50.0	48.43	55.38	1.38

Source: compiled and calculated by the authors on the basis of the materials from Oxford Insights (2022), UNCTAD (2022), and World Energy Council (2022).

Thus, to accelerate the development of digital energetics based on the technologies of Industry 4.0 aimed at achieving the Sustainable Development Goal 7 (SDG 7), a new (alternative) approach and scientific and methodological support for its implementation are required. The significance of SDG 7 is that it goes beyond the interests of particular categories of beneficiaries of the energy economy (e.g., affordability of energy for society, reduction in expenses for the development of the energy economy for the state, and increase in profits for energy companies) and forms a consistent idea of how to simultaneously and comprehensively maximize the benefits of the energy economy for all stakeholders (He et al., 2022; Yu et al., 2022).

In this regard, SDG 7 sets such priorities as sustainability (deficit-free energy, balance of global energy markets, stability of global and local energy prices to ensure its wide affordability, reliable and flawless operation of value chains in the energy economy), and environmental friendliness (mitigation of environmental risks of energy production and transportation, reduction/prevention of the depletion of natural resources for their conservation for succeeding generations, and the transition to "clean" energy) of the energy economy (Che et al., 2021; Firoiu et al., 2021; Madurai Elavarasan et al., 2021).

The purpose of this article is to conduct global monitoring of the development of digital energetics based on the technologies of Industry 4.0 and propose a new (alternative) approach to managing this development with a focus on supporting the practical implementation of SDG 7. The novelty of this study and its contribution to knowledge consist in forming a consistent scientific concept of the benefits of using Industry 4.0 technologies for the sustainable and environmentally friendly development of the energy economy.

DIGITAL ENERGETICS BASED ON THE TECHNOLOGIES OF INDUSTRY 4.0: IOT, BLOCKCHAIN, ROBOTS, AND AI

This article is based on the theory of digital energetics. In the available literature, numerous benefits from advanced technologies of Industry 4.0 in the energy economy are noted as follows:

→ The Internet of Things (IoT) makes it possible to integrate production and distribution networks and processes into a single cyber-physical system of Industry 4.0 in digital energetics (Krishnan and Jacob, 2022; Zhao et al., 2022).
→ Blockchain increases the transparency and control of value chains in the energy economy (Gawusu et al., 2022; Mahmoudian Esfahani, 2022).
→ Robots increase the productivity of energy companies (Huang et al., 2022).
→ Artificial Intelligence (AI) increases the flexibility and efficiency (through intelligent management decision support) of value chains in the energy economy (Bezbakh and Frolova, 2022).

In the works of Amir et al. (2022), Chen et al. (2022), Favi et al. (2022), and Vlasov et al. (2019), the use of advanced Industry 4.0 technologies in the energy economy provides advantages in both production and distribution processes. Maggiore et al. (2021), Morelli et al. (2022), Wachnik et al. (2022), and Zaidan et al. (2022) indicated that, in order to fully take benefit of the advanced technologies of Industry 4.0 in the energy economy, it is advisable to actively use them by representatives of all interested parties: energy companies, state regulators of the energy economy, and energy consumers. Baxter (2012), Inshakov et al. (2019), Kabeyi and Olanrewaju (2022), Kapitonov et al. (2019), Kluczek et al. (2021), and Ratner et al. (2022) stated that the digitalization of the energy economy based on advanced technologies of Industry 4.0 is universal—it is suitable for all countries, regardless of their energy efficiency, role, and position in global energy markets.

Based on the above publications, it can be concluded that the existing approach to the development of the energy economy based on Industry 4.0 technologies recognizes digitalization as a priority of this development with the secondary sustainability of energy (it is assumed that digitalization provides it). However, the relationship between digitalization and energy sustainability is poorly studied and not confirmed, which is a research gap. The identified gap is filled in this study by clarifying the relationship between the use of advanced Industry 4.0 technologies and energy sustainability.

DIGITAL COMPETITIVENESS OF ENERGY ECONOMIES AND ANALYSIS OF ITS DIFFERENCES AMONG CATEGORIES OF COUNTRIES

In order to achieve this goal and verify the hypothesis put forward, this article conducts global monitoring of the development of digital energetics based on the technologies of Industry 4.0. Monitoring is aimed at accurately quantifying the level of development of digital energetics as a vector of growth and sustainable development of the energy economy.

The study is based on the experience of the top four countries with the highest energy efficiency of the economy (according to the criterion of GDP per unit of energy use, constant 2017 PPP $ per kg of oil equivalent), the top four countries with the largest energy imports, net (% of energy use), and the top four countries with the largest fuel exports (% of merchandise exports) according to the materials of the World Bank (2022). The sample of countries formed for this study made it possible to comprehensively highlight the modern experience of digital energy development, which is considered from the standpoint of two groups of indicators.

The first group: Industry 4.0 technology development indicators: 1) “AI Readiness Index 2020” Oxford Insights (2022), designated AIR; 2) Readiness for Frontier Technologies Index 2021, presented in the UNCTAD report (2022) and designated RFT. The second group: the “World Energy Trilemma Index 2020 Report” World Energy Council (2022) as an indicator of sustainability and environmental friendliness of the energy economy, designated by ETI.

Based on the systematization of the data of both groups, the digital competitiveness of the energy economy [DCEE = (ETI, RFT, and AIR) is estimated/3] and its efficiency [DEEF = ETI/(RFT + AIR)/2]. The classical concepts of economic efficiency as the ratio of results (in our case: sustainability and environmental friendliness of the energy economy) to costs (in our case: technologies of Industry 4.0) (Akram et al., 2022; Gorus and Karagol, 2022) and competitiveness in terms of achieved results compared to other competing countries (in our case, identified by means of rankings) (Nagel et al., 2022; Shuai et al., 2022) served as the prerequisites and the basis for the calculation methods. The study is conducted according to data for 2021. The initial data and the results of their analysis are presented in **Table 1**.

The global monitoring of the development of digital energetics based on the technologies of Industry 4.0 in 2021, presented in **Table 1**, led to the following results:

→ The digital competitiveness of the energy economy as a whole is high in all the categories of countries considered. It is highest in the top countries by energy imports (76.97 points) and in the top countries by GDP per unit of energy use (76.24 points), and in the top countries by fuel exports, it is estimated at 61.80 points.

→ The efficiency of digitalization of the energy economy is low in all categories of countries (it has not reached 1.5). The digital energy economy is inefficient in the top countries by energy imports (0.94—costs exceed benefits, less than 1) and low-efficient (benefits slightly exceed costs) in the top countries by GDP per unit of energy use (1.07) and in the top countries by fuel exports (1.19).

→ This leads us to the conclusion that the introduction, expansion, and use of technologies of Industry 4.0 (i.e., the transition to the digital energy economy) guarantees an increase in the digital competitiveness of the energy economy but does not indicate an increase in its efficiency (from the perspective of contribution to the sustainability and environmental friendliness of the energy economy).

→ Hence, this calls for more complex management of the development of the digital energy economy, which will ensure not only an increase in the level of its high technologies (the use of Industry 4.0 technologies—IoT, blockchain, robots, and AI) but also improved results from the perspective of increasing the sustainability and environmental friendliness of the energy economy. The contribution of the suggested methodology to the more intensive acquisition of new knowledge is that the methodological guidelines of the authors allow improving the accuracy and reliability of the quantitative measurement of the efficiency and competitiveness of the digital energy economy.

→ The authors’ methodology allows obtaining highly detailed evaluation results and, thus, identifying the cause-and-effect relationship between changes in the efficiency and competitiveness of the digital energy economy and their weaknesses and strengths. As a result, it is possible and recommended to develop a national economic policy to manage the development of the digital energy economy, aimed at increasing the efficiency and competitiveness of the digital energy economy.

THE LEVEL OF THE DEVELOPMENT OF DIGITAL ENERGETICS AS A VECTOR OF GROWTH AND SUSTAINABLE DEVELOPMENT OF THE ENERGY ECONOMY: A NEW MANAGEMENT APPROACH

In order to determine the contribution of digital energy to the sustainable development of the energy economy based on empirical data from **Table 1**, the following regression model was obtained by regression analysis:

$$ETI = 67.9697 + 0.2240 * RFT - 0.1678 * AIR. \quad (1)$$

According to model (1), energy sustainability increases by 0.2240 points when the readiness for Frontier technologies index increases by one point but does not demonstrate a positive dependence on the government AI Readiness Index. The significance of F for model (1) was 0.0628. The multiple R in model (1) was 0.6778. The advantage of the regression analysis method that has been chosen for the pursuance of the research in this study is its high accuracy—this is one of the most reliable methods of statistical economics (econometrics).

The existing concepts of the potential relationship between these indicators (Ghobakhloo and Fathi, 2021; Kluczek et al., 2021) and the successful identification of individual manifestations of this relationship in previous works by Hidayatno et al. (2019), Knez et al. (2022), and Koyuncu et al. (2021) served as the prerequisites and the basis for the calculation methods for obtaining the regression model that is presented to determine the contribution of the digital energy economy to the sustainable development of the energy economy. Also, by the method of correlation analysis, the following was found:

→ Readiness for Frontier Technologies Index is positively associated with energy sustainability only in the top countries by GDP per unit of energy use (correlation 0.91), in the top countries by energy imports (−0.65), and in the top countries by fuel exports (−0.17%); the relationship of these indicators is negative.

→ The Government AI Readiness Index is positively associated with energy sustainability only in the top countries by GDP per unit of energy use (correlation 0.78), in the top countries by energy imports (0.67), and in the top countries by fuel exports (−0.99%); the relationship of these indicators is negative.

This brings us to the conclusion that Industry 4.0 technologies make a considerable and significant contribution to ensuring the sustainability and environmental friendliness of the energy economy. In this regard, a new (alternative) approach to the development of digital energetics based on the technologies of Industry 4.0 is proposed, which supports the implementation of SDG 7 and assumes a focus on the digitalization of energy companies, the flexibility necessary to consider the characteristics of each category of countries, and the priority of the efficiency of the digital energy economy.

Based on model (1), the new approach is expected to increase energy sustainability by 6.20% (73.24–77.78 points) while maximizing the readiness for advanced technologies of the index (+33.83%, 74.17–100 points). The established approach to the development of digital energetics based on the technologies of Industry 4.0 is versatile—it can be implemented around the world (by large energy suppliers and exporters and by large energy consumers and importers, as well as by other countries). This approach will ensure the accelerated digitalization of the energy economy and increase its efficiency; as a result, it will support the global implementation of SDG 7.

DISCUSSION

The article contributed to the development of the theory of digital energetics by clarifying the relationship between digitalization and energy sustainability. In contrast to Amir et al. (2022), Chen et al. (2022), Favi et al. (2022), and Vlasov et al. (2019), the use of advanced Industry 4.0 technologies in the energy economy provides advantages only in the production (but not in distribution) processes. The argumentation of this conclusion is based on the fact that the relationship of energy sustainability with the readiness for Frontier Technologies Index and with the government AI Readiness Index among countries of different categories is much stronger in the top countries by GDP per unit of energy use compared to other categories of countries. Consequently, advanced technologies of Industry 4.0 contribute to the growth of energy efficiency of the economy, but only to a small extent improve distribution processes.

In contrast to Maggiore et al. (2021), Morelli et al. (2022), Wachnik et al. (2022), and Zaidan et al. (2022), it was justified that, in order to take advantage of the use of advanced technologies of Industry 4.0 in the energy economy, it is advisable to actively use them only in entrepreneurship, while their use in society and the state does not provide advantages with the current approach to the development of the energy economy based on Industry 4.0 technologies. The reasoning of this conclusion is based on the revealed absence of a positive contribution of the government AI Readiness Index to the sustainability of energy.

Unlike Baxter (2012), Inshakov et al. (2019), Kabeyi and Olanrewaju (2022), Kapitonov et al. (2019), Kluczek et al. (2021), and Ratner et al. (2022), it was proved that digitalization of the energy economy based on advanced technologies of Industry 4.0 is not universal—it should be based on a unique organizational model for each category of countries, considering its peculiarities. The reasoning of this conclusion is based on the fundamental differences in the connection of energy sustainability with the readiness for the Frontier Technologies Index and with the government AI Readiness Index among countries of different categories.

Furthermore, this study contributes to the development of the methodology for monitoring the development of digital energetics based on the technologies of Industry 4.0. The methodological guidelines proposed in this study allow for the highly accurate quantification of the competitiveness (through the arithmetic mean of Industry 4.0 technologies, sustainability, and environmental friendliness of the energy economy) and efficiency (through the ratio of sustainability and environmental friendliness of the energy economy to Industry 4.0 technologies) of the digital energy economy.

This is of particular assistance in the "decade of action"—in the modern global context, where the implementation of SDG

7 is the priority of the development of the digital energy economy. Authors' guidelines have established a methodological basis for the measurement (evaluation formulas, regression model) and management (a new approach to the development of digital energetics based on the technologies of Industry 4.0) of the development of the digital energy economy to support the implementation of SDG 7.

CONCLUSION

Therefore, the global monitoring of the development of digital energetics based on the technologies of Industry 4.0 has shown that, with the current approach, the connection between digitalization and energy sustainability is weak. Although Industry 4.0 technologies generally determine the sustainability and environmental friendliness of the global energy economy by 67.78%, their relationship is contradictory at the level of certain categories of countries. In the top countries in terms of GDP per unit of energy use, Industry 4.0 technologies determine the sustainability and environmental friendliness of the energy economy by 78%–91%. In the top countries in terms of energy imports, this contribution is lower and amounts to 65%–67%, whereas in the top countries in terms of fuel exports, no positive contribution has been identified. This indicates significant differences in the development of digital energetics based on the technologies of Industry 4.0 (IoT, blockchain, robots, and AI) across the world.

In order to solve this problem, a new (alternative) approach to the development of digital energetics based on the technologies of Industry 4.0 is proposed, supporting the implementation of SDG 7 and assuming a focus on the digitalization of energy companies, the flexibility necessary to consider the characteristics of each category of countries, and the priority of the efficiency of the digital energy economy.

The theoretical significance of the study is to substantiate the primacy of energy sustainability over its digitalization. This fundamental conclusion allowed us to more accurately determine the order of development of digital energetics based on the technologies of Industry 4.0. The practical significance of the article is explained by the fact that the proposed new approach to the development of digital energetics based on the technologies of Industry 4.0 allows accelerating this development and increasing its efficiency, considering the peculiarities of countries of different categories.

AUTHOR CONTRIBUTIONS

VK, VL, NF, and EP contributed to the conception and design of the study. VK, VL, NF, and EP wrote sections of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

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