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Energy 6.0 In Industry 6.0: A Review Of Perspective Development

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Abstract

The shift in scientific and technological progress expectations from human-centric development (Industry 5.0) to achieving socially significant environmental, primarily climate, goals (Industry 6.0) requires ensuring a "seamless" Fourth Energy Transition – without restrictions on the access of all countries of the world to cheap energy, with a characteristic consistent reduction in greenhouse gas emissions and adherence to the climate agenda. Today, scientists have experience in studying the digital technologies of Industry 4.0 and forecasting their development to the level of 6.0. However, less attention is paid to the prospects for the formation of their Energy 6.0 platform. In this regard, the purpose of this Review is to accumulate the experience of research on Industry 6.0 for transfer to the energy sector based on the existing research groundwork for Energy 6.0. In this regard, the purpose of this Review is to analyze the content and structure of publications in the field of Energy 6.0. The main result of the research is a comprehensive overview of research papers in the field of Industry 5.0 digital technologies' evolution from the characteristic human-centricity to the nature-centricity inherent in Industry 6.0. Energy 6.0 is defined as an environmentally oriented technological platform for the energy sector in the second half of the 21st century, based on the expansion of digital technologies (emotional artificial intelligence, the Internet of Everything, digital triples and hyper-connected enterprises, predictive multi-industry analytics of Big Data and their quantum processing, computational experiments and virtualized assembly) in basic industries. The most promising areas of future research on Energy 6.0 are identified. These are the roles of Industry 6.0 technologies in a seamless Fourth Energy Transition: overcoming inequality in access to renewable energy among different countries, balancing the achievement of energy and climate goals for sustainable development, and further development of digital technologies beyond cyber-physical systems. They also include an analysis of Energy 6.0 place in the system of transition to Industry 6.0, as well as its consideration as a structural shift in the economy. The Review concludes that further research on Energy 6.0, focusing on digital technologies that accelerate the balance between achieving energy and climate Goals of Sustainable Development, the movement towards a "seamless" Fourth Energy Transition, and ESG investments, is relevant and significant for both theory and practice.

Keywords

Internet of Everything, Energy 6.0; Renewable Energy, Fourth Energy Transition, Industry 6.0, Zero Emissions, Digital Triplets, Emotional Artificial Intelligence.

Introduction

The advent of the Industry 6.0 era – a global technological platform connecting material and immaterial production – is expected in the second half of the 21st century. It is when machines are to move from independent learning (Industry 4.0) and imitating human behavior (Industry 5.0 – the near future of humanity) to the formation of a single resource with human labor, not so much increasing productivity as radically improving living conditions without reducing its quality (Pathak et al., 2023). Moreover, artificial intelligence, acquiring a human-centricity when the world is going to move from Industry 4.0 to 5.0, becomes an important tool for adapting to climate change and preventing cataclysms by modeling future climate scenarios (Reddy et al., 2024). The lack of an alternative to a compromise between the development of basic industries and digital technologies is due to the fact that the refusal to burn fossil fuels for the sake of zero greenhouse gas emissions would entail the death of a significant part of humanity (Zonova et al., 2024) and a rollback in the quality of life by 20-40 thousand years (Babkin et al., 2024a).

This fits the concept of a "seamless" Fourth Energy Transition (to renewable energy) within a few decades, in connection to important United Nations Sustainable Development Goals (UN SDG): 7 "Affordable and Clean Energy", 9 "Industry, Innovation and Infrastructure", 12 "Responsible Consumption and Production", Goal 13 "Climate Action" (The UN Sustainable Development Goals, 2025). That is if the upcoming Fifth Industrial Revolution (Industry 5.0) is expected to be human-centric in certain technologies (including in the context of providing society, including the "digital" one, with cheap energy (Energy 5.0) (Aleshina, 2024), then expectations from Industry 6.0 are shifting towards global nature-saving and restorative digital technologies (the Internet of Everything, the Artificial Intelligence of Things, digital twins and triplets, blockchain, online platforms, etc.) (Nozari, 2024). Thus, we are discussing the symbiosis of industrial technologies for material production and advanced digital technologies aimed at creating a clean global environment where human needs are fully satisfied (Isupova et al., 2023; Zlotnikov et al., 2024). It can be considered a continuation of ESG research (Gerasimova, 2023) in the context of a shift in generations of digital technologies (Momenta Ventures, 2025), which is particularly applicable to mining enterprises that are also involved in a deep digitalization process (Visnap et al., 2023).

Since the late 2000s, as digital technologies of Industry 4.0 have expanded, technologically advanced countries (the USA, Japan, China, etc.) have demonstrated accelerated growth in per capita GDP, gaining an advantage over countries in "catch-up development" (Figure 1).

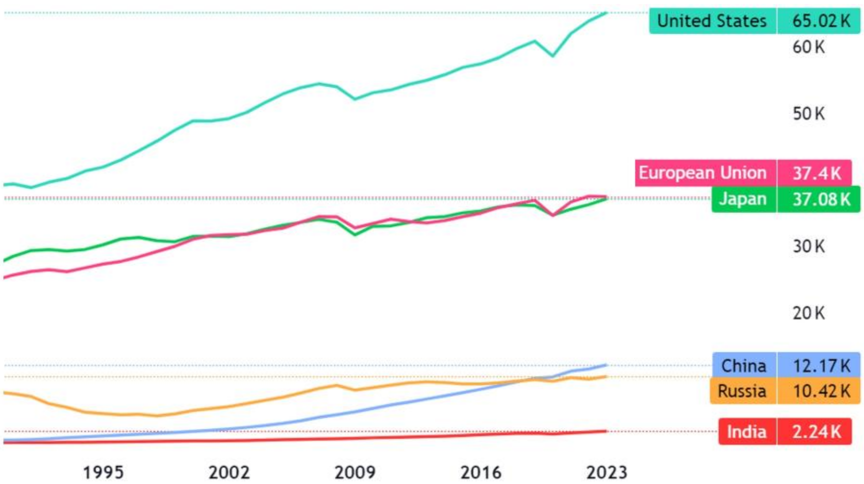

Fig. 1. GDP per capita, USD (Trading View, 2025)

The data in Figure 1 reflect the multiple superiority in per capita GDP of the countries leading the transition to Industry 4.0 over the countries whose economies are filled with Industry 2.0 and 3.0 technologies (such as India and Russia). A similar picture is observed in the participation of countries in the Fourth Energy Transition (Figures 2 and 3).

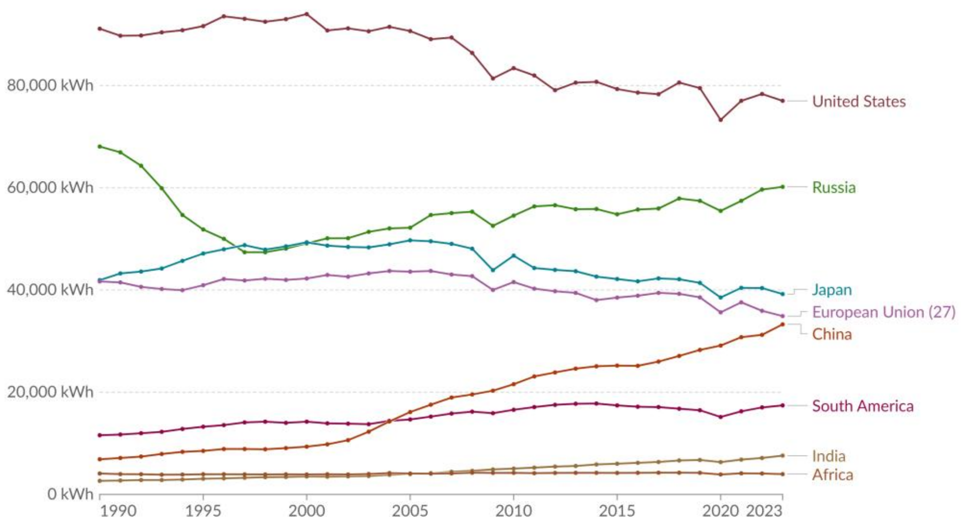

Fig. 2. Energy use per person (University of Oxford, 2025)

Figure 2 clearly shows the reduction in specific energy consumption in the USA, Japan, and the European Union, which began in the mid-2000s and was caused by the transition to digital energy-saving systems of Energy 4.0, which marked the Fourth Energy Transition. In turn, the countries of Africa and South America, as well as China, Russia, and India, are not reducing but increasing their energy consumption (Figure 3).

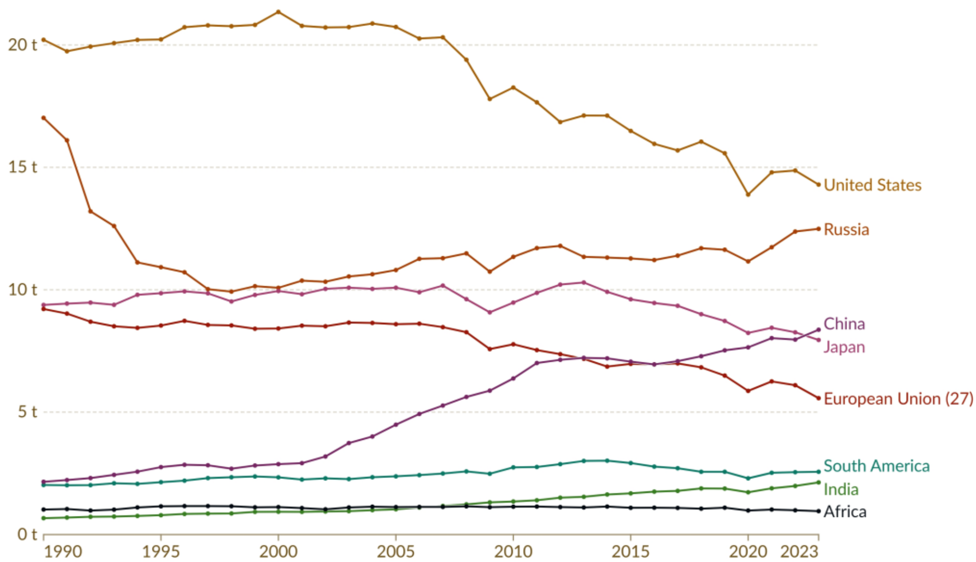

Fig. 3. Per capita CO_2 emissions from fossil fuels and industry (University of Oxford, 2025)

Figure 3 illustrates a decline in per capita CO_2 emissions since the late 2000s in countries leading the Fourth Energy Transition (the USA, Japan, and the EU) and countries actively transitioning to biofuels (South America) and solar energy (Africa). At the same time, in India, China, and Russia, the growth of CO_2 emissions has accelerated due to reliance on fossil fuels in industrial development.

Thus, the expansion of Industry 4.0 and its Energy 4.0 platform, accompanying the Fourth Energy Transition, is uneven across the world. Therefore, those countries that must increase their per capita GDP (Africa and South America, China, Russia) face the task of an accelerated transition to a human-centric Industry 5.0 and flexibly managed and energy-saving Energy 5.0. In turn, it can be expected that the transition to a nature-centric Industry 6.0 and climate-balanced Energy 6.0 will be headed by the countries that are current leaders in reducing CO_2 emissions and implementing digital technologies.

In relation to energy, Industry 6.0, as the most anticipated heritage of the already tangible human-centric Industry 5.0, is associated, firstly, with development not despite but thanks to the fight against greenhouse gas emissions (Skripko et al., 2024) and secondly, with fair access to energy (Hasan et al., 2024) and CO_2 emissions reducing (Shutko et al., 2024). It can be achieved due to the fact that the production systems of the future will consist of rapidly integrated human and artificial intelligence (Akhmatova, 2023), ecosystems for stimulating environmental and resource-saving innovations (Subbiah et al., 2024), embodied in Society 6.0 (in such sectors of the economy as intelligent healthcare, industrial production, transport, and agriculture) (Mahat et al., 2024). Thanks to them, the transition to Energy 6.0 can be associated with overcoming energy limitations in the development of both digital and financial technologies (Jain, 2024). For example, today, the accelerated introduction of 6G networks is being held back by their high energy intensity (Taneja et al., 2023), and the prospects for fossil energy sources are being discussed in accordance with the suspension in the decarbonization of the economy (Shuvalova, 2024).

It is expected that business in the era of Industry 6.0 will be the result of integrating production, logistics, and finance on the one hand and environmental protection and healthcare on the other (Nozari, 2024). The financial integration of Industry 6.0 and society (Society 6.0) is also considered when investment and loan platforms facilitate the integration of man, machine, and environment on the "for all" principle (Jain et al., 2024). In this context, Industry 6.0 acts as a visible evolution "crown" of the paradigm of society's technological development during the expansion of quantum computing and neural integration, advanced biotechnology, and decentralized autonomous production systems – Figure 4 (Almusaed et al., 2023).

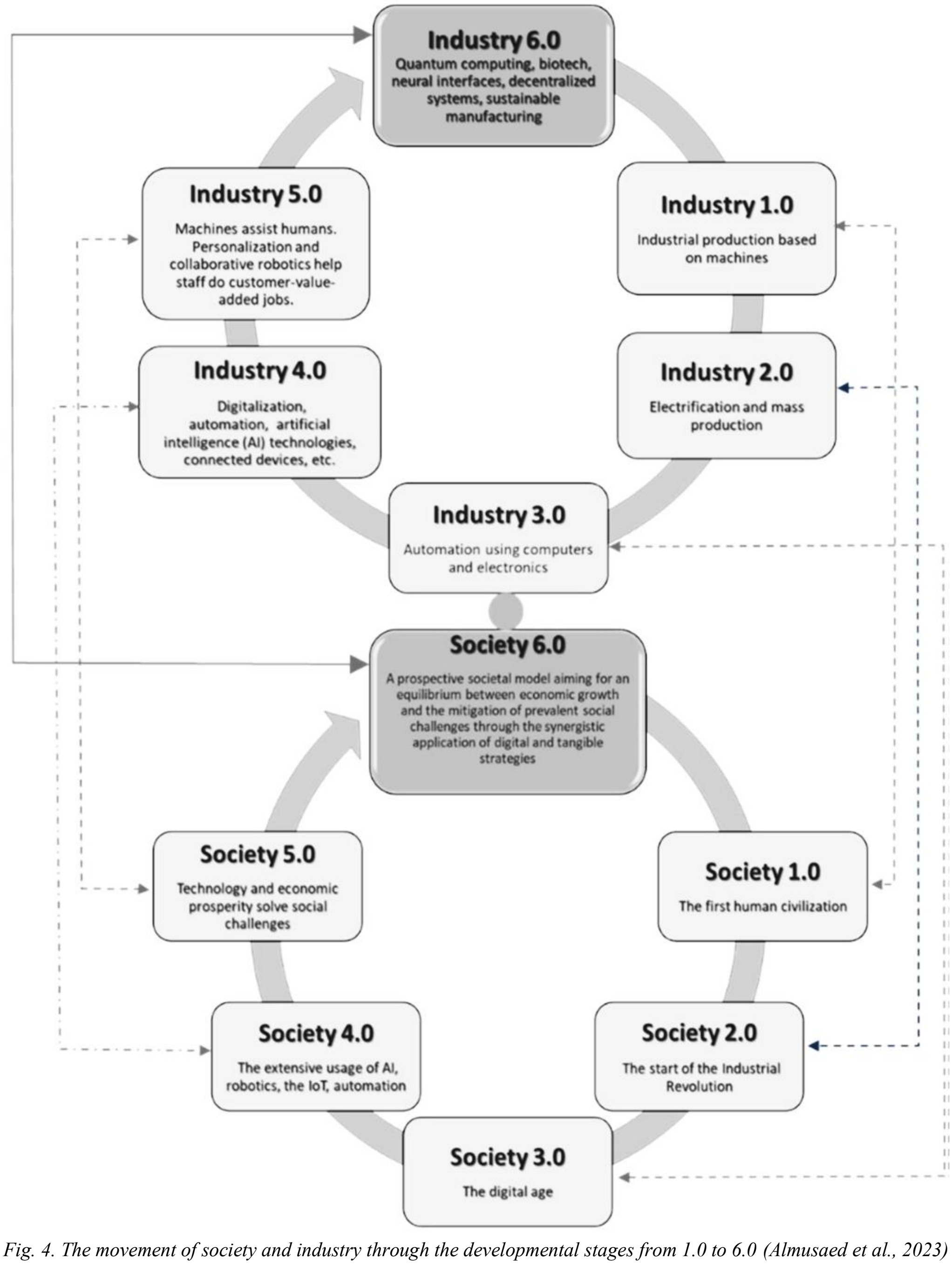

Fig. 4. The movement of society and industry through the developmental stages from 1.0 to 6.0 (Almusaed et al., 2023)

The concept of replacing human-centric Industry 5.0 with nature-centric Industry 6.0 can be considered the synergy of smart sensors, cloud computing, and the Artificial Intelligence of Things, from which deep optimization of production and consumption of material goods and energy is expected (Eswaran et al., 2024). This goal should also be served by the expansion of edge computing (data processing close to the source), connected with digital triples of processes in entire industries, inheriting the virtualization of individual processes in enterprises (Shafik, 2024). It also correlates to the rising voice of developing countries with the demand for equality in access to affordable energy (Meena et al., 29), which should be reflected in the balance of traditional and alternative energy carriers and technologies, reduction of greenhouse gas emissions and their capture (Maddikunta et al., 2024).

The evolution of Digital Industry 4.0 to Cyber-Physical 5.0 (characterized by Smart Cities and Enterprises) extends to Industry 6.0. It is worth mentioning climate stability systems (Sharma et al., 2024), which are based on human-machine cooperation (Kumar et al., 2024) and technological convergence for training by some deeply digitalized industries, aiming to achieve the UN SDGs (Stankosky, 2019). This can be seen as a synergy of artificial intelligence and machine learning, which is considered the paradigm of Industry 6.0, characterized by a radically higher level of optimization in the production and consumption of resources (Kumaneeva et al., 2023), including energy (Pattanaik et al., 2024). It gives a chance to burn fossil energy carriers if human and machine creativity is combined in digital triplets and added intelligence (Yadav et al., 2024).

Thus, the research on the place of Energy in Industry 6.0 is intended not only to advance the analysis of the "seamless" energy transition. It is also an intention to consider the possibilities of achieving the UN SDGs without impairing the rights of developing countries to access energy in the future.

The goal of the research is to structure and qualitatively investigate publications devoted to energy technological platforms in the long-term future (Energy 6.0), the achievement of UN SDG in terms of energy availability, infrastructure development, and the fight against climate change, the balance of non-renewable and renewable energy carriers in achieving the imperative of decreasing CO_2 emissions to zero.

The context of the Review is an objective selection and constructive criticism of works, the use of which by various researchers in compiling bibliographic lists and determining the state-of-the-art will help to identify the trends of future research into nature-centric technology platforms in basic sectors of the economy, such as Energy 6.0.

To achieve this goal, we set the following tasks for this Review:

- description of the most promising areas of research in Industry and Energy 6.0
- decomposing the researchers' interest in the problems of comprehensive decision-making concerning the approach to zero greenhouse gas emissions and ensuring fair access to energy for future generations;
- identifying the principles and conditions for accelerating the diffusion of digital technologies evolving from Industry 5.0 to 6.0 in basic industries, taking into account the "seamless" transition to renewable energy.

In accordance with these tasks, the Review structure includes the following sections. Section 1, Introduction, reflects the relevance of the study of the transition processes to Industry 6.0, their causality, and the main vectors of their deployment. Section 2, Methodology, contains the goal and tasks, structure of research, and criteria of papers' selection. Section 3, Industry 6.0 Review, reflects an analysis of papers devoted to the transition from production-centric Industry 4.0 to cyber-physical Industry 5.0 and further – to nature-centric Industry 6.0. Section 4, Energy 6.0 in the Transition to Industry 6.0, examines approaches to the analyses of the prospects for technological modernization of energy production, distribution, and consumption based on advanced digital technologies in the context of global incentives to move toward zero emissions and in accordance with the imperative of fair access to energy in developing countries. Section 5, Energy 6.0 as a Structural Shift in the Economy, is devoted to expected changes in the proportions of involvement of digital and physical means of production and redistribution of capital sources in the context of the Fourth Energy Transition and a change in the vectors of state energy policy. Section 6, Discussion, shows the main achievements of research, its limitations, and the ways to overcome them. Section 7, Policy Implications, reflects the Authors' proposals to accelerate the transition to nature-centric Energy 6.0. Section 8, Conclusions and Prospects, contains the summary of provisions.

Methodology

The following research methods were used in this Review: continuous bibliographic search; typological method for dividing publications devoted to the Fourth, Fifth, and Sixth Industrial Revolutions; analytical and synthetic method for identifying significant elements of a bibliographic query, their analysis, and terminological processing; deductive method for constructing theoretical conclusions and provisions based on specific facts.

For sample selection in the literature review, the following sequence of actions was employed: identification (defining criteria for relevant publications and excluding non-relevant ones), screening the bibliometric bases and quality assessments, and disclosure of the list of research items included in the Review. Free software Zotero 7.0 was used to manage references.

We used the following bibliometric bases: Clarivate, Elsevier Scopus, Google Scholar, PubMed, ScienceDirect, SpringerLink, and GeoRef in our research.

The keywords were (in alphabetical order): Artificial Intelligence; Digital Triplets; the Emotional Internet of Everything; Energy 6.0; Fourth Energy Transition; Industry 6.0; Renewable Energy; Sustainable Development Goals; Zero Emissions.

Figure 5 reflects the separation of research papers observed in this research by years.

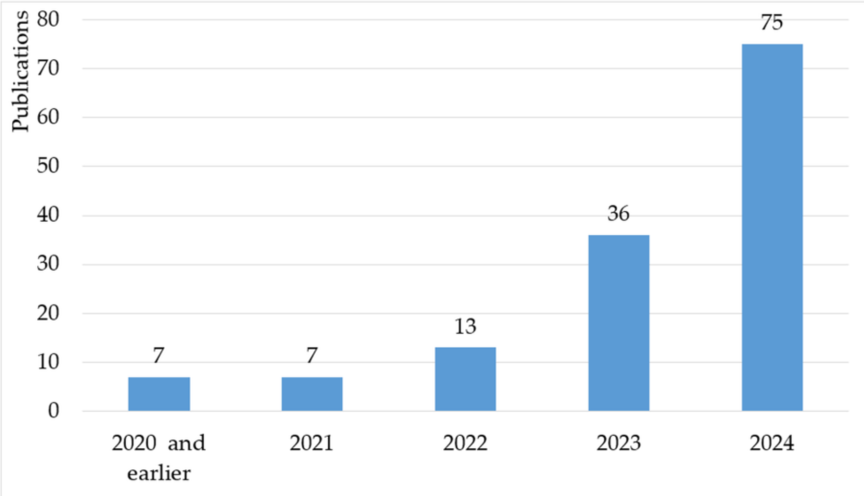

Fig. 5. The separation of Review sources by years

Figure 5 shows that the majority of observed publications fall within the 2023-2024 period (111 out of 138). This indicates the initial stage of research into Energy 6.0 as an industry platform for Industry 6.0 – a fairly controversial area of scientific thought, as confirmed by the large number of articles devoted to this topic (Figure 6).

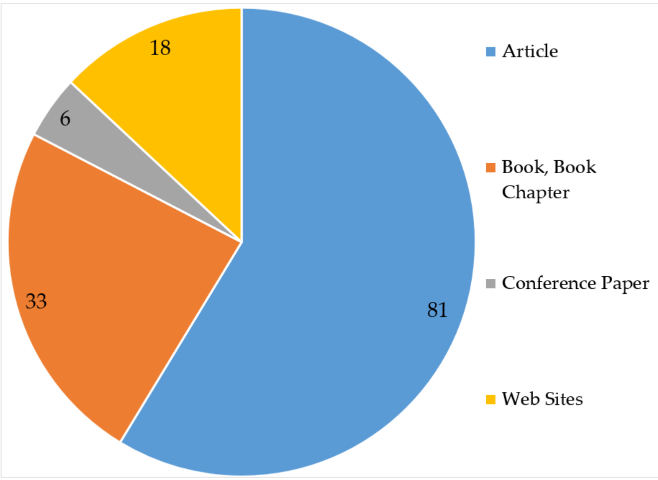

Fig. 6. The separation of papers observed in the Review by type

It follows from Figure 6 that scientific articles and monographs (chapters), which create a significant reserve for future research on Energy 6.0, represent the majority of publications. The separation of papers observed in this Review by keywords is reflected in Figure 7.

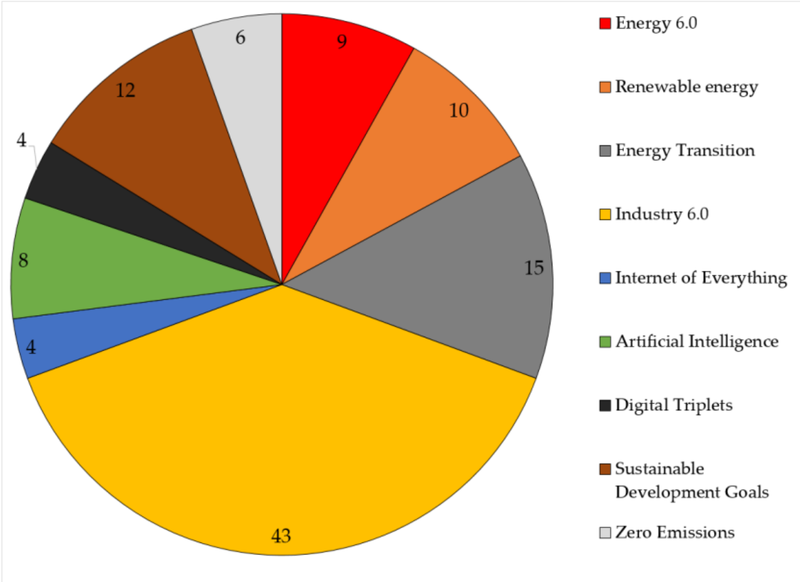

Fig. 7. The separation of areas of the Review by keywords

As can be seen from Figure 7, the greatest interest of researchers is concentrated in the area of research into the transition to Industry 6.0, with the second place taken by issues related to the energy transition (mainly its fourth stage) and renewable energy development. All these are the backgrounds of Energy 6.0, so its research looks promising in the coming years.

The results of the bibliographic search were considered representative after checking scientific publications in several databases and excluding duplicates. Preference was given to publications of the Article and Review types, regardless of the number of citations, as well as to materials from international conferences. A graphical representation of the relationships between the keywords used in the bibliographic search and those more widely represented in the publications reviewed is shown in Figure 8.

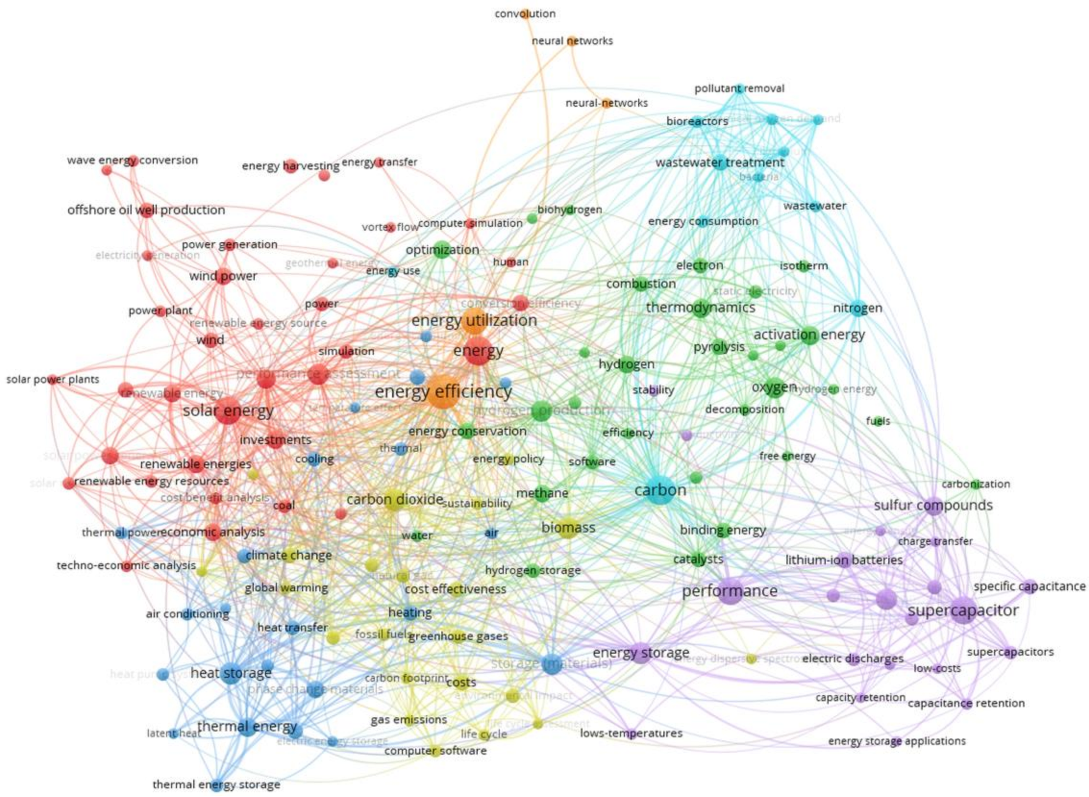

Fig. 8. VOSviewer map of keyword relationships in articles used in the Review, based on the search results in Scopus (VOSviewer, 2025)

The map of relationships between keywords in reviewed articles (Figure 8) made it possible to identify areas of maximum research interest in the field of Energy 6.0, which allowed drawing the following conclusions.

First, there is the greatest strength of relationship between such clusters of research interest as:

1) Orange cluster: energy efficiency, energy utilization, transfer and conversion, neural networks and computer simulation; red cluster: renewable energy, solar energy, wind power, investments, economic analysis; yellow cluster: carbon dioxide, biomass, greenhouse gases, fossil fuels; dark blue cluster: thermal energy, heat storage, heat transfer, climate change.

2) Violet cluster: performance, supercapacitor, lithium-ion batteries, energy storage, low-costs; green cluster: methane, hydrogen, oxygen, energy conservation, thermodynamics, combustion; light blue cluster: carbon, nitrogen, pollutant removal, wastewater treatment, energy consumption.

Second, at the intersection of these clusters of relationships, such enlarged areas of interest of researchers of the Energy 6.0 problem as the transition to renewable energy sources, energy efficiency and productivity, and climate change were identified. This served to highlight the Review sections, such as "Energy 6.0 in the Transition to Industry 6.0" and "Energy 6.0 as a Structural Shift in the Economy".

Third, we foresee an increase in interest in research at the intersection of blue, green, and violet clusters, which will result in new publications in the field of energy storage from non-renewable sources to compensate for fluctuations in the load on renewable sources, as research in the field of nature-centric Energy 6.0 develops.

Overall, the results of the Review indicate that there is growing interest among researchers in analyzing the prospects and limitations of nature-centric Energy 6.0 in relation to the UN SDGs.

Industry 6.0 Overview

The comprehensive definition of Industry 6.0, along with a global platform for the development of material production at a higher level of digitalization and with environmental improvement (the principle of nature-centrism), includes a new industrial ecosystem based on the involvement of emotional machine intelligence, the Internet of Everything, etc. (Industry 5.0) (Reddy et al., 2024) in the full-scale activities of the entire society to overcome environmental problems and future limitations (climate, water resources, pollutants, access to energy). M. Murugan and M.N. Prabadevi assign a key role in this process to the expansion of the emotional intelligence of machines – Figure 9.

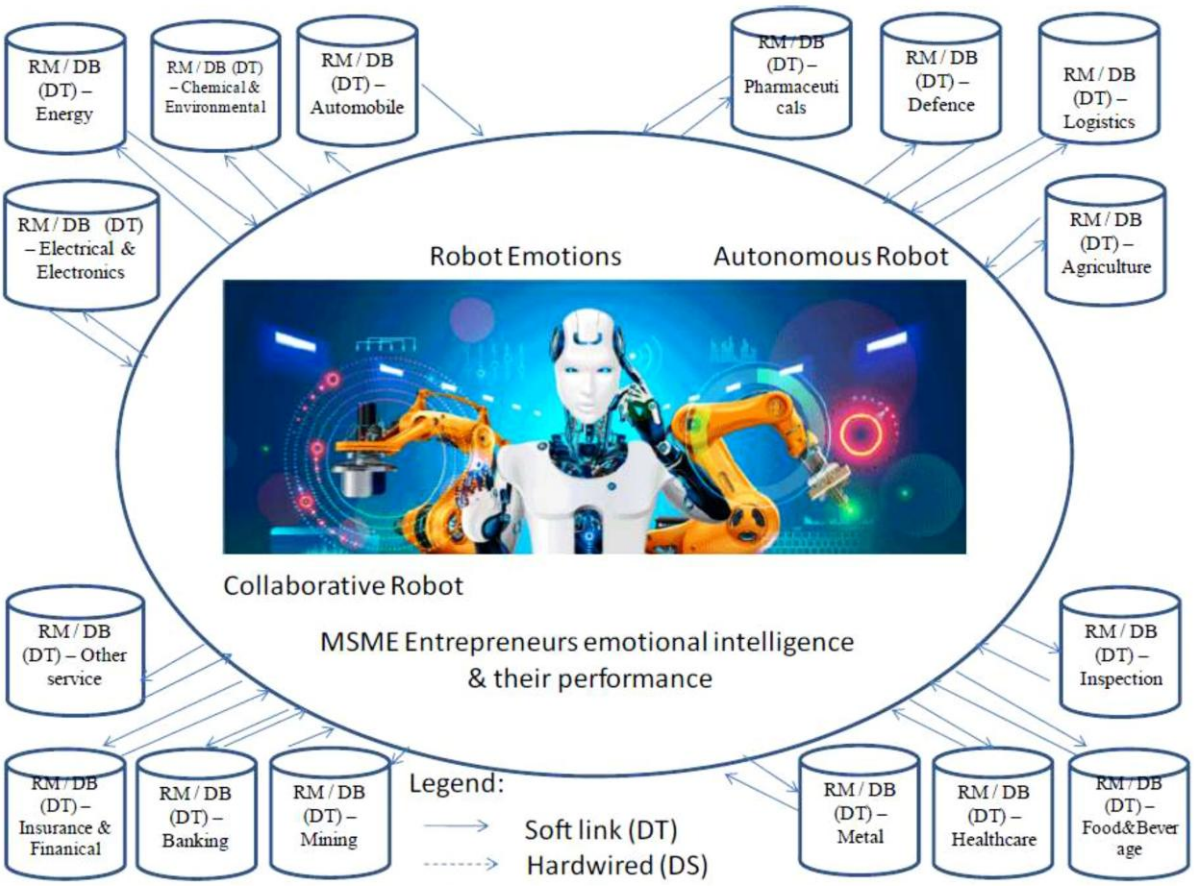

Fig. 9. Components of emotional intelligence development in Industry 6.0 (Murugan et al., 2023)

Other researchers go further in their analysis of the differences between Industry 6.0 and 5.0 and highlight emotional ("parallel") artificial intelligence (successor to the collaborative one, characteristic of Industry 5.0), artificial communities (a new type of work collectives) – successors to collaborative robots, computational experiments and parallel execution instead of virtual 3D modeling, and cyber-physical-social systems (Wang et al., 2023). This "core" of the Industry 6.0 platform is supplemented by such technologies as information flow management beyond planetary boundaries, ultra-reliable ("antifragile") production, virtualized assembly for verification of usefulness for the consumer, and information flows in hyper-connected enterprises and their quantum processing, which makes it possible to expand the boundaries of planning between enterprises (Das et al., 2023).

Such systems (cyber-physical-social ones) combine cognitive, polymodal information, mechatronic, and telecommunication components. Examples include energy production, distribution, and consumption systems that integrate real and virtual power plants connected to a network of smart homes and factories, which are already being formed in cities such as Singapore and Masdar (UAE).

As the next stage of production evolution, Industry 6.0 means creating a more reliable and sustainable production environment based on the Industrial Internet of Things (Damaševičius et al., 2023) as the basis for intelligent and interconnected production, in which there will be no disruptions in supply chains, including energy (Singh et al., 2024). The innovative and social basis of Industry 6.0 is formed within the framework of the Quintuple Innovation Helix, in which the role of "geniuses" in the formation of a technologically advanced society is increasing (Carayannis et al., 2024).

As for the "antifragile" production as a "spillover" of Industry 6.0, the key to it is seen as data flows between several administrative domains in hyper-connected industries, forming multifaceted, complex, and dynamic industrial supply chains (Yadav et al., 2022). Some authors directly talk about the metaverse of Industry 6.0, in which emotional artificial intelligence can be transferred to a robot by exchanging human behavior with devices with a high sampling frequency (Heilala et al., 2023). In such a digital metaverse, things become intelligent, functioning jointly with people and autonomous platforms for the integration of various areas of business and industry, including the production and consumption of energy (Industry 6.0 Technology, Practices, Challenges, and Applications, 2024), that is, for a full-fledged convergence of intelligent systems of human society and interactively interacting machines (Reddy et al., 2024).

This convergence is viewed as the future intersection of Big Data analytics, the Industrial Internet of Things, and machine emotional intelligence systems (Industry 5.0) (Muravskyi et al., 2024). That takes the synergy of machines and people in Industry 6.0 to a new level, allowing for the discovery of fundamentally new solutions to the problems of lean manufacturing (Ezdina, 2024) and environmental protection (Fernández-Miguel et al., 2024). Autonomous optimization of production processes by interacting machines with emotional artificial intelligence can radically transform the technological landscape of the entire industry (Vijay et al., 2024), which reflects the diversity of key technologies in Industry 6.0 (Figure 10).

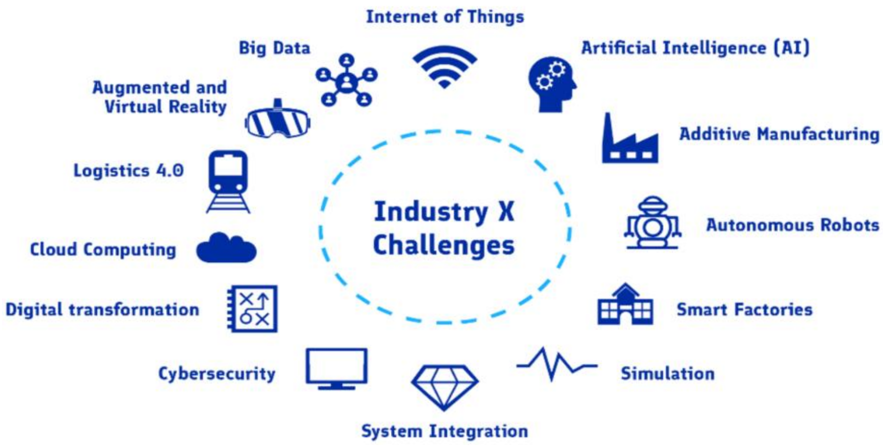

Fig. 10. Key Technologies in the Transition from Industry 4.0 to Industry 6.0 (Annanperä et al., 2021)

A significant difference between Industry 6.0 and 5.0 lies in the shift in the paradigm of industrial technological development from mass personalization of engineering and management decisions to the autonomous creation of fully integrated intelligent systems utilizing blockchain technology and cloud solutions (Kayikci et al., 2024). Industry 6.0 is also credited with new advancements in material production – intelligent and digital energy, as well as intelligent and digital water (Chavan et al., 2024).

Such digital products of basic industries are the result of the formation of a fully automated intelligent production system, autonomously designing and manufacturing a product using a heterogeneous swarm of robotic manipulators, 3D printers, etc. (Panneerselvam, 2023), each of which is equipped with individual emotional artificial intelligence, integrated into large language models (et al., 2024). Thanks to them, today we already talk about the receptors and emotions of machines, in many ways similar to human ones, from which "built-in" care for the environment and climate from basic industries (transport (Krishnamurthy et al., 2024), energy (Duggal et al., 2022)) are expected. In particular, energy savings are possible due to the optimization of mineral raw material extraction and processing in intelligent Factories 6.0 (Nozari et al., 2024).

Separately, it is necessary to note the change in the role of human capital in the transition to Industry 6.0, which will be shaped by new forms of cooperation between modern educational institutions and leading industry organizations, characterized by a completely digital nature (Goel, 2024). In turn, the requirements for employees will shift towards avoiding technological failures of cyber-physical systems (Tas, 2024), including at the stage of programming emotional artificial intelligence systems (Minz, 2024), for example, when using axiomatic design (Heilala et al., 2024).

The connections between universities and industrial companies, which in the Quintuple Innovation Helix system are oriented towards taking into account the needs of society for sustainable development and a "clean" living environment, are transformed in Industry 6.0 into "Quintuple Innovation Helix plus Artificial Intelligence", which balances human-centric and nature-centric paradigms of development of basic industries (Carayannis et al., 2024). In the area of distribution of manufactured products, a transition to Marketing 6.0 is expected with its characteristic unprecedented customer focus, achieved by changing the marketing landscape through the Artificial Intelligence of Things (Vetrivel et al., 2024).

Generally, the shift in the technological basis of material production as it progresses through industrial revolutions is reflected in Figure 11.

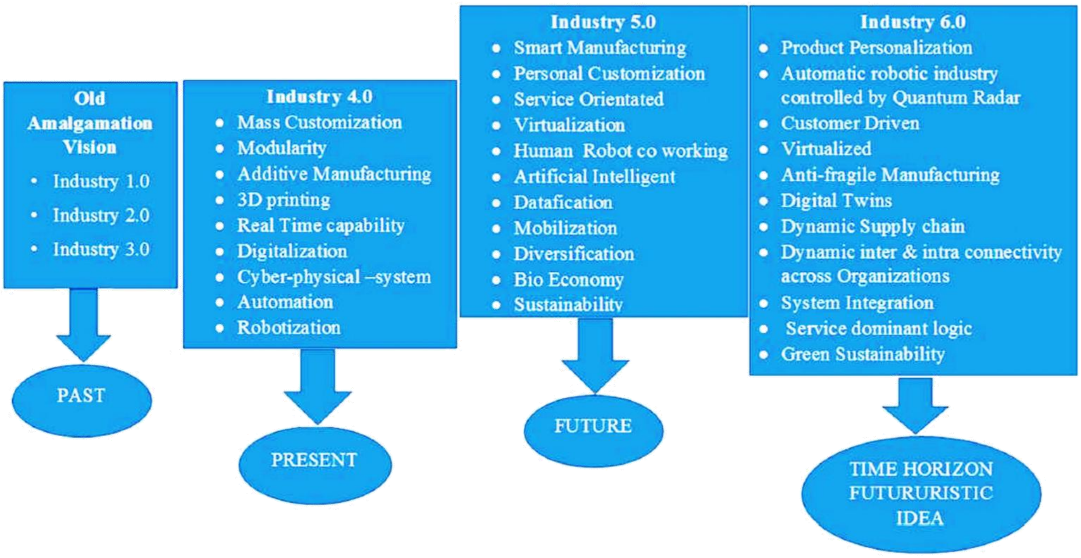

Fig. 11. The vision of transformation from Industry 1.0 to Industry 6.0 (Chourasia et al., 2022)

Figure 11 illustrates the transformation of key technologies from Industry 5.0 to 6.0, including artificial intelligence, data analytics, blockchain, and robotic process automation (Kumari et al., 2024). Ultimately, it is recognized that the goals of the Sixth Industrial Revolution can be achieved by combining artificial intelligence, satellite navigation, industrial robotics, cloud analysis, machine learning and intelligence, and 3D printing. In addition, a sign of the transition from Industry 4.0 to 6.0 can be considered the development of quantum computing and quantum control (Umbrello, 2024). It is expected that by 2050, these technologies will reach the point of synergy (Tyagi et al., 2024).

In general, the image of the sectors most susceptible to the transition to Industry 6.0 is presented in Figure 12.

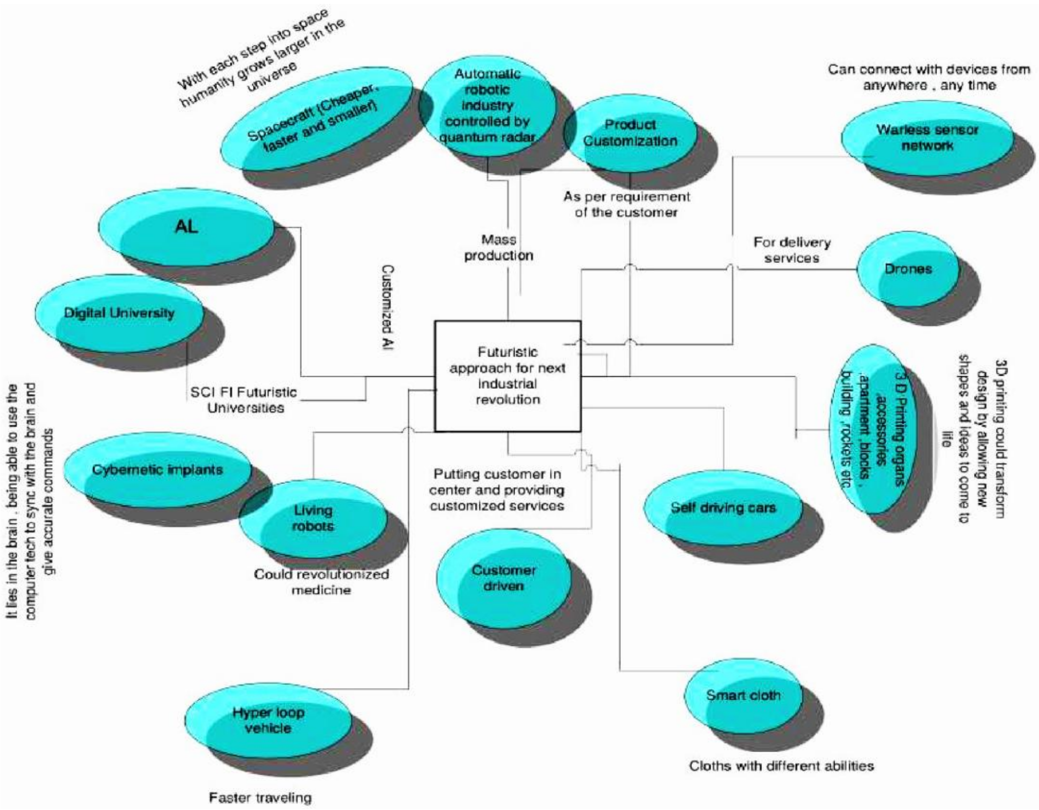

Fig. 12. Vision for upcoming industrial revolution (6.0) (Tyagi et al., 2024)

The interaction of Industry 6.0 technologies will occur in two directions. The first is human control of machines through the integration of advanced digital system interfaces, such as predictive artificial intelligence, the Internet of Everything, and machine learning (Chourasia et al., 2022). The second direction is to ensure progress in digital technologies, facilitating the achievement of sustainable development goals at a new level of synergy between digital and industrial technologies (Almusaed et al., 2023). Specifically, one can expect an "intersection" of such technologies as artificial intelligence and Big Data analytics, the Internet of Everything and machine vision, bioinformatics, and 3D printing (Duggal et al., 2022) in the management of complexes of renewable and traditional energy facilities (smart virtual generators and power plants, the Internet of Energy), as well as in the creation of new solar and wind energy systems, and the disposal of waste from thermal energy.

We can highlight its convergent essence as a result of the deep integration and mutual penetration of ideas of millions of scientific minds. The main synergistic result of such convergence can be imagined as control by the human mind of the entire variety of operations performed by smart robots on a planetary scale. In industry, such synergy leads to the formation of "antifragile" and environmentally friendly production, characterized by customer focus at the level of public needs (such as the fight against climate change), super-connected industries with dynamic supply chains (Muravskyi et al., 2024).

Energy 6.0 in the Transition to Industry 6.0

As we noted earlier, Industry 6.0 is characterized by a high level of attention to the environmental problems of modern society in the context of the desire of advanced countries to move closer to CO_2-zero emissions and climate neutrality – not only by redistributing the focus of investors' interests but also new technologies (Smajdorová, 2024). This actually means a modification of the understanding of the Fourth Energy Transition, when the G20 countries are concerned about the growth of national wealth balanced with growing energy demand worldwide and fair access to it from developing countries (Xu et al., 2021).

Despite the fact that today there are only a few definitions of Energy 6.0 – as the Industry 6.0 platform (Babkin et al., 2024b), as a trend in the development of basic industries, in particular, energy, in the context of the convergence of information, cognitive and production technologies (Kumar et al.,2024), as well as a strategy for the development of energy as the main polluter of the environment in the context of awareness of climate problems by national states and companies (Zonova et al., 2024), it is possible to identify a common basis for these concepts. It represents an imperative to reduce the environmental burden of the digital energy platform, which is formed by Industry 6.0 technologies, from which an initial orientation in its development is expected towards the environmental UN SDGs.

This understanding of Energy 6.0 is closely linked to existing forecasts, according to which the share of wind and solar energy will reach 75% in advanced countries by 2050, while up to 20% of it will be used to produce green hydrogen (Figure 13).

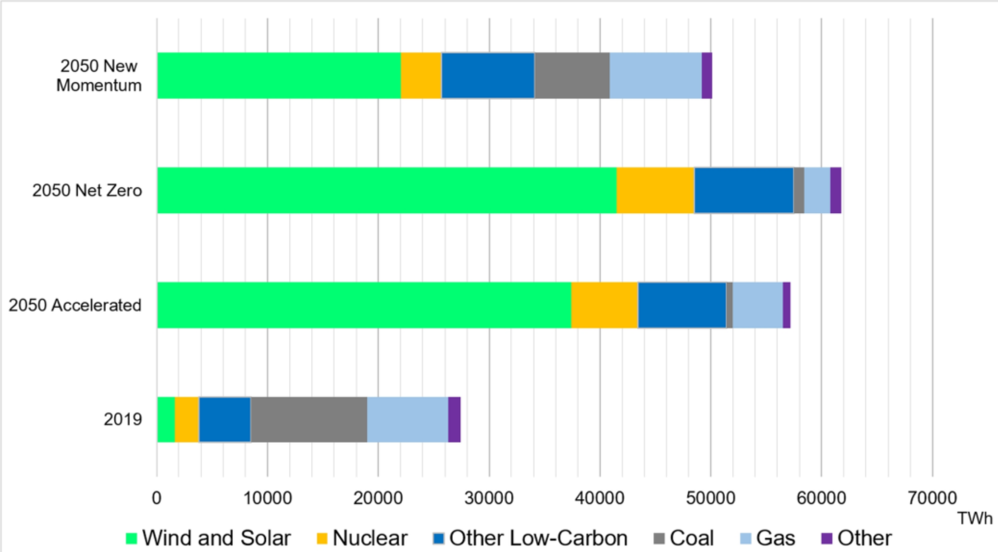

Fig. 13. Energy production scenarios by energy source according to BP Energy Outlook to 2050 (BP, 2023)

In contrast to the Net Zero scenario from BP Energy Outlook, Bloomberg NEF New Energy Outlook gives a slightly different forecast in the baseline scenario of energy production by 2050 – up to 30% of generation through the use of fossil hydrocarbons (both the combustion of coal and natural gas and the production of brown and blue hydrogen) – Figure 14.

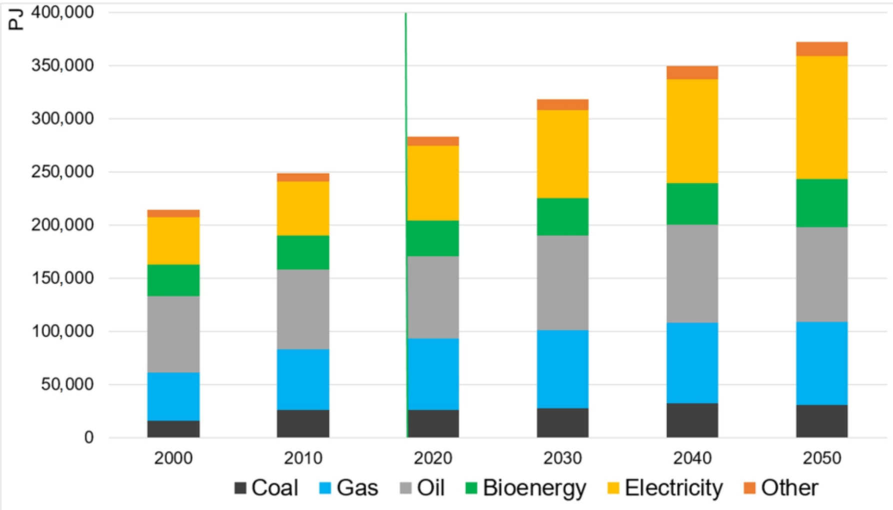

Fig. 14. Total useful energy by source (Bloomberg NEF, 2020)

However, achieving carbon neutrality by 2050 seems possible due to the improvement of digital technologies of Industry 6.0, which allows coordination of the extraction of fossil fuels and the production of green energy systems, electricity generation, and its consumption in such a way that the peak of emissions occurs as early as possible, and the rate of CO_2 utilization accelerates (BP, 2023). If the redistribution of investments between the production of energy from fossil and alternative sources (Economic Transition Scenario) allows for achieving the climate target of 2.6 °C. In that case, the driver of technological development (to the level of Industry 6.0) in the Net Zero scenario is the target of 1.750 °C (Figure 15).

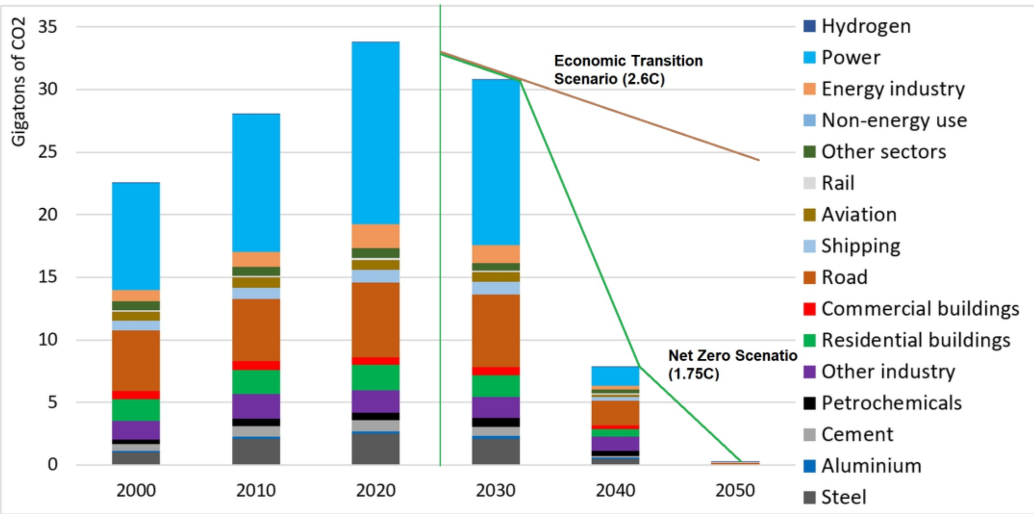

Fig. 15. Energy-related emissions – Economic Transition and Net Zero Scenarios (Bloomberg NEF, 2023)

Experience shows that economic growth in developing countries accelerates the consumption of fossil fuels (Pasupuleti, 2024). At the same time, digital technologies of smart energy networks, a combination of different sources of renewable energy at the platform of Energy 6.0 – all these give a chance to comprehensively solve the problems of reducing burning fossil fuels on air and meeting the growing energy needs of modern society (Otim et al., 2023). An important role is played by artificial intelligence, which, as it becomes generative, creates an environmental feature for the Energy 5.0 platform, distinguishing the sixth generation of power production from the fifth (Niesenbaum, 2024). The adaptability of modern energy, developing on the Energy 4.0 platform and preparing for the move to the Energy 5.0 platform, has created the ground for many companies to adopt climate neutrality and collaborative intelligent management in the face of climate change and environmental crises, which will be implemented on the Energy 6.0 platform (Maleki Nia, 2024).

Despite the fact that Industry 6.0 is the energy platform of the future (the second half of the 21st century), today, we can already observe the development of advanced digital technologies that reduce the impact of energy on the environment (Zomerdijk et al., 2024):

- additive manufacturing, including 3D printing, in power electronics production for energy management systems, which allows decreasing power consumption at large enterprises. At present, it is being developed and implemented by Toyota (Toyota Research Institute of North America), Oak Ridge National Laboratory, Virginia Tech (Lopera et al., 2021) ;
- the Internet of Energy for smart buildings with unprecedented levels of energy savings (Shahinzadeh et al., 2019), which platforms (SoM2M#IoT, SODATA#Viz, SoSECURE#IoT, SoFLEET) have been developed by Synox (Synox, 2025).

Industry 6.0, characterized by interactive customer-oriented production and a dynamic supply chain, when applied to Energy 6.0, allows talking about the use of alien resources, robotic production complexes (Tyulenev et al., 2023; Velikanov et al., 2024), anatomical improvements of workers (Sadovets et al., 2023; Chen et al., 2024) and quantum control (Mancini et al., 2004).

Evolution of Energy 5.0 to 6.0 should not be equated with the rejection of the use of fossil fuels since only the development of cyber-social systems in the extractive sector (Zhironkin et al., 2024a) can ensure its fair distribution between developing and developed countries in the coming decades (Zhironkin et al., 2024b).

At the same time, developing countries have technological, social, and economic problems that hinder the transition to Energy 5.0 and are unacceptable for Industry 6.0 (Semyachkov, 2019):

- lag in the development of educational systems and insufficient level of digital competencies of workers, as well as a high level of cybercrime;
- critical dependence on cheap energy and fossil fuels against the background of society's tolerance of environmental problems;
- insufficient national investment resources for the mass implementation of digital industrial technologies, along with political risks that can be unacceptable for transnational companies.

The global market for Industry 4.0 technologies, which are the basis for Energy 5.0 and 6.0, is projected to grow from $99.5 billion to $359.1 billion in 2024-2032 (Industry 4.0 Market, 2025); the required investment volumes in renewable energy by 2030 are expected to be at the level of $280 billion per year (IRENA and CPI, 2023). At the same time, the main risks for investors in Energy 6.0 technologies (high prices for renewable energy and insufficient global demand for it, unacceptable levels of cybersecurity risks, and low attractiveness of investments without government incentives) are the most problematic for developing countries.

The prospects for fossil fuels in the transition to Energy 6.0 depend on the development of integration of mineral resources production technologies with advanced digital ones (Nikitenko et al., 2023), which makes progress aimed at the environmental needs of society truly sustainable and in line with the UN SDG (Sayigh, 2024).

As for the problems associated with the transition to Energy 6.0 in the future, they are already visible today as digital technologies of Industry 4.0 expand and the economies of leading countries prepare for Industry 5.0, which emphasizes human-centeredness. In particular, such social problems as neo-Luddism (resistance to the replacement of workers by digital systems with artificial intelligence, primarily in the service sector) (Tunç et al., 2023), economic problems of slowing growth as we move away from fossil fuels and energy prices rise (De Cian et al., 2016), technological problems of the emergence of cybersecurity risks in the energy sector and their growth to national security threats (Venkatachary et al., 2017).

At the same time, the nature-centric character of the digital platform Energy 6.0 predetermines the emergence of specific problems of transition to it:

- capital deficit and refusal of a number of countries in Africa, Southeast Asia, and South America to increase investments in the development of digital green energy systems due to the critical dependence of economic growth on the use of cheap fossil energy sources;
- maintaining the important social and political significance of burning fossil fuels to produce energy in order to combat poverty for countries with per capita GDP below 5,000 USD;
- the impossibility of achieving zero CO_2 emissions in the presence of a large number of countries catching up in industrial and technological development – outsiders of the Fourth Technological Transition, despite the efforts of leading countries to switch to renewable energy sources;
- the lack of unified energy and economic strategies for macro-regions and entire continents that equalize the capabilities and goals of individual countries in the development of a digital energy platform.

Energy 6.0 as a Structural Shift in the Economy

In the near future, the structural shift initiated by Industry 6.0 will be associated with customer-oriented, virtualized, and "antifragile" production (Žižek et al., 2021). In the energy sector, antifragility is associated with uninterrupted access to energy at the moment and its deficit-free supply in the long-term future (Ustyuzhanina et al., 2024).

In addition to the expected reduction of CO2 emissions in line with the Climate Action UN SDG, the transition to Energy 6.0 is expected to provide future solutions to social and economic problems, such as avoiding unemployment due to the reduction of traditional energy production, accelerating economic growth in developing countries and reducing poverty (IEA, 2019).

The structural transformation of the economy in the transition to Energy 5.0 and further – 6.0 is due to the growth of employment and investment in the green (clean) energy sector, the driver of which, in turn, is the reduction in specific costs under the influence of the expansion of ultra-high-performance digital technologies of Industry 5.0 and 6.0 – people and nature-oriented. Since the late 2010s, the transition to Energy 4.0 has entailed an excess of investment and employment in renewable energy over non-renewable energy (Figure 16), led by China and India (Figure 17).

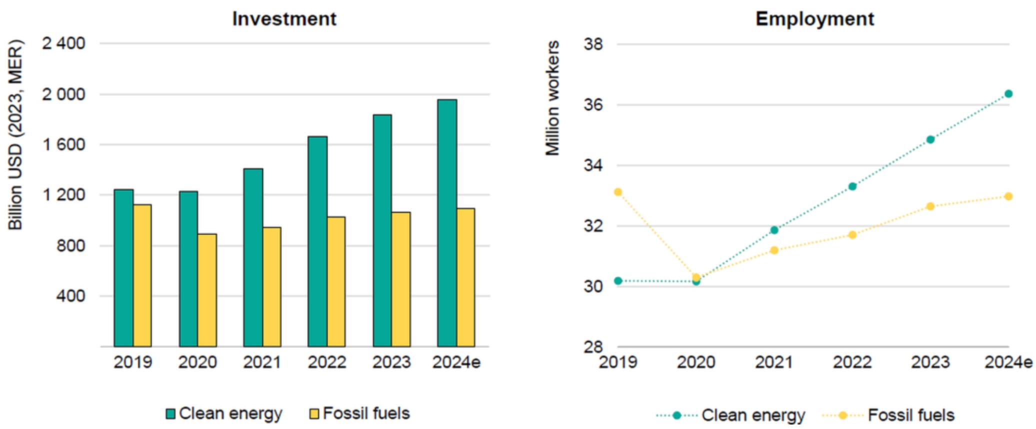

Fig. 16. Dynamics of global investment and employment in traditional and renewable energy (IEA, 2024)

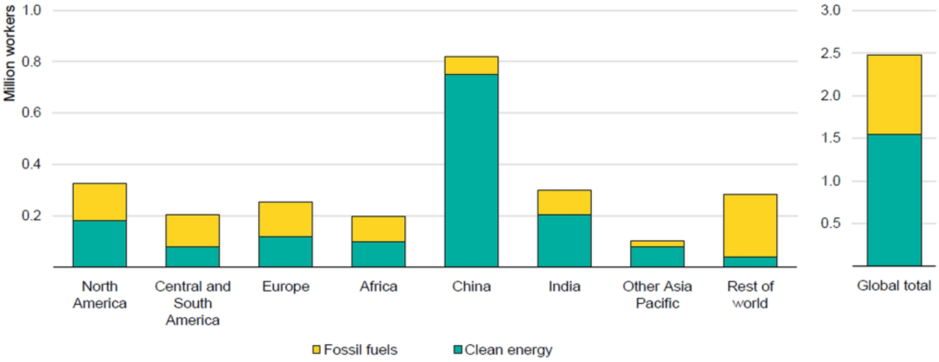

Fig. 17. Global structure of employment in the energy sector, 2022-2023 IEA (IEA, 2024)

The accelerated growth of investment in renewable energy, accumulated over recent years of the expansion of Energy 4.0, should form the basis for increasing employment by 2050 – in the era of Energy 6.0 development (Figure 18).

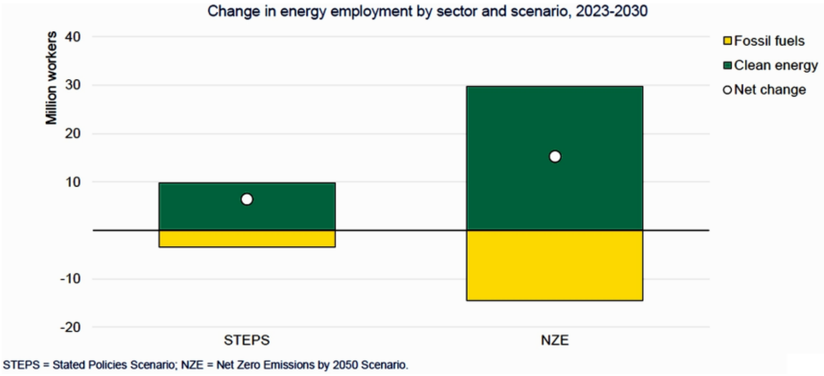

Fig. 18. Green energy employment growth by 2030 under stated policy and net zero emissions by 2050 scenarios (IEA, 2024)

In turn, the impact of the economic growth forecast for 2030 by the International Renewable Energy Agency (IRENA) provides for a significant acceleration for countries promoting the REmapE agenda (more than 50% of renewables in total final energy) – Figure 19.

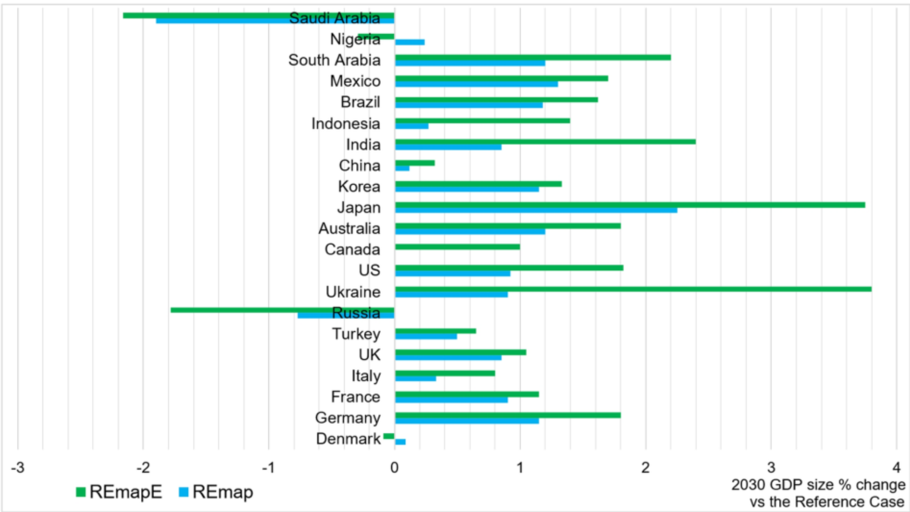

Fig. 19. Forecast of economic growth for various countries under the REmap (36% of renewables in total final energy) and REmapE (up to 50%) scenarios (IRENA, 2016)

Accordingly, growth in national wealth by 2030 is expected in countries where the digital transformation of the energy sector is driven by ambitious targets for increasing the share of renewable energy (Figure 20).

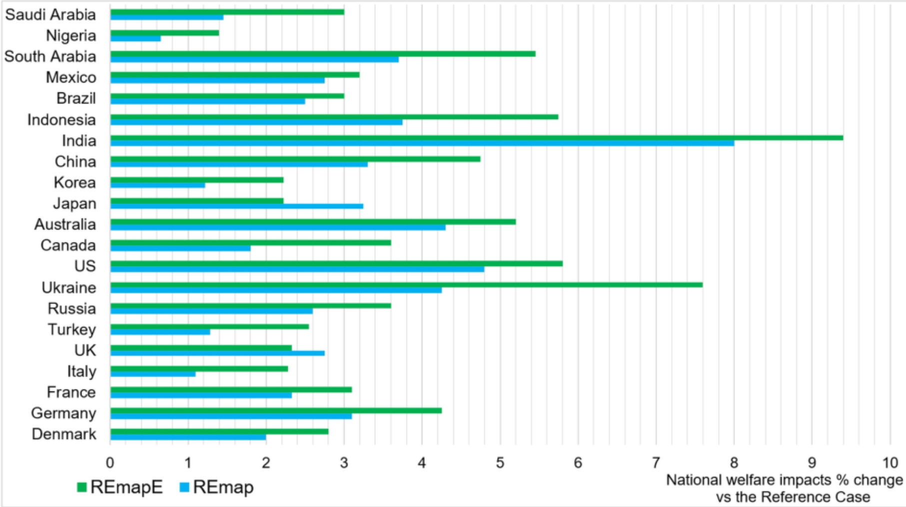

Fig. 20. Forecast of national wealth growth for different countries under the REmap and REmapE scenarios (IRENA, 2016)

Today, energy development is taking place in two parallel directions. First, it involves the expansion of alternative energy carriers (the final transition which requires investments in power production of 150 petawatt-hours). The second direction is the fossil sources development (600 million barrels of oil, 400 billion cubic feet of gas, 19 gigatons of coal reserves annual growth (in oil equivalent). This is accompanied by an annual increase in consumption of 1.4 billion barrels of oil, 4.5 cubic feet of gas, and 3.1 million tons of coal, which can lead to emissions of 39.5 gigatons of CO_2 in the long term by 2050 (Keshari et al., 2023).

Consequently, the expected qualitative state of power production by the end of the 21st century is a combination of renewable and non-renewable energy carriers, biofuels, and hydrogen – an energy mix (technocentric approach (Zavyalov et al., 2024).

The higher long-term profitability of thermal energy (Sikirica, 2024), as well as the fact that to replace 1% of electricity made with non-renewable energy carriers, it is necessary to expand renewable power generation by 1.15%, mainly using hydropower with its rapid growth (Figure 21), but with ten times smaller volumes today (Figure 22), speaks in favor of balancing fossil and renewable energy sources in a consistent move towards near-zero greenhouse gas emissions in the coming decades.

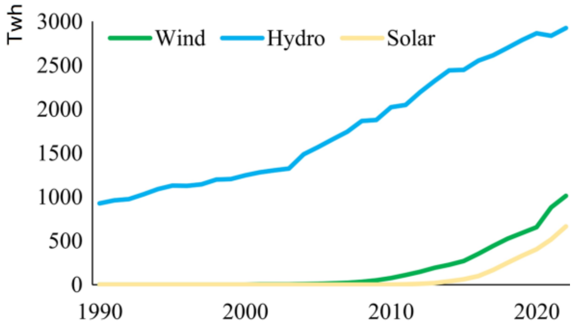

Fig. 21. Renewable energy generation in OECD countries (Twh) (Pata et al., 2024)

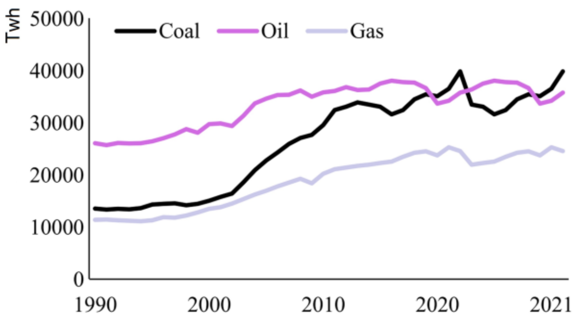

Fig. 22. Non-renewable energy generation in OECD countries (Twh) (Pata et al., 2024)

That is, the structural shift in the economy under the influence of the coming Energy 6.0 will be induced by merging the digital technologies of Industry 6.0 (Gasanov et al., 2024) with innovations in mining and oil and gas technologies (Lukyanenok et al., 2023; Cherevko et al., 2024). It will allow approaching parity in CO_2 emissions with green energy (Nicolletti et al., 2023). In particular, over the last three decades, a significant portion of these emissions has shifted from coal to natural gas (Rößler et al., 2024). In general, the economy is undergoing structural shifts from agriculture to manufacturing and services, which leads to changes in energy intensity in industry. Thus, over the past 30 years, energy consumption in industry in the 27 EU countries has remained virtually unchanged (around 13.4 EJ), which has become possible due to a 30% increase in energy efficiency (Banerjee, 2012).

Today, the issue of a "hydrogen" shift in the energy sector of the future, promising for decarbonization, is being actively discussed since hydrogen can be used in transport, heat, and power engineering (including in storage facilities) – especially to replace gas generation in regions with an underdeveloped pipeline network (Clarke et al., 2022).

By 2026, the growth in demand for electricity from data centers is expected to be 30% higher than in 2022 (Figure 23), driven by the transition to the next generation of digital technologies by 2050. Furthermore, in order to give up fossils by the middle of the 21st century, renewable energy production should be increased eightfold, provided that power demand remains constant from 2020. Nevertheless, its growth is expected, according to various estimates, up to 10 times (Kotowicz et al., 2024).

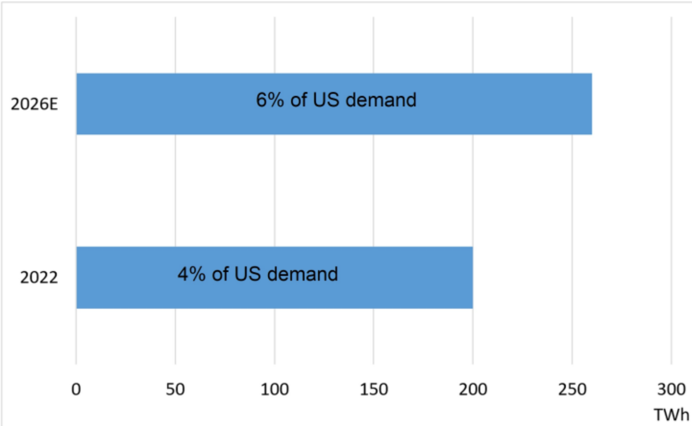

Fig. 23. U.S. electricity demand from data centers (J.P. Morgan Asset Management, 2024)

In line with the expected growth in energy demand from the digital society, it does not seem possible to meet it through a fifteenfold growth in power production using renewable sources by 2050 (Tuluhong et al., 2024). Based on several forecasts, gas use is expected to increase to 85% by 2035 in megacities, whereas current national strategic documents in the energy sector aim for a 30% reduction in the share of gas (Kotowicz et al., 2024).

A possible structural shift in the energy sector is considered in light of the widespread use of biomass (Friedemann, 2021), but its indicator, Energy Return on Investment (ERI), is lower than that of coal. Consequently, a 40% drop in coal mining worldwide can decrease the Earth's temperature by only 1.2 °C, while the negative consequences, including limited access to cheap energy, may affect up to 2 billion people (Gaafar et al., 2024). A similar shift is considered in connection with the transition to wider use of atomic energy, which, however, cannot eliminate possible energy supply failure in developing countries if thermal energy production is reduced even in the short term (Proskurina, 2024). Possible future technological breakthroughs in the use of the thermonuclear reaction of "burning plasma" with its characteristic unprecedented risks of environmental catastrophe should also be taken into account (Merceron et al., 2024). Moreover, natural gas is expected to play the role of a "bridge" fuel in the transition to carbon-free energy in the future (Mazur et al., 2023).

The transition to Energy 6.0, as a factor initiating a structural shift in the economy, can be accelerated by the expansion of electronic fuel (e-fuel), the production of which (electrolysis of water) must be sustainable and based on electricity from renewable sources, as well as CO_2 captured from the atmosphere.

Primarily, it is e-hydrogen e-H2, based on which it is possible to synthesize more adapted from the point of view of energy production technology e-methane and e-gasoline (Schäfer, 2016). These types of fuel will enable a sustainable change in the structure of the energy balance in countries actively promoting the NetZero agenda, which in the next decade cannot be compensated by anything other than traditional thermal energy (Trout et al., 2022), even with the use of local intelligent networks based on generative artificial intelligence (Hermundsdottir et al., 2024).

In relation to Energy 6.0, power production is considered a development of ESG investments (Kudryavtseva et al., 2024), with Energy Return on Investment (Li, 2023) replacing the primary evaluation criterion, and its growth is expected at the end of the Fourth Energy Transition (Saraji et al., 2024). The same investors who are active in ESG investing within Energy 5.0 are expected to be present in the Energy 6.0 systems – including transnational banks and various investment funds that manage $154 trillion in capital (Voloshin, 2023) - actively financing decarbonization projects in developing countries (Zhironkina et al., 2023).

In general, Industry 6.0, which is penetrating various sectors of the economy, encompasses autonomous intelligent production and "super-smart" enterprises in mechanical engineering and radio electronics, as well as a swarm of heterogeneous robots in mining and axiomatic design in construction (Babkin et al., 2024c). As for the spillover of Energy 6.0 technologies in the industries of the "economy of the future", today, we can already say that digital nature-centric technologies in energy production will have the following impact on various industries in the economy (Fedorova et al., 2023):

- material production industries (mechanical engineering, electronics, metallurgy, production of plastics and composite materials) – maintaining long-term competitiveness in the face of a likely increase in energy costs and ensuring uninterrupted energy supply during the mass transition to renewable energy sources;
- mining – ensuring uninterrupted supply in the context of moving towards zero emissions through multi-sector interactive planning of mineral resource extraction depending on forecasts of global demand for them;
- transport systems – achieving the highest possible "antifragility";
- construction – a radical reduction in energy consumption through the introduction of smart building energy systems at the design stage;
- production of information products – meeting the growing energy needs of countries with advanced IT sector development in order to prevent "blank spots" in digital global development.

In the national strategies, the transition to Energy 5.0 and further to 6.0 is quite widely reflected in the actions of the government and legislators. In particular, in China, further increases in green energy investment are expected to result in a 36% reduction in energy tariffs by the end of the 21st century. However, there is a clear dependence on green investment on government incentives, particularly in the case of hypothetical cancellation in China – the world leader in hydropower investment – the volume of such investment would fall by 42% by 2050 (Onifade, 2022). However, even with government subsidies, the investment risks associated with companies producing energy from renewable sources are similar to those faced by companies extracting fossil fuels (McDonnell et al., 2023). That requires increased attention to the participation of the extractive sector in the energy transition (Barbesgaard et al., 2022). Despite this, EU countries are using a policy of "nudge" towards a phased refusal from fossil fuels through price subsidies (Abnett, 2023) and tax incentives for investors in renewable energy sources (Alam et al., 2024), which indicates the preservation of the expected platform – Energy 6.0 – the imperative of meeting the environmental demands of society along with approaching to UN SDG.

Discussion

This Review reflects a certain advancement in the study of Industry and Energy 6.0, which consists in its comprehensive consideration – as a form of technological sectoral and industrial breakthrough, as well as a structural shift in the economy. If existing studies consider Energy 6.0 mainly from the perspective of technological support for zero CO2 emissions, then we are inclined to perceive it as a platform for balancing energy production from renewable and non-renewable sources.

Despite the small number of publications devoted directly to Energy 6.0, its understanding in the works of most authors is associated with the ultra-reliable ("antifragile") production of globally accessible energy, in which zero emissions are possible without the final rejection of fossil fuels, but with deep optimization of their use and minimization of CO_2 emissions and its processing.

The limitations of the Industry 6.0 paradigm, in general, and Energy 6.0, in particular, are both objective and subjective and are mainly related to the high investment costs associated with transitioning to renewable energy sources, which are comparable to the costs of designing and implementing nature-centric ultra-high-performance cyber systems within Industry 6.0. However, it is precisely this that will allow for achieving objectively minimal volumes of greenhouse gas emissions, characterizing the zero contribution of energy to climate change.

Overcoming these limitations is associated with further research into the technological transformation of energy in the context of reducing environmental damage and meeting society's growing need for affordable energy. In general, most authors expect Energy 6.0 to remove energy production from the circle of critical threats to sustainable development, as well as a long-term solution to the problem of global energy availability as demand for it grows.

We hope that the findings and provisions of this Review will enable future researchers to refine the definition of Energy 6.0 as new evidence of the development of nature-centric technologies of Industry 6.0 is obtained. They will help formulate recommendations for improving legislative and administrative practices related to investing in technologies that reduce greenhouse gas emissions, as well as the further development of digital technologies.

We also hope that this Review will enable the scientific community to form an alternative opinion on the role of digital, nature-centric technologies in simultaneously achieving the goals of reducing the negative impact of energy on the climate and ensuring access to affordable energy for all countries and people.

Policy Implications

Regarding political proposals, we believe that as green renewable energy technologies and digital technologies are integrated into the Energy 6.0 platform, national governments and legislators will increasingly focus on technological competition in the industry to achieve carbon neutrality.

As a result, the national energy strategies of the future that will be inherited by today's ones (with a maximum horizon of action until 2035, such as "USA 2030: National Energy Strategy", "Fit for 55" and "REPowerEU" for the European Union, "12th Five-year Plan on Greenhouse Emission Control" for China, "Green Transformation (GX) Programme" for Japan, "9th Basic Plan for Long-Term Electricity Supply and Demand 2020-2034 Republic of Korea") will inevitably be adjusted. The main expected changes may be as follows:

A) Considering the unevenness of digital development, renewable energy investment, and access to affordable energy among countries in North and South America, Europe, Asia, and Africa, as well as Australia, when developing global energy cooperation programs. In particular, it is necessary to understand that in the transition from human-centric Energy 5.0 to nature-centric Energy 6.0 in the future, new leaders of the "seamless" energy transition will emerge, which will determine not only the volume of greenhouse gas emissions but also the new balance of fossil and renewable energy sources.

B) The emergence of the process of reducing energy costs and attracting green investments in energy is a key factor in the international competitiveness of the national economy, which may require additional protectionist energy policy measures.

C) Creating international energy strategies that provide an equal distribution of individual countries' obligations to reduce greenhouse gas emissions in exchange for expanded cooperation in the field of digital technologies of Industry 5.0 and 6.0.

Conclusions and Prospects

Expecting fulfilling UN SDG with equitable access to power and infrastructure development, along with climate stability, are inseparable from a "seamless" Fourth Energy Transition, with movement toward zero greenhouse gas emissions with increasing energy generation and equitable access to it. The aggravation of environmental problems by the middle of the 21st century forces us to associate the technological development of the energy sector (transition to Energy 6.0) with solving socially significant problems, in particular, climate problems, to a greater extent than with individual benefits of consumers. The "nature-orientation" of future breakthroughs in the development of digital technologies for Industry 6.0 is a particular feature that distinguishes its industry platforms, such as Energy 6.0, from fifth-generation platforms (Energy 5.0).

The research presented in this Review provides a comprehensive understanding of the digital modernization of the energy sector, approaching the sixth stage (Industry 6.0), as investigated by international research groups. As a result, it was concluded that if Energy 5.0 is aimed at the fair satisfaction of the energy needs of the population in different countries of the world, then the consensus opinion of the authors regarding the quintessence of Energy 6.0 connects it with the maximum involvement of digital technologies (emotional generative artificial intelligence, digital triplets and hyper-connected enterprises, the Internet of Everything, predictive multi-industry analytics of Big Data and their quantum processing, computational experiments, and virtualized assembly, cyber-physical and social systems) in reducing future environmental damage and eliminating that which has already been caused, mainly in the form of greenhouse gas emissions.

In accordance with the above-mentioned limitations of Industry 6.0 development, we propose conducting further research in the field of Energy 6.0 in the following problem areas:

a) the balance of investments in renewable and non-renewable energy, in digital and industry technologies to achieve the imperative of zero CO2 emissions;

b) strengthening the role of Industry 6.0 technologies in a "seamless" Fourth Energy Transition;

c) overcoming inequality among technologically advanced and catching-up countries in access to energy from alternative sources as global demand for its growth;

d) further development of digital technologies beyond cyber-physical systems.

Therefore, further research into the transition from Energy 4.0 to 5.0 and further to 6.0 should not focus exclusively on overcoming technological limitations but should consider economic and political ones.

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