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DIGITALIZATION AND DECARBONIZATION: ASPECTS OF SYNERGY IN THE EU INDUSTRIES

ДИДЖИТАЛІЗАЦІЯ ТА ДЕКАРБОНІЗАЦІЯ: АСПЕКТИ СИНЕРГІЇ В ІНДУСТРІЯХ ЄВРОПЕЙСЬКОГО СОЮЗУ

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The article explores the synergy between digitalization and decarbonization within the EU's most carbon-intensive industries, with a particular focus on the green transition in the energy sector. The study examines the EU's twin transition experience, highlighting the role of digital technologies as key drivers for a climate-neutral economy. Through an analysis of digital applications in energy and industrial production, the authors identify crucial digital solutions, including smart grids, AI, and big data, that accelerate decarbonization efforts. The article provides a comprehensive review of EU initiatives, showcasing successful examples of green and digital integration to reduce greenhouse gas emissions. Key areas of synergy between decarbonization and digitalization are emphasized, illustrating how the twin transition not only reduces emissions but also improves resource efficiency and resilience to climate-related challenges. The paper organizes digital practices across EU sectors and proposes models that may serve as frameworks for building a global climate-neutral economy.

Keywords: climate-neutral economy, decarbonization, digitalization, EU Green Deal, energy policy, energy transformation, sustainable development, twin green-digital transition, distributed generation, energy as a service.

У статті досліджується синергія диджиталізації та декарбонізації світової економіки крізь призму найбільш вуглецевоємних індустрій ЄС. Основний акцент дослідження зроблено на зеленому переході енергетичного сектору ЄС, що є складним викликом в умовах російсько-Української війни та геополітичної напруженості у сфері постачання енергоносіїв. Автори аналізують досвід подвійного зеленого-цифрового переходу в ЄС, зосереджуючись на ролі цифрових технологій, таких як штучний інтелект, «розумні» мережі та великі дані, як ключових рушіїв кліматично-нейтральної економіки. У дослідженні систематизовано цифрові рішення, що прискорюють зусилля з декарбонізації. Обрано та проаналізовано показові ініціативи різних країн ЄС, зокрема програми Energiewende в Німеччині, Smart City Amsterdam у Нідерландах, проєкт електромобільності у Франції та інші. Визначено ключові сфери прояву синергії конструкту «диджиталізація - декарбонізація». Показано, що подвійний перехід сприяє зниженню викидів парникових газів, підвищує ефективність використання ресурсів і стійкість до кліматичних викликів. Розглянуто системні прикладні напрямки взаємодії зелених та цифрових ініціатив у розрізі секторів енергетики, промислового виробництва, аграрного сектору та міської інфраструктури. Показано, яким чином диджиталізація здатна сприяти оптимізації процесів, зниженню енергоспоживання та розвитку сталих рішень. У напрямку прикладної реалізації зелених політик найближчого майбутнього, розглянуто модель «енергія як послуга» (Energy-as-a-Service), яка забезпечує оптимізацію споживання енергії та стимулює впровадження низьковуглецевих рішень в ЄС, сприяючи цілям декарбонізації. У статті наведено міркування щодо перспектив розвитку розподіленої генерації та мікромереж для розвитку кліматично-нейтральної економіки, що дозволяють децентралізувати енергопостачання та знижують залежність від централізованих постачальників. Визначено роль диджиталізації у цих процесах на прикладі досвіду економіки та кліматичної політики ЄС.

Ключові слова: кліматично-нейтральна економіка, декарбонізація, диджиталізація, зелений курс ЄС, енергетична політика, енергетична трансформація, сталий розвиток, подвійний зелений-цифровий перехід, розподілена генерація, енергія як послуга.

Introduction. The modern global economy is evolving amid powerful megatrends that foster transformative synergies, with one of the most compelling being the intersection of digitalization and decarbonization. As digital innovation progresses rapidly worldwide, the potential to leverage digital technologies in advancing the EU’s green transition goals has become a focus of economic and environmental strategies. The drive to reduce greenhouse gas emissions has never been more urgent. As the Intergovernmental Panel on Climate Change (IPCC) noted in 2021, global emissions have surged by over 70% in the past five decades, largely due to the expansion of industrial activity [1]. This trend, compounded by the world’s heavy reliance on energy, has led to increasingly severe climate impacts. Projections from the International Energy Agency (IEA) in 2023 underscore the risks, suggesting that global energy demand could rise by 50% by 2050, driven by urbanization, industrial growth, and geopolitical instability, including the impacts of russia’s war against Ukraine [2].

Climate resilience now demands greater investments and coordinated global efforts, as climate-related economic losses are escalating. Newman’s comprehensive study highlights an estimated USD 2.8 trillion in economic damages over the past 20 years, averaging USD 143 billion annually [3]. Moreover, forecasts by Iizumi predict that by 2050, climate-related damages could cost the global economy an additional USD 1.7 to 3.1 trillion [4]. Within this context, the European Commission’s foresight calls for a twin “green and digital” transition across EU industries, aiming to harness digitalization as a tool for cutting emissions and achieving climate neutrality [5].

Digital technologies offer promising decarbonization potential, particularly within the industrial sector [6]. According to McKinsey, these technologies could lower emissions in industry by 15-20% by 2030 through improved energy efficiency and optimized production processes [7]. Applying digital solutions in sectors like energy and heavy industry within the EU could thus be instrumental in accelerating decarbonization, helping to forge a sustainable, climate-neutral economy by integrating best practices for both digital and green transformations.

Analysis of recent research and publications. Contemporary research increasingly emphasizes the practical aspects of green growth, exploring how various transformational transitions can synergize to achieve shared objectives. In particular, there is a growing focus on the digital-green transition within global industries, examining how digital advancements can drive sustainability and support environmental goals. Bauer [8], Nativi [9], and Mondejar [10] highlight the critical interplay between environmental and digital advancements, focusing particularly on developing a "digital twin" of Earth to enhance climate resilience. Geels [11], Victor [12], and Midttun [13] underscore the pivotal role of IT clusters in promoting climate sustainability, especially within high-emission sectors like metallurgy, agriculture, energy, and transportation. This topic gains heightened relevance amid active global integration. Argyriou [14] suggests that climate integration has become essential, with digital accessibility acting as a catalyst for green growth beyond mere market dynamics. Hao’s [15] research illustrates that the digital transformation of the economy significantly influences inclusive green growth, impacting key areas such as energy consumption, environmental pollution, economic expansion, human capital, industrial structure, and technological innovation. Ren [16] argues that the global trend of "digitalization for decarbonization" calls for rethinking economic models and ensuring that modern policies effectively support green-digital initiatives.

However, the scientific discourse reveals a gap in consistently outlining a global digital paradigm for the green transition, specifically in terms of how digital technologies impact climate outcomes across various economic sectors.

Formulating the objectives of the article. The purpose of this article is to explore key opportunities for leveraging digitalization to accelerate decarbonization and drive climate neutrality within the EU's most carbon-intensive sectors, notably energy and industrial production. Methodologically, the study is based on an analysis of the EU's experience in promoting a green-digital transition, incorporating findings from international reports and academic research. This approach enables a systematic identification of primary digital solutions that support decarbonization across specific industries, potentially guiding strategies for a climate-neutral global economy. The focus is placed on examining the digital-green transition within the energy sector and modern industrial production, as these areas currently represent the largest contributors to the EU's carbon footprint.

Research results. Climate neutrality serves as a benchmark for sustainable development within the global economy, with the European Union ambitiously targeting "net-zero" emissions by 2050. The twin green-digital transition is pivotal for advancing decarbonization efforts, necessitating the widespread adoption of best practices in digitalization and environmental sustainability across all business sectors.

However, achieving climate neutrality requires decarbonization across all economic sectors, each of which contributes differently to the overall carbon footprint (Figure 1).

The diagram below shows the structure of the carbon footprint of the global economy by sector. The energy sector is the largest source of carbon emissions both in the EU (38%) and globally (30%), which emphasizes the importance of this sector in environmental policy and the need to reduce dependence on carbon-based energy sources. The transportation sector is also a significant contributor to emissions at the global level (27.5%) and somewhat less so in the EU economy (20.7%). A larger gap is observed in the construction sector (17% globally and 8.9% in the EU emissions structure). An important aspect is the separation of emissions from energy

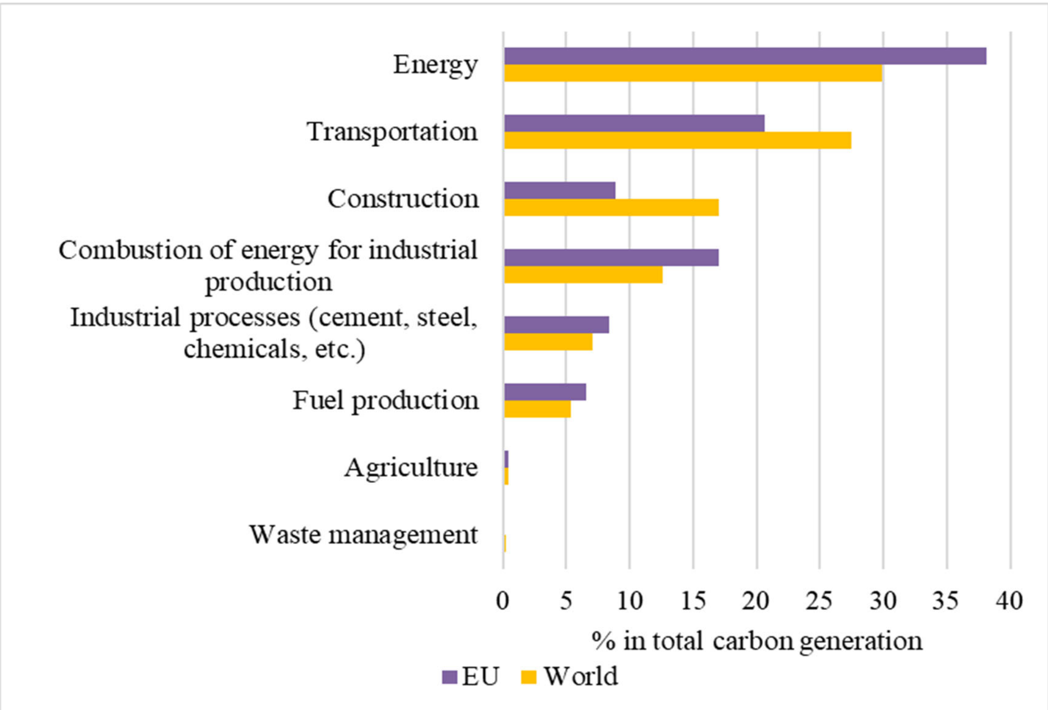

Figure 1. Industrial structure of the economy's carbon footprint

Source: authors' representation based on Global Carbon Budget statistics [17] combustion from carbon generated directly during production. This approach allows us to evaluate the decarbonization of global industries in terms of two dimensions: decarbonization of specific production processes (metal casting, cement or chemicals); and reduction of energy intensity of production. As you can see, energy combustion produces almost twice as many emissions as direct production. At the same time, fuel production is a separate issue, as it currently accounts for 5.4% of the global economy's carbon footprint and 6.6% in the EU. The smallest share of emissions comes from agriculture (0.4%) and waste disposal (0.22% globally and 0.04% in the EU).

Despite the different contribution of industries to the total emissions, there is a need for an integrated approach to reducing emissions that covers different sectors of the economy and includes measures to improve energy efficiency, innovation and waste management.

The experience of the EU countries is one of the most illustrative in developing strategies and implementing green-digital transition practices.

Some of the initiatives are summarized by the authors based on the Digital Europe Survey [18] and European Commission [5]:

1) *Energiewende (Germany).* This initiative represents a comprehensive approach to transforming the energy sector with a focus on decarbonization and sustainability. By implementing smart grids and integrating renewable sources, Energiewende not only optimizes energy consumption across sectors but also serves as a model for large-scale renewable adoption. It prioritizes energy reliability and affordability, positioning Germany as a leader in the climate-neutral transition. This initiative sets a precedent for other countries aiming to balance high energy demand with sustainable practices, with active collaboration between public administration and major industries.

2) *Smart Grid Gotland (Sweden)*. The Smart Grid Gotland project on the Swedish island of Gotland is a pioneering effort to create an advanced energy grid that effectively integrates renewable energy sources. This project showcases Sweden's commitment to resilience and sustainability by improving grid efficiency and stability, even in remote areas. By incorporating cutting-edge smart grid solutions, Gotland serves as a testing ground for future energy systems that can adapt to increased demand while lowering greenhouse gas emissions. The initiative is notable for its inclusive approach, involving public administration, large businesses, and local citizens in fostering a sustainable energy future.

3) *Smart City Amsterdam (Netherlands)*. Amsterdam's Smart City initiative uses digital technologies to tackle urban challenges like traffic congestion and pollution. A standout feature of this project is its focus on optimizing transportation through data-driven solutions, which reduces CO_2 emissions and enhances urban life quality. By deploying smart systems for traffic flow management and promoting public transport, Amsterdam is setting a benchmark for sustainable urban planning. This project aligns with the Netherlands' broader objectives of sustainable urban spaces, with a strong emphasis on collaboration among public administration, large businesses, and citizens.

4) *Electric Mobility (France)*. France's Electric Mobility initiative is transforming the transportation sector by building infrastructure for electric vehicles and employing artificial intelligence to optimize charging stations. A notable aspect is the project's aim to make EVs widely accessible, reducing reliance on fossil fuels and significantly cutting CO_2 emissions. This initiative promotes cleaner transportation and addresses France's climate neutrality targets, involving collaboration across public administration, large businesses, and citizens. It represents a nationwide commitment to creating a sustainable, low-emission transportation network.

5) *Superbonus 110% (Italy) & Smart Buildings (Finland)*. This program both focus on enhancing energy efficiency in buildings, a sector with a substantial carbon footprint. Italy's program offers financial incentives for homeowners to retrofit properties with energy-efficient and renewable solutions, making sustainable housing accessible to more people. Meanwhile, Finland funds smart construction projects that utilize cutting-edge technology to lower emissions. Both initiatives reduce the energy demands of heating, cooling, and powering buildings, benefiting public administration and citizens while promoting sustainable living as a foundation for climate neutrality.

6) *Digital Farming (Denmark)*. This initiative utilizes artificial intelligence and the Internet of Things to modernize agriculture, focusing on reducing emissions from fertilizer and water use. By harnessing digital tools, this project helps farmers improve resource efficiency, lower greenhouse gas emissions, and enhance crop productivity. This initiative is distinguished by its innovative application, making it a key

part of Denmark's climate goals. It promotes sustainable agricultural practices by involving large and small businesses in the green-digital transition.

7) *Smart Agriculture (Spain)*. Spain's Smart Agriculture project leverages big data to optimize agricultural management, increasing productivity while minimizing environmental impact. The initiative stands out for its use of data analytics to improve decision-making in areas like crop management, water allocation, and resource usage. By enabling more efficient agricultural processes, it contributes to Spain's sustainability targets. This project emphasizes the role of digitalization in transforming traditional agriculture into a data-driven, sustainable industry, engaging large businesses, SMEs, and farmers.

These remarkable initiatives illustrate the synergy between green and digital transition towards climate-neutral economy (Figure 2).

Thus, the synergy between digitalization and decarbonization lies in combining technological solutions to reduce the carbon footprint and promote sustainable development. This approach optimizes processes across various economic sectors, reduces environmental impact, and establishes a foundation for a climate-neutral economy. At the same time, the implementation of the twin green-digital transition has certain peculiarities and challenges in different sectors of the economy, which should be considered separately in the most carbon-intensive sectors of the economy.

The energy sector produces the largest share of carbon emissions in the carbon footprint of the EU and global economy. The increasing availability and relative reduction in the cost of renewable energy technologies in the last decade has put the energy sector at the forefront of climate policies. Moreover, research by Victoria [19] shows that prioritizing and

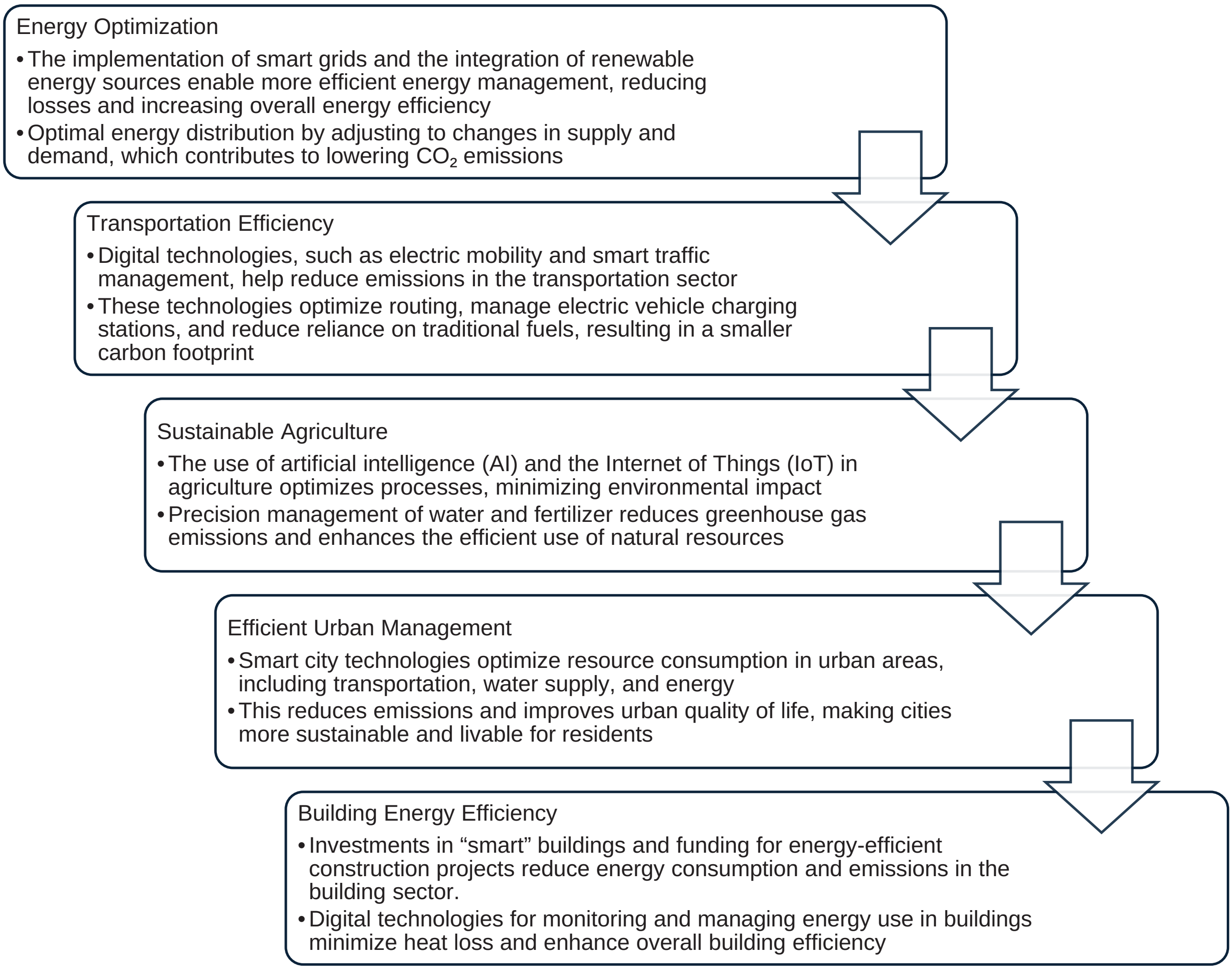

Figure 2. Key areas of decarbonization-digitalization synergy

Source: authors' representation

sustaining emissions reductions in this sector is the most cost-effective pathway to climate neutrality. The relative drop in prices for different types of energy is shown below (Figure 3).

As we can see, there has been a rapid decline in the cost of alternative energy production. In just one decade, the cost of solar energy has fallen by 89%, wind energy by 69%, and biomass by 25%. This reduction in the cost of alternative energy is a powerful lever for the green transition of the global energy market. Over the last decade, the energy sector of the economy has demonstrated 2 positive trends towards achieving climate neutrality – an increase in the share of renewable energy use from 16.7% in 2013 to 23.2% in 2023 against the background of a reduction in primary energy consumption from 1380 million tons of oil equivalent to 1260 million tons, respectively, from 2013 to 2023.

Current russia's military aggression against Ukraine has accelerated the paradigm shift in the EU energy sector towards greater energy independence and protection of critical energy infrastructure. Under these conditions, the important emphases of the green-digital transition of the energy sector, taking into account the objectives of achieving "net zero" emissions according to the European Commission [5], are

– secure energy supply and protection of the digital energy system from cyberattacks and possible IT system failures;

– reducing the need for fossil fuel imports amid rising energy prices, which requires energy savings and energy efficiency;

– the need to accelerate the transformation of energy towards renewable and clean sources to reduce energy dependence.

The EU Briefing [21] showed that measures to support renewable energy and energy efficiency could reduce the EU's dependence on russian gas imports by two-thirds by 2025 through the implementation of the Fit for 55 package. Climate-neutral electricity generation is becoming the basis of the green transition. Wind and solar energy remain the most cost-effective way to generate alternative electricity. This trend is characterized by the dynamics of global investments in renewable energy Irena [20], the lion's share of which is solar and wind energy, which over the past 15 years have formed a powerful pool of the global energy market (more than 90%).

According to Oliveira [22], an important area of the green-digital energy transition is also the development of hydrogen technologies, primarily in the direction of replacing traditional fuels. "Green hydrogen" can be used in many areas, including aviation, long-distance road transportation, residential heating, and industry. The development of the EU Hydrogen Bank is one of the vectors of support for such an initiative. The European Commission predicts that zero-carbon fuels, such as hydrogen,

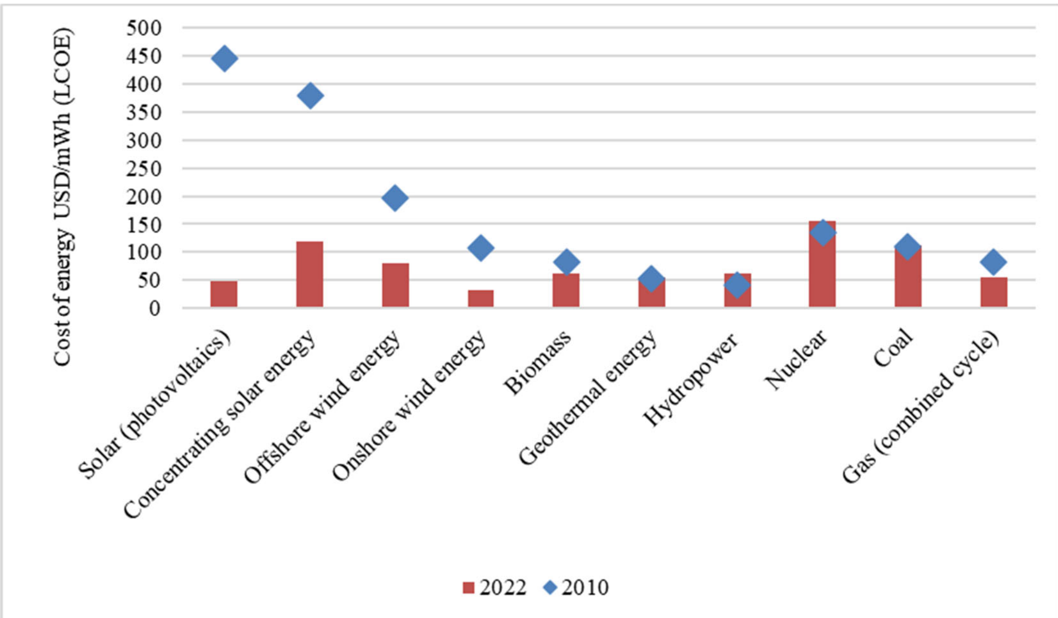

Figure 3. Dynamics of falling energy cost LCOE (by type)

Source: compiled by the author based on Irena [20] should replace fossil fuels where electrification is not possible.

According to a report by the International Energy Agency [2], the EU is actively implementing digital tools to model electricity demand, while using gamification and metaverse models to adjust consumer behavior and energy consumption habits. Digitalization is a key enabler for the development of self-organized energy networks, which are crucial for dealing with the increasingly decentralized and variable structure of electricity production in the EU [12]. Such self-organized microgrids are small power systems that can be interconnected whenever reinforcement is needed. Their use seems especially promising, as analysts at the International Energy Agency predict that by 2050 the load on the power grid will double, in particular due to charging of electric vehicles. In terms of security, such systems will make it relatively easy to prevent outages and restore power supply due to infrastructure damage caused by the extreme effects of climate change. At the same time, according to Borowski [23], this important area of energy transition is only possible with widespread digitalization, which relies on the broad integration of ICT and, in the future, blockchain technology.

Moreover, self-organized microgrid networks are driving the development of local energy markets in the EU by reducing the dominance of large players and increasing the involvement of households as suppliers of surplus energy on the basis of market competition. Allied Market Research [24] shows that the global microgrid market will amount to 55–190 billion euros in 2030. Against the backdrop of the trends outlined above, a new innovative, digitally-oriented business model, Energy-as-a-Service (EaaS), is emerging that is changing the way energy suppliers and consumers interact. Currently, energy suppliers offer electricity, fuel, and heat to end users. EaaS is a different approach, where an energy service provider offers end-users new ways of energy solutions that do not involve a specific type of energy, but rather a "turnkey energy product", Allied Market Research [24]. The EaaS business model is manifested in a wide range of solutions, including energy efficiency, renewable energy, and solutions for stabilizing power grids. The main advantage of EaaS for end users is that this model reduces the need for initial investment and simplifies energy supply. According to the European Commission's Foresight [5], Energy as a Service is a growing segment of the energy market with an expected compound annual growth rate of 7.6% by 2030 and a market capitalization of 113 billion euros, which can contribute to job creation and increase innovation. Moreover, EaaS can reduce energy poverty in countries by optimizing the prices of energy services and encouraging the most energy and cost-effective suppliers. However, the introduction of EaaS implies greater transparency in terms of data exchange between grid consumers and suppliers regarding energy use, which will require additional digital security protocols.

In general, achieving climate neutrality through the green-digital transition in the energy sector will require coordinated policies to reorient the EU energy system towards climate-oriented development, strengthen the regulatory framework for emissions regulation, support the entry of new players into the energy market, overcome possible public resistance to the transition to new energy consumption models, and prevent a possible rebound effect.

Conclusions. An analysis of the EU's approach to a twin green-digital transition underscores the crucial role of digital solutions in achieving climate neutrality, particularly in the most carbon-intensive sectors like energy. The findings confirm that the integration of digital technologies in these key sectors significantly accelerates the decarbonization process and supports the EU’s climate neutrality goals. Moreover, the best practices in twin green-digital transition are already contributing to considerable reductions in greenhouse gas emissions and enhanced resource efficiency.

Through a review of reports from international institutions, it becomes clear that digital technologies such as artificial intelligence, the Internet of Things, blockchain, and big data not only optimize monitoring and management but also unlock new opportunities for green economic growth. This affirms the hypothesis that an integrated approach to digitalization and decarbonization is critical for achieving climate neutrality in the coming decades.

In particular, the adoption of digital tools within the energy sector fosters greater decentralization of energy markets and supports the development of self-sustaining microgrids, which are vital for resilient energy supplies in the face of climate challenges. The emergence of the "Energy as a Service" business model enables optimized energy consumption, reduces upfront costs, and increases the accessibility of low-carbon energy solutions. Additionally, the integration of hydrogen technologies is playing an increasingly important role in transitioning to clean energy sources for industrial applications. The decreasing costs of renewable energy generation, especially solar and wind power, further drive these technologies' integration into the energy market.

Digitalization emerges as a pivotal force in driving climate neutrality by offering advanced solutions for process optimization across diverse sectors. However, realizing the full potential of this twin transition requires substantial international support from governments and private enterprises to ensure the widespread implementation of digital-green initiatives.

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