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GLOBAL ENERGY MARKET SUSTAINABILITY: MODERN CHALLENGES IN SCOPE OF UKRAINIAN CONTEXT

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Abstract. The paper addresses the issue of sustainable development and the long-term efficiency of the energy market, taking into account modern geopolitical threats. Energy, and electricity in particular, are regarded as major prerequisites for open and non-open conflicts between countries on the global stage. Furthermore, an energy deficit is considered to give some countries a huge strategic advantage over others. The natural potential and generating capacities of key energy market actors all over the world constitute an enormous political advantage. The use of innovative technologies, such as 3D printing, could transform cargo transportation by reducing the volume of physical transportation, opening avenues for optimising transport infrastructure and reducing logistics costs. This would be essential for the stable provision of export and import operations in the future. The energy dominance of certain regions has been demonstrated to engender hitherto unparalleled market advantages, compelling other countries to establish bespoke transition collaboration schemes with a view to differentiating various markets and functional processes. In the context of intergovernmental collaboration and net-zero initiatives, the trajectory of global development is inextricably linked to the effective management of natural resources and the attainment of comprehensive energy efficiency, facilitated by technological advancements and the objectives of coalition partners. The present study is founded upon a comprehensive methodological framework. In order to comprehensively explore the scientific aspects of the issues addressed in this research, a range of explanatory research methods were employed. Firstly, a comparative analysis will be conducted to identify both the similarities and the differences between the extant energy sector models in Ukraine and in other countries. Secondly, the historical method is employed to summarise the key prerequisites of various scientific paradigms and to assess potential development risks. The primary research method employed is secondary data analysis, which is based on an in-depth evaluation of global energy data. A comprehensive overview of the current peculiarities of the global energy market in the context of various sectors was conducted by means of extensive secondary data analysis. The aim of this analysis was to highlight the major daunting tasks in the geopolitical arena based on irreversible shifts caused by the Ukrainian context. Moreover, in order to generate reliable forecasts for Ukraine's electricity production up to 2030, a mathematical extrapolation method was applied in order to develop a probable scenario. In light of the findings from contemporary research and empirical studies, which have employed a systemic analytical approach, a plethora of pragmatic policy-altering measures are put forward. It is anticipated that a sophisticated development strategy for the energy market will serve as a pivotal catalyst for sustainability and mutually beneficial international collaboration. In the long term, the key milestones of global sustainability within markets will be energy safety and multi-stakeholder dialogue.

Keywords: sustainable development, sustainability, energy efficiency, energy safety, international collaboration, international relations.

JEL Classification: F5, Q01, Q47

1. Introduction

Energy, in general, and electricity, in particular, are widely regarded as significant factors in the emergence of both open and non-open conflicts among nations on the global stage. Furthermore, it is widely acknowledged that the energy deficit is set to become a significant strategic factor in the global balance of power. It is evident that the key energy market actors worldwide possess significant political advantages, which are derived from their natural potential and generating capacities. The energy dominance of certain regions has been

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demonstrated to engender hitherto unparalleled market advantages, compelling other countries to establish bespoke transition collaboration schemes with a view to differentiating various markets and functional processes.

Taking into account modern geopolitical challenges, the energy sector in Ukraine is one of the most vulnerable and crucial sectors of the economy. At the same time, the Ukrainian energy industry has already faced numerous new and increasingly threatening challenges, such as nuclear terrorism involving the seizure of nuclear power plants, as well as significant damage to critical infrastructure, including electrical and gas networks. Furthermore, demand for energy products has decreased significantly due to a large proportion of the Ukrainian population leaving the country. Consequently, a significant number of business premises and production facilities are being left behind due to a combination of factors, including a lack of demand and workforce, as well as high operational risks resulting from persistent attacks and regulatory uncertainty. These pivotal shifts have resulted in a substantial decline in energy payments, and the decision to maintain synchronisation of Ukraine's energy system with that of Continental Europe, despite ongoing hostilities and a fuel crisis, is particularly noteworthy. Notwithstanding the aforementioned challenges, Ukraine is considered to become a full-scale member of the European Union in the upcoming prospect.

In the context of the present circumstances, Ukraine is perceived to adopt dualistic roles, as both the victim and the innovator, within the context of the ongoing war. Conversely, the persistent damage to production facilities engenders irreversible shifts in the domestic market. Nevertheless, such a vulnerable position may open new horizons and bring about unprecedented innovations to already existing business practices, thus leading to a different market model.

2. Energy Market Model in Ukraine: From Soviet Heritage to Modern Unbundling System

The energy market of Ukraine is a fundamental sector of the state economy, with a significant historical background. The focus of the generational capacities is primarily on nuclear sources, with active incorporation of various production processes based on oil and coal, biofuel and natural gas. Furthermore, the utilisation of renewable energy sources such as solar energy, wind turbines and water stations has already been implemented in Ukraine. This sector is a state priority as it constitutes a significant part of the national economy.

Ukraine has a powerful base in the energy sector, which was established during the Soviet Union era. The primary production commenced in the 1970s with the construction of 750 kWh transmission lines, which were constructed with the purpose of transmitting substantial quantities of electricity in a westerly direction, including to Eastern Europe. Nevertheless, in the context of the crisis that occurred in the 1990s, the prevailing network of 750 kWh ensured the energy security of the country in circumstances that were wholly unforeseen, both in terms of the situation and the regime.

From an evolutionary perspective, the primary consumers were representatives of the industrial sector. The collapse of the former USSR (1991-1996) resulted in a severe economic crisis in Ukraine, leading to a significant decrease in electricity demand. This decline has led to a substantial decrease in electricity production, domestic consumption, and export. The most significant decline in electricity production was observed at thermal power plants, attributable to a decrease in the extraction of organic fuel and its subsequent decline in quality. At the same time, the energy produced by the existing power plants was sufficient to cover the total demand in the system. Electricity consumption in Ukraine decreased to 166.9 billion kWh in 2000 and 169.2 billion kWh in 2001, which was only 63% of the electricity consumption in 1990.

The challenges posed by technology were further compounded by the comprehensive restructuring of the administrative and economic management of energy facilities during the 1990s, a period marked by the transition of these facilities from state ownership to corporate and private entities. The establishment of a new electricity market was characterised by the presence of a sufficient number of market elements, including generation, transmission and supply. Nevertheless, the Ukrainian energy industry demonstrated its resilience by stabilising its operational state and achieving a recovery after 2000, accompanied by a modest improvement in technical and economic indicators.

Since the time of independence, the Ukrainian energy industry has undergone significant transformations. Technological processes and equipment have been modernised, business processes at enterprises have been enhanced, and many reforms have been carried out with changes to legislation and other regulatory acts. In the contemporary era, approximately 3% of the population is employed within the Ukrainian energy industry, which is the leading sector in terms of taxation, contributing almost a quarter of the nation's entire budget and up to 8% of its GDP. Moreover, energy companies in Ukraine are also engaged in the export of energy resources.

Ukraine has successfully implemented a series of reforms within its energy sector, with the objective of aligning its legislative framework with those of the European Union. The Ukrainian government was responsible for the process of unbundling of gas and electricity transmission system operators between 2019 and 2021. This process was confirmed by the unified certification, which was based on the principles of complete independence and transparency. Gas and electricity markets have undergone significant structural changes.

It is evident that the system under scrutiny is characterised by the presence of multiple structural branches, devoid of a clearly defined central controller. Enterprises that generate resources are responsible for supplying the necessary materials to the network, which are then distributed to the ultimate consumer. Concurrently, local networks are interconnected via dedicated substations. From the perspective of management and ownership, the Ukrainian energy system comprises primary transmission lines and generation capacities. Concurrently, the lines are state-owned and thus ineligible for privatisation. The majority of generating capacities are state-owned, encompassing hydroelectric power plants and nuclear power plants, in addition to a specific percentage of thermal power plants and combined heat and power plants. Nevertheless, there is a significant number of TPPs and CHPs, as well as renewable energy sources such as wind and solar power plants in private ownership. Furthermore, there are several CHPs that are communally owned. The primary governing body within the electricity sector is NPC Ukrenergo, which is categorised as a private joint-stock company, with the entire shareholding being state-owned. The company is under the management of the Ministry of Energy of Ukraine and provides energy transportation to distribution companies.

Moreover, a continuing process of corporate governance reform is underway. NPC Ukrenergo, Ukraine's TSO for electricity, has been preparing the country's power system for synchronisation with ENTSO-E since 2017, when the Agreement on the Conditions for Future Interconnections was signed. During this period, the preparatory measures encompassed the testing of the power units of Ukrainian NPPs, TPPs, CHPs and HPPs, and the development of a mathematical model of the power systems of Ukraine and Moldova. This facilitated the ENTSO-E Consortium's conduct of a study on the static and dynamic stability of the energy systems of Ukraine and Moldova when operating within the network of continental Europe. Ukraine's accession to the ENTSO-E Continental Europe Synchronous Area was executed with a year's anticipation. The energy systems of Ukraine and Moldova have now been fully synchronised with ENTSO-E networks.

3. Energy Sector in Ukraine: Current Situation and Development Trends

3.1. Research Methodology

The extent of scientific issues under consideration in terms of international relations in the energy field between Ukraine on the one side and the global community on the other is based on the theory of *neoliberalism*, which is a relatively recent development and has received comparatively little critical attention.

Neoliberalism itself appeared as a continuation of more classical foundations of liberalism advocated mainly by Adam Smith (2012). As Nofal (2023) asserts, the neoliberal thought paradigm emerged as a response to the prevailing conditions that characterised the inter-war period. The conditions that prompted a divergent line of debate among liberals centred on the war consequences, the Great Depression, the emergence of fascism and Nazism, and other challenges that confronted the classical liberal approach. This context is highly relevant to contemporary geopolitical challenges, given the economic intricacy present within diverse marketplaces. Furthermore, the substantial scientific burden imposed by both economic gurus and antagonistic opponents compelled the conceptualists to formulate principles grounded in more empirical concepts. Harvey (2007) thus asserts that neoliberals have adopted neoclassical principles of competitive markets and individual rationality, thereby accepting the general equilibrium model developed by Walras (1954). Despite this, they did not repudiate several principles of classical theories, with their most notable adoption of Smith's notion of the "invisible hand" keeping the neoliberal doctrine in opposing governmental intervention theories. In contrast to neoclassical economists, neoliberals do not prioritise the issue of monopoly power. This is a salient concern for countries with an energy sector that is entirely state controlled.

Taking all factors into consideration, it can be posited that this novel economic paradigm, which has emerged in the wake of policy-making initiatives, represents an ideology that is concomitant with the recent stage of capitalist society's development. Munck (2005) posits the hypothesis that the efficient allocation of resources constitutes the most crucial goal of any economic system. The author further contends that market mechanisms represent the most effective means of achieving such allocation.

Recent historical analysis (Ariely, Bartels, Freeman, Venugopal, Whyte) has enabled the understanding of neoliberalism as a distinct political theory. The manifesto calls for the establishment of political and economic institutions that are firmly rooted in a liberal and capitalist ideology. These institutions

would be complemented by a constitutionally constrained democracy and a modest welfare system. Neoliberals advocate for the safeguarding of individual liberties and the principles of a free market economy as mechanisms to ensure personal autonomy and stimulate economic growth. While they value democracy, they emphasise its limitations alongside its importance. Furthermore, neoliberals typically advocate for the government's role in providing social insurance and public goods, while concurrently expressing caution regarding regulatory overreach, excessive government expenditure, and state-driven countercyclical policies.

The neoliberal paradigm posits the prioritisation of financial capital over social security, thereby consolidating the process of reorientation of free society with rational citizens to that of dependent consumers. The gradual financialisation of the economy has been demonstrated to contribute to a shift in the focus of development from innovation in production to capital accumulation, as well as the concomitant cycles.

Markets facilitate the facilitation of mutually beneficial exchanges among individuals with divergent values, thereby fostering co-operation despite the presence of disagreements. In contradistinction, socialism is predicated on a central plan, entailing the imposition of specific and frequently contentious values and objectives on the populace as a whole. In order to address these conflicts and enforce a unified plan, socialist governments must centralise political power.

Neoliberalism is frequently the subject of critique on account of its organisation of society around market principles, the commodification of relationships and the subtle steering of individuals towards serving the interests of commerce and economic productivity. It is argued that this results in the structuring of society around a "cash nexus". However, in contrast to overt capitalism, neoliberalism operates in a more covert manner, necessitating substantial scholarly effort to unearth its mechanisms. While neoliberalism is not inherently an ethos, it may be perceived as fostering overly capitalist or transactional interactions between individuals. However, within the framework of neoliberalism theory, an active role is assigned primarily to non-state stakeholders, whose activities are aimed at strengthening multi-polar management of strategic processes of a sustainable economy formation at both local and international levels.

In order to maximise the disclosure of some scientific aspects of the issues raised within this research, the following explicative research methods are used:

– The comparative analysis method is employed to identify both the common and distinctive features of the extant energy sector models in Ukraine and abroad.

– The utilisation of the historical method entails the condensation of the fundamental prerequisites inherent to a plethora of scientific paradigms, in conjunction with a comparative analysis of potential development risks.

The present work was established within a highly extensive methodological framework. The principal research method employed was *secondary data analysis*, underpinned by a comprehensive evaluation of global energy data. Furthermore, in order to provide valid future *forecasts* for electricity generation in Ukraine up to 2030, a mathematical forecast was constructed using the *extrapolation* method. This was done in order to develop a probable scenario.

It is evident that both theoretical and practical perspectives are given due consideration in order to provide a logical framework for the further sustainable development of the electricity generation industry in Ukraine. This is achieved by taking into account both domestic factors and geopolitical challenges.

3.2. Geopolitical Context and Global Energy Market: Future Prospects

In 2024, the global energy industry is undergoing a period of substantial transformation and encountering unanticipated challenges. On the one hand, there has been a rapid increase in the comprehensive interest in renewable energy sources. Conversely, there is a plethora of ongoing discourse surrounding the future of conventional energy carriers such as oil and natural gas. Leading organisations highlight the growth in clean energy investment and the active digitalisation of the energy sector, as well as the impact of geopolitical and economic factors on the global energy market. The key factors that will shape future energy strategies are global economic conditions, the increased production of electricity from renewable sources, and the reduction of dependence on fossil fuels (see Table 1).

In light of the global intricacy of the energy sustainability issue, and the global demand for long-term solutions, it is projected that renewables will account for up to 50% of global electricity generation by 2030 and 85% by 2050. This growth is primarily driven by solar and wind power. Furthermore, the implementation of contemporary technologies pertaining to carbon capture, utilisation and storage (CCUS) has the potential to markedly curtail the reliance on renewables. This assertion is contingent, however, on the presence of political endorsement and the attainment of cost reductions in the implementation of such advancements. Nuclear energy is also considered a potential crisis-altering approach. Without the aforementioned CCUS, coal is expected to gradually phase out of the energy sector. Instead,

the generation of electricity will increase in gas-fired plants that have been adapted to run on hydrogen, in order to ensure grid stability.

Despite the required significant reductions in carbon emissions, all energy transition scenarios remain above the 1.5 °C pathway and result in global warming of between 1.6 °C and 2.9 °C (McKinsey & Company, 2023). As demonstrated in the 2024 report by *McKinsey & Company*, the increase in global emissions would result in a rise in global temperatures above 1.5 °C by 2050. This increase would begin at approximately 1.8 °C in the Sustainable Transformation scenario, rise to around 2.2 °C in Continued Momentum, and reach approximately 2.6 °C in the Slow Evolution scenario (McKinsey & Company, 2024). It is evident that substantial investments are imperative to facilitate a seamless transition in such circumstances. It is anticipated that annual investment in the energy sector will exhibit a growth trajectory of 2-4% per annum, in accordance with global GDP growth, and is projected to reach 2-3.2 trillion USD by the year 2040.

In addition to the imperatives of sustainability and affordability, the assurance of a reliable and secure energy supply constitutes a fundamental component of the energy trilemma. In 2023, the total international trade of oil, gas and coal was 53% higher than it was in 2000. Collectively, the North American, European and Asia-Pacific regions consumed 78% of the world's total energy in 2023. Additionally, 2023 marked a second successive record year for global primary energy consumption, which expanded by 2% to reach 620 EJ. Its growth rate was found to be 0.6% above its ten-year average and over 5% above its 2019 pre-pandemic level. Notwithstanding, a novel record in the consumption of fossil fuels (in absolute terms) was documented. In 2023, the figure fell to 81.5%, compared to almost 81.9% in 2022. Demand for natural gas, a relatively low-carbon fossil fuel, has remained static. Concurrently, demand for oil and coal, which are higher-carbon fuels, has increased. This has resulted in a record high in energy-related greenhouse gas emissions, which exceeded 40 $GtCO_2e$ for the first time (Energy Institute, pp. 10-12).

The energy transition is undergoing accelerated development, yet the road forward remains uncertain due to a variety of factors, including evolving technologies, geopolitical risks and unpredictable consumer behaviour. This uncertainty complicates the development of robust investment strategies that can succeed across diverse scenarios. Consequently, those with the authority to make decisions are confronted with mounting challenges in achieving a balance between multiple competing priorities. These include the need to achieve long-term targets for the reduction of carbon emissions, whilst also having to respond to short-term demands for economic returns.

Table 1
Recent developments and emerging trends on global energy market

MODERN TRANSITION – ENERGY TRILEMMA			
	Sustainable	***Affordable***	***Secure***
trend 1	Over 2019-23 carbon emissions continued to increase with an average rate of 0.8% per year .		
trend 2	Investment in low carbon energy have grown around 50% since 2019 at approximately 1.9 trillion USD in 2023 with high concentration in developed economies and China.		
trend 3	Much of investment has been deployed in renewable power with doubling wind and solar power generation over 2019-23. This trend has been driven by solar due to continuing falls in solar modules cost (by around 60%).		
trend 4	Growing role of green industrial policies within governments, increasing attention on the security of energy supply chains and utilisation of local fossil fuel resources.		
trend 5	The war in Ukraine, as well as recent disruptions in the Middle East, have heightened the importance of energy security.		
trend 6	Global energy demand has continued to grow at around 1% per year over 2019-23 driven by increasing prosperity and growth in emerging economies.		
trend 7	In 2023, fossil fuel consumption reached an unprecedented high, primarily driven by a substantial increase in oil consumption. The total investment in oil and gas upstream activities amounted to 550 billion USD.		
trend 8	The prevailing circumstances are marked by a notable escalation in natural gas demand within emerging Asian economies, concomitant with disruptions to Russian pipeline exports to Europe. This has led to an augmentation in the significance of liquified natural gas within the global gas market.		
trend 9	The downward trend in energy efficiency improvement is evident. The amount of energy used per unit of economic activity has fallen by slightly over 1% per year – a rate that is slower than the previous 10 years and weaker than the 4% annual rate targeted in the COP28 energy efficiency pledge.		
TREND 10	In recent years, growth in electricity has continued to outpace the growth in total energy demand as the energy system has become increasingly electrified. Additionally, growth in less mature, higher-cost, low-carbon energy vectors and technologies, including low-carbon hydrogen, synthetic biofuels, and carbon capture and storage, remains at a very early stage.		

Source: own compilation based on KPMG and British Petroleum reports

The previous year established fundamental records for total fossil fuel consumption, precipitating substantial shifts in emissions from the energy sector, with particular consequences for renewable energy production, largely attributable to the development of wind and solar energy. In light of the prevailing global geopolitical uncertainty, a range of regional events have persisted in exerting influence on the global energy market. For instance, the war in Ukraine has been a contributing factor to the redistribution of gas resources within Europe. The overall demand for gas has decreased sufficiently to establish a new consumption paradigm, and Russia's share of total gas imports to the European Union has diminished. With regard to Ukraine, discernible shifts in market equilibrium have also been observed. Specifically, there have been significant changes in energy strategy in response to new geopolitical challenges that have arisen as a result of the war. The focus is given to distributed generation in a comprehensive manner, with the objective being to ensure the stability and flexibility of the energy system in its entirety. Among the innovative measures being implemented is the expansion of gas generation through mini-TPPs and CHPs. Consequently, a number of state-owned enterprises have disclosed their intention to augment their production capacities. Renewable energy sources are also maintaining their market relevance. Evidence of this can be seen in the joint projects being undertaken with the EBRD, as well as the involvement of international companies such as Vestas, Notus Energy and Goldbeck Solar. These factors indicate a growing interest in renewable energy sources within Ukraine.

In general, despite the significant advances that have been made since the momentous Paris Agreement nine years ago, the global energy transition is now entering a more arduous phase. This is characterised by mounting costs, escalating complexity and technological challenges. In order to achieve the objectives set out in the Paris Agreement, it is imperative that immediate action be taken and a more rapid rate of transformation be initiated. Furthermore, the transition to clean energy must be meticulously balanced with the assurance of affordability, energy system resilience and energy security within an increasingly uncertain macroeconomic framework.

3.3. Modern State of Electricity Generation Market in Ukraine

The electricity generation industry is widely regarded as being of paramount importance with respect to GDP provision throughout the historical period of Ukraine. The range of production facilities is subject to variation in accordance with the energy sources employed, which may include coal, renewables, and nuclear, amongst others. Prior to the invasion in 2022, the Ukrainian energy industry was a highly influential and multi-sectoral entity, enabling it to exercise considerable control over its generation capacity. According to official data provided by the National Power Company (NPC) Ukrenergo, as of January 2022, Ukraine's total installed capacity was 34 GW, comprising 2 GW from wind power plants, 6 GW from solar power plants, 5 GW from hydro power plants, 1 GW from pumped-storage hydroelectricity, 6 GW from combined heat and power stations and biofuel stations, and 14 GW from nuclear power plants.

As demonstrated in the preceding data set, the predominant source of electricity is derived from large thermal and nuclear power plants, accounting for over 70% of the total production. This electricity is subsequently transmitted to consumers through primary transmission lines and distribution networks. Electricity from almost every power plant in the country can be transmitted to any area throughout Ukraine via at least two established routes. The primary system requirement is predetermined by the characteristics of the good itself, as the amount of electricity produced must be equal to the amount of electricity consumed. Regulation is usually carried out by switching individual power plant units on and off in a timely manner (mainly hydroelectric power plants due to their flexibility and capacity for manoeuvring). If the existing generating capacity is insufficient, or if power lines/transformers cannot transmit the required electricity from remote power plants (including those in Europe), consumers in certain regions are disconnected so that the rest of the power system can continue to operate.

In addition, the price of electricity from a particular grid is usually lower than the comparable price of electricity from autonomous generation systems. It is also clear that electricity consumption patterns throughout the day in different regions may be uneven. For example, consumption at night may differ by more than two times from the equivalent consumption during peak hours (morning or evening). Similarly, there are seasonal fluctuations, as consumption is significantly higher in winter due to the significant increase in the use of artificial lighting and space heating.

Consequently, the winter evening and morning hours pose the greatest challenges to the effective functioning of the power system. Another trend that has become increasingly evident in recent years is the increased use of solar power plants connected to the grid. It is a well-established principle that such power plants do not typically possess electricity storage capabilities, and their generation is significantly influenced by meteorological conditions. Peak generation occurs during the daytime in summer, when demand for electricity is relatively low. In Ukraine, solar generation currently accounts for up to 5%

of the energy balance, which is not particularly dominant. However, given European trends, this factor must be taken into account when planning the development of the power supply system.

It is evident that the full-scale invasion and targeted terrorist actions perpetrated by the Kremlin against this sector of the economy resulted in considerable destruction and weakening. Primarily, this destruction impacted the capacity of the Ukrainian generation sector. The consequences of these changes are far-reaching, with irreversible shifts occurring across various aspects of the Ukrainian generation system and the global landscape. In particular:

– March 2022 *Zaporizhzhia* NPP, the largest in Europe, was seized, resulting in minus 6 GW or 42% of the country's entire nuclear generation;
– after the attack on April 11, 2024, the *Trypilska* TPP, the largest one in Kyiv Oblast, was completely destroyed with a minus of 3.2 GW in the system (*Centerenergo* lost 100% of its power generation capacity);
– March 2024 *Zmiivska* TPP (2.175 GW) was destroyed by a Russian strike in the Kharkiv Oblast;
– July 2022 *Vuglehirska* TPP (3.6 GW) in the Donetsk Oblast has been occupied by Russian troops;
– March 2024 *Kharkiv* TPP-5 (0.54 GW), one of the largest in Ukraine, was completely destroyed after the Russian attack, thus a big city Kharkiv lost its main thermal and electrical energy generation capacities;
– March 2024 missile strikes at the *Ladyzhyn* TPP (1.8 GW) and the *Burshtyn* TPP (2.3 GW) damaged all power units;
– April 2024 Russia attacked the *Sumy* TPP with guided aerial bombs;
– March 2024 the Kremlin struck Ukraine's largest *Dnipro* HPP (Zaporizhzhia) with the complete stop of operations at HPP-1 and HPP-2 (1.5 GW);
– June 2023 the *Kakhovka* HPP (0.35 GW) was blown up by the Russians, which caused, among other things, the largest environmental disaster;
– the *Dniester* HPP (0.7 GW) and the *Kaniv* HPP (0.4 GW) were also attacked and partially destroyed.

Consequently, the aggregate losses in electricity generation as of June 30, 2024, are estimated to be approximately 22,565 GW (State Energy Efficiency of Ukraine). A mere 11,435 GW of theoretically surviving capacities remain, with a significant proportion of these being solar power plants. However, it is important to note that these power sources will not be capable of providing such an amount of electricity during the winter months. This has resulted in a substantial deficit of electricity, precipitating widespread blackouts.

In this research study, the main goal is to try to take into account different scenarios of international development. As previously mentioned, there are several forecasts that have been cited. However, a prediction of electricity production in Ukraine for the near future is proposed herein. With the help of the EXCEL add-in, an in-depth analysis of secondary data on electricity generation in Ukraine for the period 1990-2023 was carried out in order to provide a forecast for the period 2024-2035. The FORECAST function is used to predict future values based on linear regression. It is evident that the functionality under discussion also employs supplementary components, including the *confidence interval function*. The latter is responsible for calculating the amount to be added to or subtracted from the sample mean in order to obtain a confidence interval. It is imperative for effective data analysis and reliable future forecasting. This is not only true for electricity generation in general, but also for both optimistic and pessimistic scenarios (see Figure 1).

The situation in terms of the "before-after" potential is considered to be rather complicated in terms of defining the most beneficial scenarios. Prior to the invasion in February 2022, the Ukrainian energy market was among the most influential in Europe, a position determined by its geographical prerequisites and territorial area. It is evident that Ukraine possesses a substantial electricity generation capacity, ranking among the foremost in Europe. Furthermore, the nation boasts a significant underground gas storage capacity, which is regarded as the most substantial in the European continent. More than half of Ukraine's electricity is generated from nuclear, hydro and renewable sources, leading the country towards a neutral future with a decreased amount of CO_2. Furthermore, there are a large number of fuel transition facilities for reliable and long-lasting collaboration with neighbouring European countries.

Since 2014, Ukraine has been engaged in a process of reducing its reliance on Russian gas. Nevertheless, the country was still dependent on fuel imports, either partially or in its entirety. Prior to the Russian invasion in February 2022, Ukraine had succeeded in meeting up to 75% of its domestic coal demand through domestic production. In instances where requisite resources were scarce, a diverse array of competitive suppliers was integrated into the import schemes to facilitate effective collaboration.

At the onset of military operations in Ukraine, the domestic market was predominantly reliant on oil product imports from Russia and Belarus. At that time, Ukraine's domestic provision of resources was only 30%. In June 2022, NNEGC ENERGOATOM entered into a series of agreements with AMERICAN WESTINGHOUSE ELECTRIC COMPANY, stipulating the terms of a nuclear fuel supply agreement. Over the following few weeks, the power systems of Ukraine and Moldova were synchronised with the EU network, ENTSO-E. Ukraine has

Figure 1. Electricity generation forecast for 2024-2035 in Ukraine (probable, optimistic, pessimistic)

Source: author's own compilation

successfully started commercial electricity trade with the European Union since June 2022.

It is important to note that the potential for renewable energy is set to become a more prominent area of focus in the global context, given its strategic importance. Nevertheless, the situation has always been somewhat precarious, even prior to the invasion.

Ukraine has also demonstrated its determination to contribute to this global trend. The solar energy market is one of the fastest-growing sectors worldwide. It is predicted that, by 2050, renewable sources may account for 85% of electricity generation. In 2019, the share of wind and solar generation in electricity production was 3.3%, increasing to 6.6% in 2020 and reaching 10% in 2021 (The Ministry of Energy of Ukraine). The attainment of these milestones can be attributed to the rapid expansion of green energy production facilities on a nationwide scale. However, financial incentives were also present, encouraging businessmen to invest in green energy in Ukraine. The primary catalyst for the accelerated development of alternative energy sources was the introduction of the highest green tariff in Europe, which stipulated the open purchase of energy generated by renewable sources by the state at prices significantly higher than market rates. For instance, in mid-2021, the mean level of this green tariff for industrial solar power plants was 13 EUR cents per 1 kW of electricity (fixed in euros until 2030).

It is an inevitable consequence of the prevailing circumstances that alternative energy has become one of the most attractive investment opportunities in the domestic economy. According to contemporary analytical perspectives, approximately 7.2 billion USD was invested in Ukrainian renewable energy sources during the period spanning from 2015 to 2020. However, in 2019, a radical shift in the situation was observed. Almost immediately after the introduction of the electricity market in Ukraine, disruptions in payments began to occur under the fulfilment of green tariff. In June 2020, a special agreement was concluded between the government and specialised associations. According to this agreement, the state pledged to settle its debts, while investors committed to reducing the electricity purchase price. However, as of the beginning of October 2021, the debt to businesses had not yet been settled, resulting in its total amount reaching approximately 28 billion UAH. In order to settle outstanding debts, NPC Ukrenergo issued Eurobonds amounting to 825 million USD (NPC Ukrenergo). The state utilised the financial proceeds from the transparent sale of the aforementioned bonds to fully settle all renewable energy producers in November, with the exception of the DTEK holding.

Notwithstanding the gradual reduction of green tariffs and issues surrounding the state's fulfilment of obligations to investors, solar energy persists as a highly prospective domain for investment, given

that the payback period for an industrial solar power plant is typically 5-7 years. It is widely acknowledged that the entity in question is a highly lucrative commercial enterprise.

Furthermore, the sector is subject to constant change and evolution, irrespective of war and active military actions that result in direct destruction and exclusion. In the Sustainability Plan of Ukraine, presented by the President of Ukraine at the end of 2024, one of the key areas is energy, with a particular emphasis on sustainable and safe energy sources. The primary focus is on the advancement of nuclear generation as an indisputable cornerstone of energy security. In addition, the creation of regional sustainability passports is scheduled for completion by the conclusion of 2024. The purpose of these passports is to evaluate the energy status of each region. Consequently, in 2025, generation passports will be implemented for the effective management of energy resources.

These incentives are also extended to the corporate level. In order to implement the most grounded changes, it is necessary to refer to the Resolution of the Cabinet of Ministers of Ukraine "On Approval of the Strategy for Implementation of Sustainability Reporting by Enterprises". The Strategy underscores the significance of the introduction in Ukraine of the preparation, submission and disclosure of sustainability reports by enterprises based on the European Sustainability Reporting Standards (ESRS). It is imperative to acknowledge the introduction of procedures for auditing sustainability reports of enterprises in Ukraine, along with the establishment of an effective mechanism for the quality control of such audit services.

It is evident that the war in Ukraine has had a considerable impact on the energy sector, as evidenced by the destruction of infrastructure, supply disruptions, and extensive changes in energy policy (Verkhovna Rada of Ukraine, 2024). The comprehensive destruction of generating stations, power grids, gas pipelines and other key facilities has become one of the most pressing challenges currently facing the world. The restoration of these facilities necessitates substantial financial resources and temporal investment, whilst concomitantly effecting a diminution in the nation's production capacity.

It is evident that the provision of support from European partners is of critical importance for the energy sector of Ukraine. Nevertheless, it is important to note that delays and reductions in the aforementioned support, in addition to the accumulation of debt in the market, may result in the government being compelled to reduce subsidies for vulnerable segments of the population and increase tariffs. This, in turn, may result in an increase in electricity prices. The domestic market has witnessed an escalation in prices, a phenomenon attributable to a diminution in state support. It is also probable that the government will focus on implementing green projects and developing energy storage to ensure the stability of energy supply in the post-war period. Private sector will also take the lead following the example of *DTEK* company with *Tyligulska* windfarm to generate 1.7 TWh annually since 2025 constituting the largest windfarm built in a decade in Eastern Europe (DTEK).

In light of the aforementioned forecasts, it is anticipated that nuclear energy will continue to play a pivotal role in Ukraine's energy portfolio. Natural gas, which currently accounts for less than 10% of electricity generation, is set to play a pivotal role in heating systems. Its share is projected to rise after 2030, driven by net-zero initiatives, with a view to replacing coal-fired generation.

Notwithstanding the challenges confronting Ukraine's energy sector, its development prospects encompass a transition to clean and sustainable energy sources, the integration of new technologies and a broad diversification of its energy mix. The success of these efforts is contingent upon sustained international support and effective management of domestic resources.

4. Conclusions

The war in Ukraine has precipitated an array of unprecedented challenges on a global scale. The advent of a new existential paradigm has been precipitated by a series of irreversible shifts in terms of independence and security, encompassing various international markets. This paradigm shift has been driven by the imperative to attain tangible certainty regarding fundamental geopolitical issues. The challenges faced by Ukraine in connection with the full-scale military operations on the territory of this country are particularly undeniable and serious for the energy sector. This is applicable to two distinct scenarios. Firstly, the prompt restoration of infrastructural facilities in the aftermath of missile attacks. Secondly, the facilitation of a less harmful passage of the autumn-winter heating period, which is currently anticipated to be arduous for the entire European continent as well as for the Russian military. Furthermore, it is imperative that the matter of strategic energy industry restoration and potential generation renewal is addressed in the context of Ukraine's acquisition of EU candidate status with utmost urgency. It is anticipated that identifying the optimal solution for each challenge may present a significant challenge. However, it is imperative to define and record strategic priorities as well as financial sources and economic capabilities correctly, in order to ensure the development of energy regulation systems is as predictable and transparent as possible for all energy market participants.

In order to address the critical issue of the energy trilemma, with regard to future compliance with global targets and challenges, as well as the provision of a reliable electricity supply to consumers, a number of practical solutions can be considered. Firstly, the construction of additional generating capacities in regions is imperative in order to balance the demand and supply of electricity and minimise the flow within the power system. Concurrently, such distributed generation exhibits reduced vulnerability to enemy attacks due to its diminished size and local impact from a shutdown. In terms of the prospects for further use, the most profitable option is the construction of cogeneration plants based on existing boiler houses. This will enable the most efficient use of fuel and electricity, as well as providing heating of the coolant for heating and hot water supply.

It is imperative to augment the capacity of networks, including the restoration of damaged electrical substations. This measure is likely to be optimal in peacetime, but during military action, the risks of repeated hits remain significant. It is evident that the construction (installation) of autonomous generators (diesel or gasoline) is meticulously engineered to function exclusively during periods of electricity supply interruption.

Another essential measure involves managing consumption among consumers. This would help to balance the power grid schedule and minimise the flow between individual parts of the power system, reducing the total load required by power plants. Installing powerful storage devices would also help to balance the power grid schedule. These storage devices should be installed at key points in the power system and at the homes and businesses of individual consumers.

When evaluating the relative merits of the various options, it is important to consider not only the cost and time of implementation, but also the overall increase in system efficiency. In this regard, the energy management option is the most effective, although it is often insufficient. The issue of financing is similarly intricate. In light of the heightened risks engendered by an uncertain economic climate, which has a deleterious effect on conventional investment avenues, there is an imperative to expand the capital market and devise novel financing mechanisms that can mitigate the risk of uncertainty and facilitate private sector financing. In the context of war and economic uncertainty, all companies have prioritized the retention of their workforce and have recognised the importance of preserving and enhancing human capital. In order to enhance the productivity and competitiveness of enterprises, there is a necessity for augmented investment in human capital with a view to adapting and developing employees' technical, soft and digital skills.

The issue of Ukraine's MSMEs and their limited internationalisation must be addressed by the creation of comprehensive policy frameworks and business development instruments. The purpose of these instruments is to facilitate and support the inclusion of businesses in international supply and value chains, and their integration into the EU single market.

In the long term, it is crucial to develop a comprehensive strategy to enhance electricity generation capacity significantly, creating a distinctive energy system of which the Russians will be unaware. This involves gradually increasing energy assets, particularly gas turbines, and placing them in sufficient numbers throughout the network in places where the Russians would not expect them. This distributed system can be operated in a versatile manner and is effectively protected against potential attacks.

A further objective that is to be established for the Ukrainian energy sector, as part of the European energy system, is to achieve climate neutrality by 2050. Achieving this objective will require the development of clean, low-carbon energy sources through the utilisation of renewable generation technologies, in addition to the introduction of novel nuclear energy systems. These measures will contribute to enhancing system stability and replacing existing carbon-based technologies.

It is important to note that the primary factor influencing the cost of energy is access to affordable capital. Investors would gain access, potentially on a competitive basis, to inexpensive debt capital through the introduction of state support in the form of annual balanced quotas for the development of renewable energy, maneuverable capacities and storage facilities. Investment decisions continue to be characterised by a high degree of risk, not only in the context of the war (in view of the fact that war risks can be accommodated, as evidenced by the actions of certain governments), but also with regard to the unpredictability of regulatory risks. A further consideration is that Ukraine must initiate a course of action that is economically viable with regard to the issue of carbon pricing, in order to comply with the provisions of the Carbon Border Adjustment Mechanism (CBAM) with effect from 2026.

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