# ASSESSING THE IMPACT OF INNOVATIVE TECHNOLOGIES ON THE SUSTAINABLE DEVELOPMENT OF ENERGY SYSTEMS: A COMPARATIVE ANALYSIS OF TECHNICAL AND ENVIRONMENTAL INDICATORS

**Cited as:**

Borychenko, O., Cherniavskyi, A., Pobigaylo, V., Savchenko, V., & Lyudmyla, M. (2024). Assessing the impact of innovative technologies on the sustainable development of energy systems: a comparative analysis of technical and environmental indicators. ***Revista Gestão & Tecnologia***, *24*, 257-286. https://doi.org/10.20397/2177-6652/2024.v24.2836

**Olena Borychenko**, PhD in Engineering, Associate Professor, Department of Power Supply, Educational and Research Institute of Energy Saving and Energy Management, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine. borichenko_olena@ukr.net, http://orcid.org/0000-0002-6127-2945

**Anatolii Cherniavskyi**, PhD in Engineering, Associate Professor, Department of Power Supply, Educational and Scientific Institute of Energy Saving and Energy Management, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine. canatoliy1976@gmail.com, https://orcid.org/0000-0003-2858-8224

**Vitaliy Pobigaylo**, PhD in Engineering, Associate Professor, Department of Power Supply, Educational and Research Institute of Energy Saving and Energy Management, National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Kyiv, Ukraine. https://orcid.org/0000-0003-2673-7329

**Vasyl Savchenko,** PhD in Engineering, Assistant Professor, Head of the Department of Machine Operation and Service of Technological Systems, Polissya National University, Zhytomyr, Ukraine. dgs-ua@ukr.net, http://orcid.org/0000-0002-0921-1424

**Mykhailova Lyudmyla**, PhD in Engineering, Professor, Dean of the Faculty of Energy and Information Technologies, Higher Education Institution "Podillia State University", Kamianets-Podilsky, Ukraine. mihajlovaimesg@gmail.com, https://orcid.org/0000-0002-3419-5446

## ABSTRACT

**Objective:** The study aims to evaluate how innovative technologies impact the sustainable development of energy systems, focusing on indicators like resource consumption, green energy dynamics, and environmental efficiency.

**Methodology:** Analytical methods, including comparison and data visualization, were used for analysis, with Microsoft Office Excel 10. Data from various sources like the International Energy Agency, State Statistics Service of Ukraine, Our World in Data, Eurostat, BloombergNEF, IRENA, The World Bank, and legislative documents from Ukraine and the EU were utilized.

**Originality**: This study fills a theoretical gap by examining the contradiction between energy and environmental efficiency in current energy systems, emphasizing the need for country-specific adaptations and learning from successful country experiences.

**Main results:** Findings suggest that green energy expansion is significant in regions with supportive government policies, but there's a discrepancy between energy and environmental efficiency, calling for tailored energy system adaptations.

**Theoretical/methodological contributions:** The research shifts the paradigm from "produce as much as I consume" to "produce as much as I can, consume as needed," driven by political decisions for green energy policies and technological innovations like distributed energy systems, energy storage technologies, and SMART Grid technologies.

**Social/management contributions:** The study underscores the importance of innovative capacity, smart grid development, and balancing renewable resource distribution with environmental efficiency in shaping sustainable energy systems. Governance and security measures are advocated to manage the globalization and decentralization of energy resources, considering the political leverage of fuel and energy resources in global economic management.

**Keywords:** Innovative technologies. The sustainable development. Energy systems.

## EVALUACIÓN DEL IMPACTO DE LAS TECNOLOGÍAS INNOVADORAS EN EL DESARROLLO SOSTENIBLE DE LOS SISTEMAS ENERGÉTICOS: UN ANÁLISIS COMPARATIVO DE INDICADORES TÉCNICOS Y MEDIOAMBIENTALES

### RESUMEN

**Objetivo:** El estudio pretende evaluar cómo influyen las tecnologías innovadoras el desarrollo sostenible de sistemas energéticos, centrándose en indicadores como el consumo de recursos, la dinámica de energía verde y la eficiencia medioambiental.

**Metodología:** Para el análisis se utilizaron métodos analíticos, como comparación y visualización de datos, Microsoft Office Excel 10. Se utilizaron datos de diversas fuentes, como la Agencia Internacional la Energía, el Servicio Estatal de Estadística de Ucrania, Our World in Data, Eurostat, BloombergNEF, IRENA, el Banco Mundial y documentos legislativos de Ucrania y la UE.

**Originalidad:** Este estudio llena un vacío teórico al examinar la contradicción entre eficiencia energética y medioambiental en sistemas energéticos actuales, haciendo hincapié en necesidad de adaptaciones específicas para cada país y aprender de experiencias de países que han tenido éxito.

**Principales resultados:** Los resultados sugieren que expansión de la energía verde significativa en regiones con políticas gubernamentales de apoyo, pero existe discrepancia entre la eficiencia energética y medioambiental, lo que exige adaptaciones a medida del sistema energético.

**Aportaciones teóricas y metodológicas:** La investigación cambia el paradigma de "produzco tanto como consumo" a "produzco tanto como puedo, consumo tanto como necesito", impulsado por decisiones políticas de políticas de energía verde e innovaciones tecnológicas como sistemas de energía distribuida, tecnologías de almacenamiento de energía y tecnologías SMART Grid.

**Contribuciones sociales/de gestión:** Se aboga por medidas de gobernanza y seguridad para gestionar la globalización y descentralización de recursos energéticos, teniendo en cuenta la influencia política de combustibles y recursos energéticos en la gestión económica mundial.

**Palabras clave**: Tecnologías innovadoras. Desarrollo sostenible. Sistemas energéticos.

# AVALIAÇÃO DO IMPACTO DE TECNOLOGIAS INOVADORAS NO DESENVOLVIMENTO SUSTENTÁVEL DE SISTEMAS DE ENERGIA: UMA ANÁLISE COMPARATIVA DE INDICADORES TÉCNICOS E AMBIENTAIS


## RESUMO

**Objetivo:** O estudo tem como objetivo avaliar o impacto das tecnologias inovadoras no desenvolvimento sustentável dos sistemas energéticos, centrando-se em indicadores como o consumo de recursos, a dinâmica da energia verde e a eficiência ambiental.

**Metodologia:** Métodos analíticos, incluindo comparação e visualização de dados, foram utilizados para análise, com o Microsoft Office Excel 10. Foram utilizados dados de várias fontes, como a Agência Internacional de Energia, o Serviço Estatal de Estatística da Ucrânia, Our World in Data, Eurostat, BloombergNEF, IRENA, Banco Mundial e documentos legislativos da Ucrânia e da UE.

**Originalidade:** Este estudo preenche uma lacuna teórica ao analisar a contradição entre a eficiência energética e ambiental nos actuais sistemas energéticos, salientando a necessidade de adaptações específicas a cada país e de aprender com as experiências bem sucedidas dos países.

**Principais resultados:** Os resultados sugerem que a expansão da energia verde é significativa em regiões com políticas governamentais de apoio, mas existe uma discrepância entre eficiência energética e ambiental, o que exige adaptações do sistema energético.

**Contribuições teóricas/metodológicas:** A pesquisa muda o paradigma de "produzir tanto quanto eu consumo" para "produzir tanto quanto eu posso, consumir conforme necessário", impulsionado por decisões políticas políticas de energia verde inovações tecnológicas como sistemas de energia distribuída, tecnologias de armazenamento de energia e tecnologias SMART Grid.

**Contribuições sociais/de gestão:** O estudo sublinha a importância da capacidade inovadora, do desenvolvimento de redes inteligentes e equilíbrio da distribuição dos recursos renováveis. São preconizadas medidas de governação de segurança para gerir globalização e descentralização dos recursos energéticos.



**Palavras-chave:** Tecnologias innovadoras. Desenvolvimento sustentável. Sistemas energéticos.

Editor Científico: José Edson Lara
Organização Comitê Científico
Double Blind Review pelo SEER/OJS
Recebido em 13.11.2023
Aprovado em 15.03.2024


## INTRODUCTION

Today, the impact of innovative technologies is becoming more and more noticeable. Innovations have transformed almost all areas of human activity, including energy systems. First of all, this applies to economically developed countries or countries with active economic growth. New approaches, such as improving technological processes in terms of energy intensity and energy saving, as well as expanding energy production from renewable sources, allow for a gradual transition to green energy. However, in such circumstances, there is a need to study the impact of innovative technologies on the sustainable development of energy systems according to certain criteria, such as technological and environmental indicators. At the same time, it is necessary to study the trends that are most influential on these characteristics.

Therefore, the purpose of this paper was to study the impact of innovative technologies on the sustainable development of energy systems.

Technological and environmental indicators were selected as indicators, including: countries' ability to innovate, total resource consumption, dynamics of changes in green energy volumes and environmental efficiency indicators, and indicators of the energy trilemma,

The relevance of the work is confirmed by the need to assess the sustainable development of energy systems in different countries.

## THEORETICAL FRAMEWORK

Moving towards improving the quality of society, the world community has developed a new concept of development, in which the increase in the welfare of society is accompanied by a careful attitude to the environment and the preservation of natural resources for future generations. This concept is known as the concept of sustainable development, and a certain strategy has been developed for its implementation. Yakymenko et al. (2022), as well as a large number of other researchers, identify three main interdependent components of the sustainable development strategy: 1) economic development (economic component); 2) environmental protection and preservation (environmental component); 3) social development (social component). In her work prepared under a grant from the European Commission Melnyk (2018), she notes that economic development is now closely linked to the concept of a green economy. Its main priorities are high energy efficiency and minimal environmental impact. At the same time, the energy efficiency policy Redko, Denyshchnko, Dobrovolska, Lukyanenko, & Kyryllova (2022) for each country is built on the basis of its national characteristics and priorities Buzugbe (2023) Suprunenko, Pylypenko, Trubnik, & Volchenko (2023), based primarily on international best practices Bozhkova & Halytsia (2022), Vdovichena, Vidomenko, Tkachuk, Zhuzhukina, & Lukianykhina (2022) and innovative technologies Kibik et al. (2022), Tymoshenko, Saienko, Serbov, Shashyna, & Slavkova (2023). It is well known that energy efficiency is a component of the assessment of each energy system Abdolmaleki & Bugallo (2021), Brugger, Eichhammer, Mikova, & Dцnitz (2021) and this means that the study of the impact of innovative technologies on the sustainable development of energy systems is timely and relevant.

## METHODOLOGY

In the course of the study, the methods of analysis of indicators were used (to characterise the dynamics of changes in the state of energy efficiency in quantitative terms through a system of absolute and relative indicators).

Analytical methods used: comparison; generalisation; data visualisation. Microsoft office Excel 10 was used as a tool for data analysis and visualisation.

As an information base for the study, open access materials were used, such as works published. Data from information publications and methodological recommendations of the International Energy Agency, the State Statistics Service of Ukraine, as well as data from the non-profit project Our Word in Data and Eurostat Statistical Yearbook (2022, 2023) were also used. BloombergNEF, New Energy Outlook 2022, IRENA (2017, 2022), ESTAT:Eurostat, (2019). The World Bank (2020, 2022), some materials of the legislative framework of Ukraine and the European Union (EU).

Data from different sources were compared with each other. If the data from different official sources differed significantly, the average value was chosen.

## RESULTS

Due to the rapid growth of energy needs and the shift in energy production towards greening, modern energy systems face the need for significant changes through technology development and innovation. According to, Law of Ukraine “On Innovative Activity” Verkhovna Rada of Ukraine (2002): defines innovation as “newly created (applied) and (or) improved competitive technologies, products or services, as well as organisational and technical solutions of a production, administrative, commercial or other nature that significantly improve the structure and quality of production and (or) the social sphere”.

A country's place in global rankings is an indicator of the effectiveness of the state's innovation policy. Many international rankings and assessments of the level of development of countries have been developed. One of them is The Global Innovative Index (2022) or GII, which is widely recognised as a source of information on innovation. The GII assesses the level of innovation development in a country, its expenditures on innovation and the results of decisions made. The index takes into account the conditions for starting and developing a new business, the country's tax policy, the quality of education, and the availability of macro-financing and venture capital. Figure 1 shows the top 20 countries in the overall ranking of 132 countries in 2022. Ukraine ranks 57th in this ranking, India 40th.

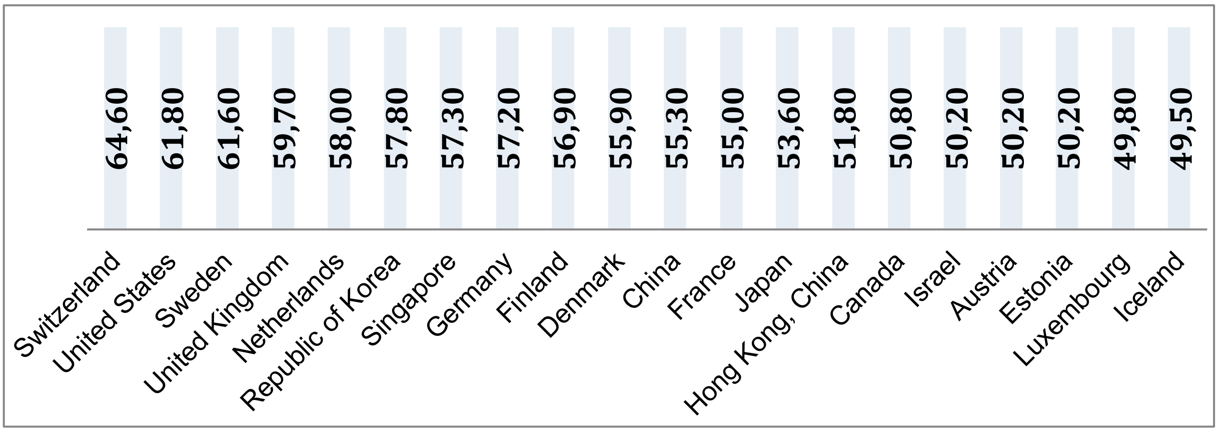


**Fig. 1** GII countries in the top 20 of the overall list.
Compiled by the authors based on (The Global Innovational Index, 2022)

There is a need to maintain or increase their sustainability, reliability, and efficiency. The introduction of innovative technologies, including SMART technologies (Zang, Tian, Go, Liu, Li, Zhu & Wu, 2022), artificial intelligence (Entezari, Aslani, Zahedi, & Noorollahi, 2023; Sukhodolia, 2022), and other modern solutions opens up wide opportunities to improve the functionality of power systems and adapt them to the growing needs of consumers (Bakhmachuk & Bakhmachuk, 2018).

In general, a classic power system consists of the following elements:

1. Electricity generation capacity
2. Consumers
3. Highways connecting producers and consumers
4. Control rooms that manage the process.

Historically, most countries in the world have developed a generation system based on the principle: how much we produce is how much we consume. That is, we are talking about the energy balance (Kuznietsov & Melnyk, 2020). Maintaining this balance is one of the key factors of classical energy systems. Unfortunately, producing more energy than needed is just as harmful as producing less energy than needed. In both cases, this affects the quality of electricity, primarily the AC frequency and voltage. Therefore, a classical power system combines different sources of electricity to ensure its balanced operation. For their participation in creating a balance, it is important to correctly assess two factors: controllability and manoeuvrability (Khomenko, Plakhtii, Nerubatskyi, & Stasiuk, 2020; Muratori et al., 2020).

All power plants can be divided into two groups as shown in Table 1

**Table 1** - Types of power plants by control principle

| Controllability of stations | |
|---|---|
| **Managed** | **Conditionally controlled** |
| Power plants that allow for the metered conversion of primary energy into electricity are called controlled power plants. They include thermal power plants (TPPs), nuclear power plants (NPPs), biogas power plants, and hydroelectric power plants (HPPs). | Conditionally controlled power plants are those whose capacity can be controlled only by shutting down some equipment, inverters, turbines, etc. These include solar and wind power plants. |

Compiled by the authors based on (Khomenko et al., 2020).

Controlled plants complement conventionally controlled ones to achieve a balance between electricity produced and consumed.

The second factor is manoeuvrability: i.e. the ability to quickly change the generated power, which is mostly related to controlled sources. The manoeuvrability indicator is how long it takes for a plant to reach zero to rated power generation capacity and vice versa (Muratori et al., 2020). The quality of electricity depends on the balance between generated and consumed power. Accordingly, each source of the power system provides a share of the electricity load, considering its own characteristics (Efimov, 2020). Nuclear power plants and combined heat and power plants provide the basic, unchanging part of the daily load change schedule, while slow and planned fluctuations are covered by thermal power plants and renewable energy sources. Peak loads are met by hydro and pumped storage power plants (PSPPs). In other words, in a classical power system (Komar, Lezhniuk, Lesko, Malogulko, Netrebskyi, & Sikorska, 2022), its balance is ensured by hydro and thermal power plants. The balance between consumption and generation is achieved by changing the load of HPPs and TPPs, but the load of TPPs varies within a limited range, usually not exceeding 30% of the installed capacity of the power unit. Another 1/3 of the regulatory range is provided by HPPs and PSPPs, provided there is sufficient water and hydraulic units are in operation. However, about a third of the difference between peak and night consumption remains unregulated. The problem has to be solved by shutting down overnight and then starting up pulverised coal-fired power plants in the morning. In some periods, the number of such operations reaches dozens of starts/shutdowns per day.

Renewable energy sources are conditionally controllable (Lezhniuk, Komar, & Kravchuk, 2019), which means that in a classical power system, controlled and manoeuvrable sources are needed to balance them. It turns out that with the development of renewable sources, more thermal and large hydroelectric power plants need to be built, which are harmful to the environment. This creates a green-coal paradox (Bakhmachuk & Bakhmachuk, 2018). That is, the use of thermal power plants leads to additional greenhouse gas emissions, and large hydropower plants change the hydrological regime, lead to the destruction of banks, flooding of large areas of land, which has a negative impact on the environment.

Several ways have been found to resolve this paradox. The most promising of these are related to changing the architecture of the power system itself - the transition from centralised to distributed Aydin (2019), Lezhniuk et al. (2019) and from manual to SMART control (Doddamani & Kapale, 2019). An example of such a solution Kuznietsov & Melnyk (2020) is shown in Fig. 2.

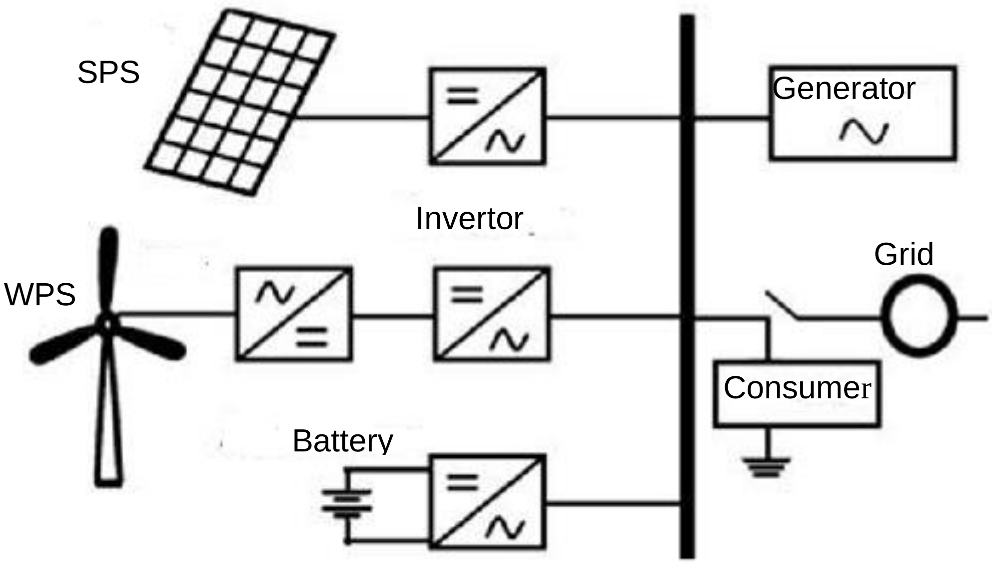


**Fig. 2 -** Diagram of the combined grid-autonomous power system. (Kuznietsov, & Melnyk, 2020).

Figure 2 shows a hybrid energy storage system connected to a variable microgrid. Such a system can work both with the grid and autonomously. The energy sources are connected in parallel to a common AC bus through individual converters, which allows them to operate independently in grid mode. The storage battery is charged/discharged depending on the situation, the current capacity of the generators or the needs of the consumer. In autonomous operation, each energy source supplies the consumer directly, and the battery maintains the voltage level. The maximum power point for each source is provided separately in grid mode, and in stand-alone operation, only when the battery is used.

A solution within the framework of a classical power system: the creation of balancing groups (Gan, Jiang, Lev, & Zhou, 2020). Currently, a balancing group is an association of different types of renewable energy sources (wind, solar, bio-, and small hydro generation) in which participants balance each other, making joint generation more manageable and predictable and without the participation of thermal power plants. However, when working with wind and solar RES, it is necessary to take into account their variability, an example of which is shown in Fig. 3.

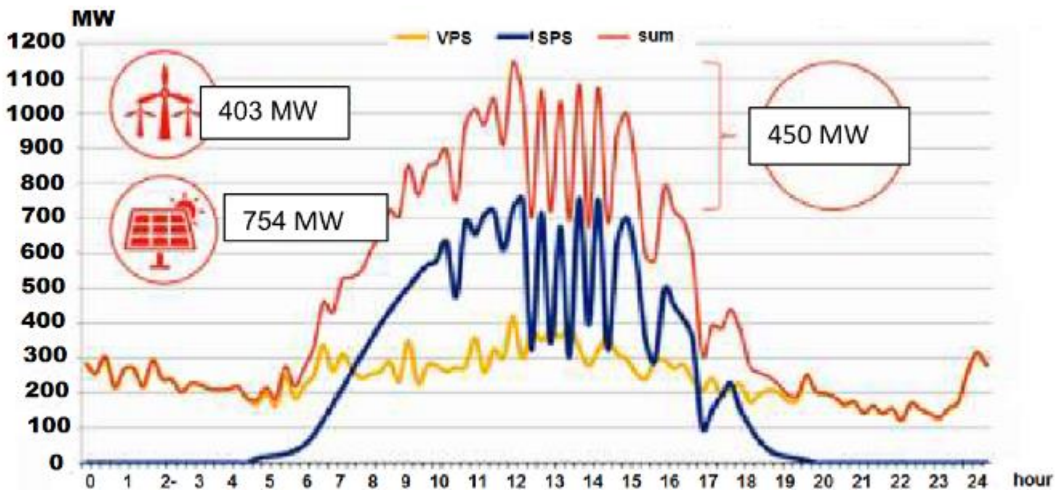


**Fig. 3 -** an example of the operation of the existing RES volatility at the beginning of 2018 according to the data of Ukrenergo's SC (Kuznietso & Melnyk, 2020)

The way out is to create a balancing group whose members are quite geographically distant.

The basic idea of a balancing group is that it is a voluntary association of market participants. Energy producers under the feed-in tariff are united into one balancing group, and the party responsible for the balance is the guaranteed buyer. It works as follows: producers under the green tariff declare their projected schedule for the next day, and then the guaranteed buyer collects them all into a single application and sells it on the market for the day. When the day of output arrives, not all energy producers fulfil their declared volume. Therefore, a certain imbalance is created Klusactk, Drapela, & Langella (2023), but since one producer could under-apply and another over-apply within the same balancing group, the aggregate of all applications somewhat smooths out their overall imbalance. In other words Parol et al. (2020), the larger the balancing group, the smaller the imbalances of each individual participant. It is worth noting that the following balancing groups that produce energy do not pollute the environment.

Thus, the modern energy sector is switching to a new principle instead of the previous one: from generating as much as we produce to generating as much as we consume, and when it is profitable, consuming when and where it is needed. In the former case, the generation tried to guess the demand of consumers and had to keep reserve capacities in reserve in case of an increase in demand. The modern concept of energy is based on economic and environmental feasibility (Levytska, Mulska, Ivaniuk, Vasyltsiv, Lupak, 2020; Novak, Pravdyvets, Chornyi, Sumbaieva, Akimova, & Akimov, 2022; Svitlak & Huts, 2022; Redko et al., 2022). That is, energy is generated where and when it is most appropriate from an economic and environmental point of view. And it is consumed where and when it is needed. For this purpose, humanity is learning to store energy and has already achieved some success in this: various types of energy storage are being developed on an industrial scale.

The European association for storage energy (EASE) has developed a structure of existing energy storage technologies, which provides for the division of the physical principle of operation into: thermal, electrothermal, chemical, electrochemical and mechanical. By type, the technologies are divided into: PSPP technologies (in the US, the share of PSPPs is almost 95%, the rest are thermal storage, battery-type electrochemical storage, compressed air storage, flywheel storage); electrochemical batteries (there are different types of batteries based on chemical compounds NaS, NaNiCl2. Li-ion, etc.); thermal batteries that convert electricity into heat and vice versa; electromechanical batteries (flywheel system receives energy by converting electrical energy from the grid into the kinetic energy of a rotating element that can move up to 4 hours without recharging); hydrogen batteries (using hydrogen instead of natural gas).

Analysis of the use of energy storage systems (ESS) (mainly battery type) has been carried out Child et al. (2017), Child et al. (2019), Larsson & Brjesson (2018). The International Renewable Energy Agency (IRENA, 2017) has developed methods and software that can be used to calculate LCOS - the average cost of electricity in storage systems, and on its basis (Child et al., 2019) “the CAPEX of battery-based ESS is projected to decrease from 300 euros/kWh in 2020 to 150 euros in 2030 and 75 euros in 2050”. According to (The World Bank, 2020), “the capital cost of SPVs has decreased by 87% over the past 10 years and is expected to more than halve by 2030 and triple by 2035”, and according to the EcoPolitics website from 2021, “in 10 years, this sector in the world has grown 48 times, with an average annual growth rate of 47%. Bloomberg NEF forecasts that by 2040, the total capacity of solar PV in the world will exceed 1 TW".

The energy system is highly dynamic. Millions of small and large changes occur every second. For example, various appliances and mobile devices are switched on and off, electric vehicles move and stop, etc. All these events change the consumption of electricity and, according to the classical system, require changes in its generation. Until recently, these processes were regulated exclusively by dispatching tools, both global and local. Changes in the structure of the energy sector require changes in the control system. Fundamentally different systems are coming to the aid of classical dispatchers. They are called microgrid and SMART Grid (Kharrazi, Sreeram, & Mishra, 2020; Parol et al, 2020; Poliak, 2021). A microgrid is a decentralised group of electricity consumers that usually operates in sync with the traditional grid but can also disconnect from it and operate autonomously depending on the need. An example of such a system is shown in Fig. 2. SMART Grids are a new approach to organising electricity supply. In a SMART Grid system, thanks to modern information and communication technologies, energy regulation, consumption, and regeneration are much faster than in a classical system. SMART Grid is basically a round-the-clock electricity exchange, where computers detect the slightest change in demand and generation in a fraction of a second and change the price of electricity accordingly. Consumers' computers react to this by slowing down or increasing consumption. This balances supply and demand and significantly reduces the load on generating facilities, which are then able to operate in a more stable mode.

A SMART Grid is a network that has not only energy flows but also information flows. It transmits not only energy, but also information about what kind of energy it is, where it comes from, how much more it can be, and so on.

Today, according to the International Energy Agency (IEA, 2022), the largest programmes are being implemented in the US, Canada, and all EU countries, especially Latvia, Italy, France, and Germany. India, Brazil, Mexico, Portugal, China, and Japan are also implementing their own projects. In Ukraine, a number of energy companies (Sukhodolia, 2022), such as NEC Ukrenergo and DTEK, are implementing SMART Grid elements.

Fig. 4, based on the data from (IEA, 2022), shows the countries that have made significant progress in deploying SMART Grid and the level of investments they plan to invest in relevant projects, the data corresponds to 2022, but the EU plans to use the relevant funds by 2030, and China - by 2025, the data are given in billion US dollars.

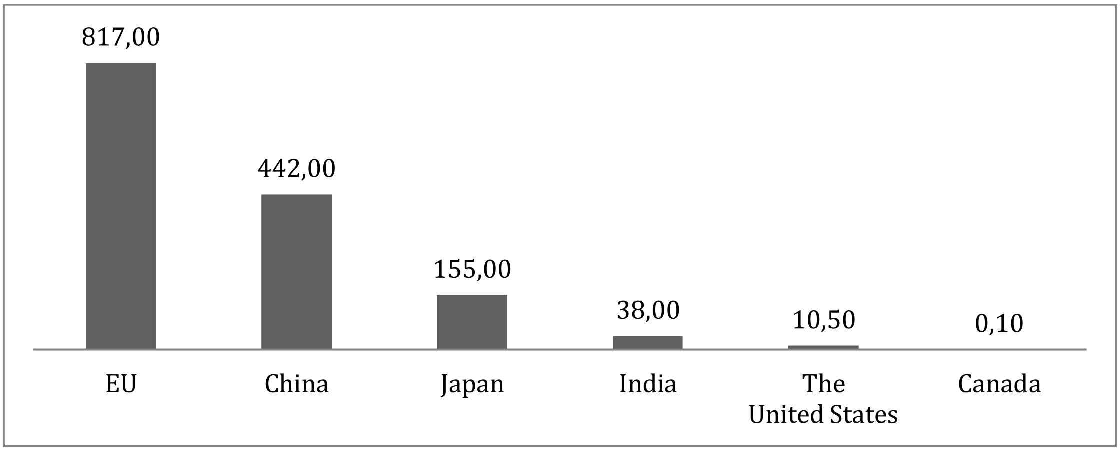


**Fig. 4** Countries by the level of investment in SMART Grid. Based on data (IEA, 2022).

The second difference between the new system and the classical one is that it is possible to build small and medium-sized plants. Nowadays, the installation of medium-sized power plants is gaining momentum, which are installed directly at production facilities and farms. This is a global trend, and it has led to the emergence of new energy actors - prosumers (Klusactk et al., 2023; Sukhodolia, 2022) (the word is created from two -English words - producer and consumer). A prosumer is a consumer who has its own resources in the form of its own sources and has the ability to choose when to consume and when to produce electricity.

Recently, according to the data provided by (Sukhodolia, 2022), the cost of building one kW of installed solar power capacity has decreased by almost 5 times, while the volume of generation in the grid has doubled and continues to grow rapidly.

Modern solar panels have a lifespan of up to 30 years, and their operating costs are significantly lower than those of thermal and nuclear power plants.

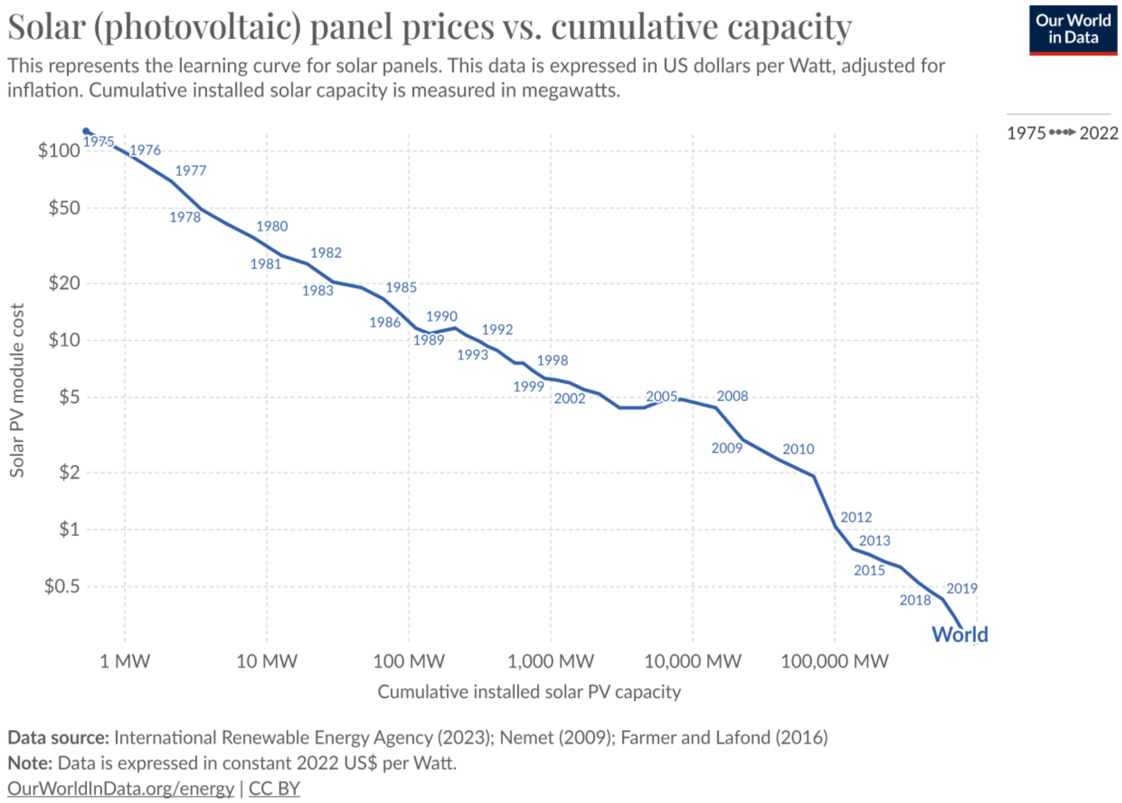


**Fig. 5** Dynamics of changes in the cost of solar PV panels from 1978-2022. (Our Word in Data, 2022).

Currently, solar power plants with a total capacity of about 5 GW have been built in Ukraine (according to finans.ua, at the end of 2021 there were more than 6.32 GW, but for known reasons, there was a reduction in the volume), these are large and small stations. Solar and wind power plants complement each other. So, there is more wind in winter and lighter in summer. Both solar and wind power plants do not depend on the availability of fuel, but they do depend on external conditions - the brightness of the sun and the strength of the wind. But then other types of green energy come to the rescue, such as biogas combustion and small hydropower.

According to various sources, for example (Melnyk, 2018; Yakymenko et al., 2022), every year humanity needs more and more energy. Currently, NPPs and CHPs produce ¾ of the world's energy. Every year, more and more fossil fuel combustion products are released into our atmosphere. In 2018, global CO2 emissions exceeded 33 billion tonnes, with a third of these emissions coming from coal-fired power plants.

Figures 6 - 8, which are based on the data Ritchie & Rosado (2020), show the share of different types of energy resources in global energy consumption. Fig. 6 shows the 2022 figure, and Fig. 7 and Fig. 8 show the dynamics of changes for the period from 2018 to 2022 for renewable and non-renewable resources, respectively.

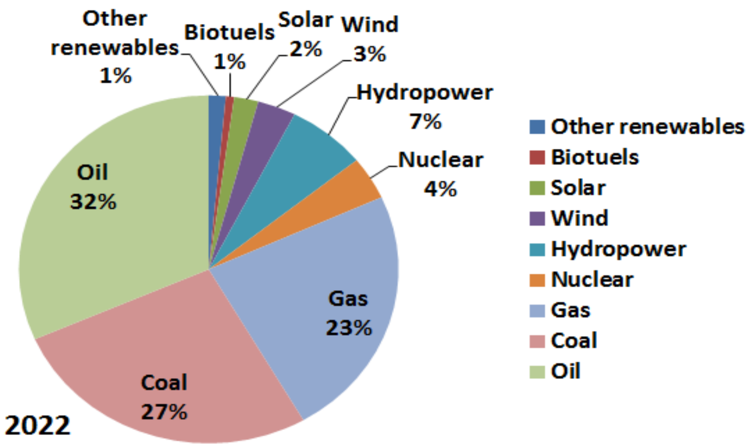


Fig. 6. Energy consumption by source in the world in 2022. Created by the authors based on data from the OurWordinData website Rounding to whole percentages is done for clarity. (OurWordinData.org/energy) Data source: Energy institute: - Statistical Review of World Energy (2023)

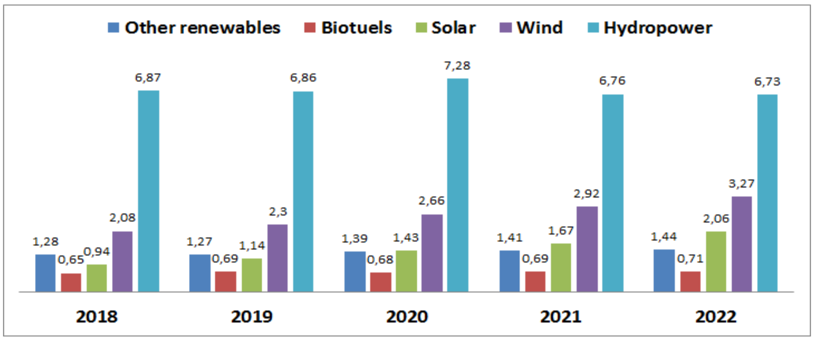


**Fig.7** - World production of electricity from renewable sources in 2019 - 2022. Built by the authors according to Ritchie and Rosado (2020).

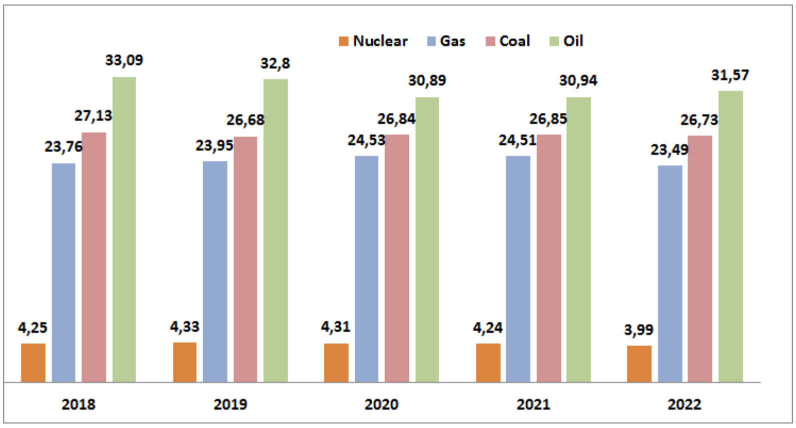


**Fig. 8 -** World production of electricity from non-renewable sources in 2019 - 2022. Built by the authors according to Ritchie and Rosado (2020).

In the case of natural resources, perhaps the most critical example is the situation with the planet's energy resources. For example, the share of different types of energy resources in global energy consumption in 2019 was almost 87.7% provided by fossil fuels (Fig. 8) - coal, oil and gas (26.68% by coal, 32.8% by oil, 23.95% by natural gas), 4.33% by nuclear energy and 12.26% by renewable resources (Fig. 7), of which almost 6.86% are hydro resources, and wind and solar energy on a global scale provide only 3.44% of energy resources.

In 2022, there is an increase in the use of renewable resources, while the share of hydro resources decreases, which obviously reflects their overall decline in a number of countries due to climate change. Despite the growth of green energy, global energy systems are only beginning to change. This is evidenced by the share of non-renewable resources used for electricity generation in 2022 (Fig. 6). Thus, our energy system has only just begun to change. For the most part, it still remains the same as before, but it is increasingly using more and more renewable energy sources (Fig. 7). This not only changes the amount of coal and oil we burn but also changes the quality of life. Renewable energy affects not only the economy but also society Verkhovna Rada of Ukraine (2019, 2021). In fact, the second birth of renewable energy was the result of the growing social demand for a clean environment and clean energy. This is what led to technological and economic changes (Melnyk, 2018).

Given the large share of non-renewable resources, as shown by previous data, innovative solutions in the coal and oil and gas sector are also important. These solutions may include innovations in the extraction or improvement of raw material quality, reduction of methane emissions, transition to low-carbon technologies, and ensuring the safety of operations (monitoring, mechanical integrity in changing external conditions, improved labour safety, etc.)

Programmes that stimulate the development of RES

Investments in green energy have contributed to its growth. Stimulation of RES (Renewable Energy, 2022, February) development takes various forms: grants and compensation for construction in Germany and by the government of California in the US, special tariffs for the purchase of electricity generated by RES, so-called green tariffs, auctions where the state puts up certain generation capacities of coal and RES and bids for them, and the lowest bidder wins. Special tariffs and government incentive auctions gave the transition the final step - the market determines the price.

In addition, there are programmes Acosta, Zabrocki, Eugenio, Sabado, Gerrard, Nazareth, & Luchtenbelt (2020), Hutt & Breene (2019) that promote the search for new types of renewable energy. For example, the international ITER project Hutt & Breene (2019) is being implemented with the participation of the European Union, India, Japan, China, South Korea, and the United States, which aims to build a 500 MW experimental fusion reactor, with the project scheduled to be completed in 2025.

In parallel, according to the website uk.m.Wikipedia.org: The USA (TAE Technologies, Helion Energy, etc.), Japan (EX-Fusion, etc.), China (ENN Energy), Germany (Marvel Fusion), Canada (Fusion Energy Technologies, etc.), and the EU (EURO Fusion) are working on their own national projects in this area.

According to Green Deal: Clean energy (2019) and A European Green Deal: Striving to be the first climate-neutral continent (2019) in December 2019, the European Commission unveiled a new growth strategy, the European Green Deal (EGD), which has been adopted by most EU countries. The EGD policy is primarily aimed at continuing the direction set in 1987 (World Commission on Environment and Development, 1987) to reduce $CO_2$ emissions to zero by 2050. In the energy sector, the GAP proposes to increase energy efficiency, switch to renewable energy sources, introduce innovations in emissions, etc. It also plans to interconnect the countries' energy systems, integrate renewable energy sources into the existing grid, and digitalise them.

It is expected that this, as well as the promotion of information technology, energy efficiency, and environmentally friendly production, will help empower consumers and help the Member States fight energy poverty. Increased regional and cross-border cooperation in the use of clean energy sources, and the promotion of EU standards and technologies at the global level will allow the full potential of European wind energy to be developed, which is currently constrained by periodic overproduction, which is reflected in negative wind power prices (mainly in Germany, Denmark, and the Netherlands) when energy is overproduced.

The EU has proposed some innovative programmes Renewable Energy (2022), Wierzbik-Stronska (2020). For example, the Roadmaps: Transition to a competitive low-carbon economy (LCE) by 2050; Energy development by 2050; Transition to a resource-efficient Europe. Environmental Technologies Action Plan (ETAP). Competitiveness and Innovation Framework Programme (CIP). Framework programmes for research and technology development, innovation and regional development programmes, etc.

In industrialised countries, separate energy management systems are created to ensure the best possible energy consumption, which study, control, and look for ways to distribute and use energy in production. In addition, sustainable energy development requires a combination of different measures, i.e., political, technological, and economic measures.

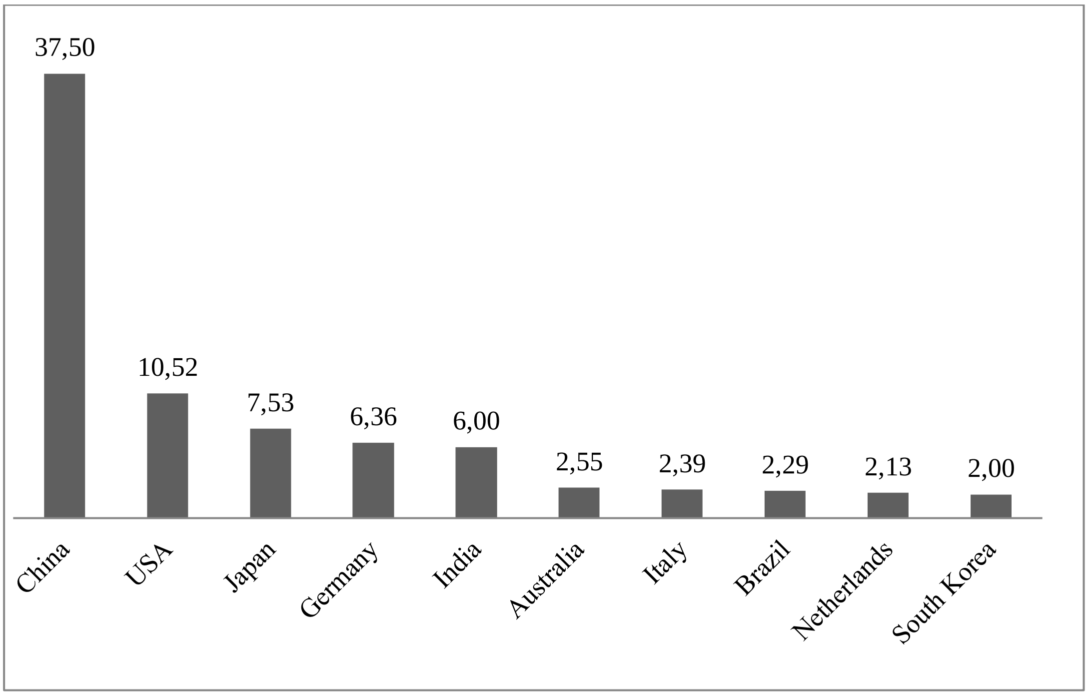


**Fig. 9** Solar energy production by country, as a percentage of total global production in 2022.

Built by the authors according to (IRENA, 2022).

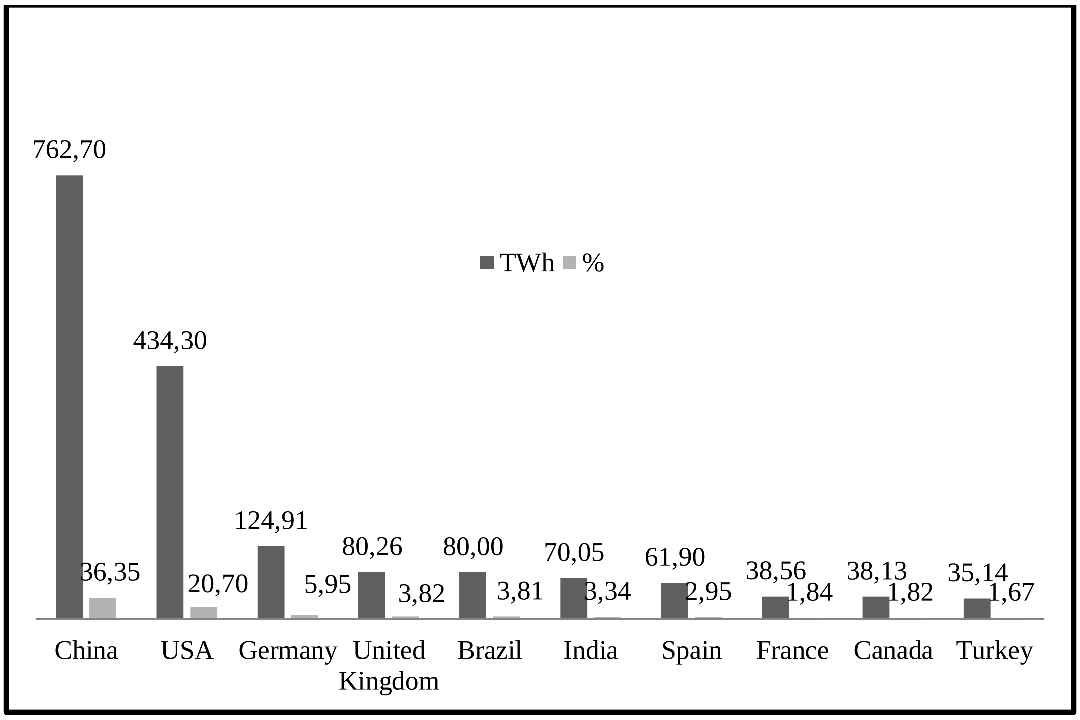


**Fig. 10** Wind energy production by country, as a percentage of total global production in 2022.

Built by the authors according to (IRENA, 2022)

The EU already provides almost 20% of its energy from renewable sources. Austria and Denmark plan to switch completely to renewable energy sources by 2030. China ranks first in the world in terms of renewable energy sources (see Figure 9 for solar energy and Figure 10 for wind energy). Renewable energy is also developing rapidly in the United States and China, which ranks first in the world in terms of renewable energy generation. For example, wind power generation in China in 2022 accounted for approximately 36,35% of the world's total. F or comparison, the United States ranks second in the world in terms of wind power generation with almost 20,7%. But unfortunately, the amount of clean energy produced in a particular country is not an indicator that unambiguously shows the energy security of the population. Sometimes it shows that there are simply no other energy sources in the country.

The production (sectoral) and territorial structure of the national energy supply is determined by the following factors: first of all, there are problems at several levels, namely, national, regional, and global. Among them:

- National supply is formed and developed within the framework of large spatial, organisational, economic, engineering, and technical systems;

- energy security of sustainable energy supply: its problems are strategic for the national development of countries and can be implemented by a multi-level approach to the management of the fuel and energy complex (FEC) of each particular country.

The trend in global development trends is an increase in electricity demand. According to experts, global energy consumption may double by 2030. Countries such as the US, China, India, etc. have major energy needs.

The conditions of the modern economy put the combination of increasing profitability and efficiency of an organisation that supplies products to the market that increase the degree of satisfaction of human needs as the basis for

Today, fuel and energy companies are already considering the prospects of using environmentally friendly chemicals, nano- and biotechnology.

Unfortunately, today the energy intensity of Ukraine's economy is more than twice as high as the global average. And it is almost three times higher than in the European Union. Thus, Verkhovna Rada of Ukraine (2014), Ukraine spends several times more on heating 1 m2 of housing than the EU and the US, but according to the Centre for Efficient Energy Use, up to 50% of heat is lost. Thus, heating costs can potentially be cut by almost half only through more efficient supply and use of heat energy.

Given the importance of energy for society, energy efficiency can be defined as an incentive for the development of the energy potential of society. In other words, energy efficiency is the efficient and reasonable use of energy resources within the framework of compliance with environmental protection requirements. Such use is the total efficiency of energy resources (including electricity) spent on maintaining the required living space conditions and the appropriate level of comfort for society.

The use of renewable natural energy sources, such as wind turbines, solar panels, heat pumps, etc., can significantly improve energy efficiency, but it must be based on specific natural conditions. For example, a number of EU countries have hydrothermal or volcanic energy sources inherent in their territory.

The US has localised areas with specific renewable energy sources. For example, solar energy is most commonly used in the Southwest, wind energy is mostly used in the mountains and the Great Plains, and geothermal energy is common in the West.

India is actively using most of the currently available renewable resources, including solar and wind energy, hydropower, and biomass energy.

Brazil's climate allowed it to become the first country to use ethanol from sugarcane processing as a biofuel.

The use of solar collectors for water heating in China (Chen, Kong, Yin, & Xia, 2022) can significantly reduce electricity consumption or provide a certain standard of living for users of autonomous systems. In South India, Sri Lanka, Bangladesh, Morocco, Kenya, South Africa, and other countries, solar photovoltaics are also widely used to provide off-grid housing.

According to studies Gan et al. (2020), Matvieieva, Vakulenko, Saher, & Petryna (2022), in the period from 2000-2021, an increase in the number of publications related to renewable energy was noted and it was noted that the leaders in the number of publications are representatives of China and the United States. The study Senthi (2022) noted that in 2021, despite the growing interest in photovoltaics research, the number of scientific papers from the EU decreased slightly in the world, and 70% of requests came from households primarily from the Netherlands and Spain. This is obviously due to a decrease in the number of grants on this topic in the EU due to changes in the policy on the feed-in tariff and its cancellation in some EU countries (e.g. Italy and Spain). By the way, in Ukraine, the feed-in tariff is supposed to be in effect until 2030, but according to the website https://forbs.ua, Chayka (2023, July) some producers have already started to abandon it.

Denmark's experience in the field of energy-saving technologies is actively used by other EU members, China, and the United States, and such areas as improving energy efficiency (in production and at the end-use stages), introducing energy-saving equipment, technologies, materials, and surveying the use of new and renewable energy sources, in accordance with the EU directive, are accepted as a general application for the strategies of modernisation of the energy sector in all EU countries.

Along with the country's energy efficiency indicators, the environmental progress of the national economy is assessed by the Environmental Performance Index (EPI, 2022). According to the website uk.m.Wikipedia.org/wiki/, this index is designed to quantify and compare the indicators of environmental policy of the world's countries, global environmental protection processes, and sustainable development. It was created to assess and develop effective measures to reduce environmental impact and rational use of natural resources, as well as to promote ecosystem viability and sustainable management of natural resources. The results of EPI calculations are published every 2 years.

According to the country ranking, according to (IEA, 2022), ordered by the environmental performance index, scored on a 100-point scale, 180 countries were evaluated, the top five places were taken by Denmark - 77.9; the United Kingdom - 77.7; Finland - 76.5; Malta - 75.2; Sweden - 72.7. USA -51,1 (43h place); Ukraine's score is 49.6 (52nd place), South Korea 46,9 (63h place; China – 28.4 (160h place) and the last is India's 18.9 (180th place).

As we can see, the countries leading in the field of energy generation from renewable resources, especially India, are not in the top five.

Among the countries that use renewable resources to the fullest extent, according to the data (King, 2023, November): Iceland - 86.87%; Norway - 71.56%; Sweden - 50.92%; Brazil - 46.22%; New Zealand - 40.22%; Denmark - 39.25%; Austria - 37.48%; Switzerland - 36.72%; Finland - 34.61%; Colombia -33.02%. The main source of energy in Iceland is geothermal (volcanoes, geysers, lava fields, etc.). It also uses wind and hydropower. Norway produces hydropower and biogas. Sweden - hydro and bioenergy. Brazil - mainly nuclear energy, New Zealand - hydro and geothermal energy and bioenergy, Denmark - mainly wind energy, Austria - hydro, wind and solar energy, Sweden - nuclear, hydro, wind and solar energy, Finland - recycling of edible and organic waste, nuclear, hydro and bioenergy, Colombia - hydro and solar energy.

Therefore, for countries (World Energy, 2022), the development of their energy policy is related to internal conditions and natural resources, geographical location and existing socio-economic systems, and each country finds its own way that is suitable for the implementation of energy policy, taking into account the national situation and priorities.

It is clear that of the driving forces for countries to use renewable energy sources, i.e. energy security; environmental security; and the cost of renewable energy, they have different weights for different countries. For example, the first one, namely energy security, is of utmost importance for Ukraine.

The World Energy Trilemma Index (World Energy, 2022) is an annual measure of national energy system performance that looks back over time to assess past energy system performance. The parameters of the index cover a country's energy security, equitable access to energy resources, and environmental sustainability. Fig. 11 shows the top countries in the trilemma ranking and the countries that have made the most progress in the trilemma in 2022.

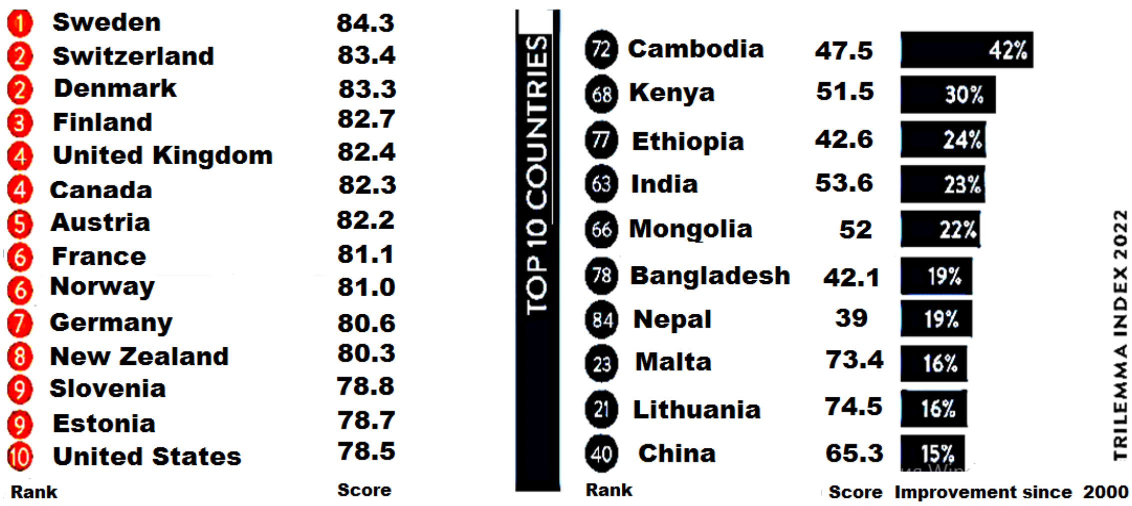


**Fig. 11 -** countries leading the trilemma ranking and countries that have made the most progress in the trilemma. Data by World Energy (2022).

We can see that Cambodia has made the most progress (42%), followed by India (23%) and China (15%). Among the leaders of the trilemma, only Slovenia and Estonia are unexpected, but they can be considered part of the EU.

## DISCUSSION

Having reviewed the studies of other authors on this topic, we note that most of them conducted bibliometric analysis using the Scopus database (Abdolmaleki & Bugallo, 2021; Gan et al., 2020; Matvieieva et al., 2022; Senthil, 2022). However, despite the different approaches, the results for the leading countries in this area are somewhat similar. But, for example, (Gan et al, 2020; Senthil, 2022) studied the topic of solar energy. According to (Senthil, 2022), the most papers on solar energy belong to China (22%), USA (18%), India (11%), Germane (5%), United Kingdom (5%), Italy (4%), Japan (4%), South Korea (4%). Spaine (4%), Australia (3%) and other country 20%. The authors Matvieieva et al. (2022) note that the five countries that most actively analyse the impact of innovation on the development of renewable energy are:

USA, China, UK, Germany and Italy, followed by: India, the Netherlands, Spain, Australia and France. In terms of the dynamics of the frequency of use of the queries "innovation" and "renewable energy" in search engines in 2008-2022, France, Denmark, Switzerland, Sweden and Germany are the most popular countries. In addition, bibliographic analysis allows us to assess the qualitative composition of research on this topic, but not the quantitative characteristics expressed through the relevant indicators, as in our case.

Kucheriava & Sorokina (2020) studied only global trends in renewable energy without the contribution of innovations. In the article Larsson and Brjesson (2018), a cost model for battery energy storage systems was studied. The Photovoltaic report (2023) by the Fraunhofer Institute for Solar Energy Systems provides a breakdown of the total installed costs of photovoltaic energy on a utility scale by country in 2021. It shows that Japan is the undisputed leader in the costs of installing solar energy equipment, monitoring and control. For almost all countries, except China, the highest costs are for modules and inverters. Among the countries with the lowest costs are China and India.

In the study Chaparro-Banegas, Escribano, Mas-Tur, & Tierno (2023), two types of analysis were conducted based on the study of sustainable development goals of countries and the Global Innovation Index. Firstly, a cluster analysis based on the study of changes that occurred in groups of regions by the sum of innovative characteristics. The study covered the period from 2015 to 2020. 122 countries were included in the study. Second, a multiple linear regression analysis was performed to assess the power of the model variables to explain the level of sustainable development. The result was the grouping of countries into 4 clusters (with low, medium, high and very high innovation incentives and development levels). Multiple linear regression analysis showed the need to take into account the limitations of economic growth in terms of innovative means to promote sustainable development. The analysis, based on the study of changes in the data, also identified countries that have moved beyond their clusters, primarily India and South Macedonia, which have significantly improved their performance, but also identified countries where there has been a significant deterioration, such as Chile, Colombia, Costa Rica, Malaysia, etc. Based on these findings, the authors suggest that the limits to economic growth and ecosystems need to be recognised at the policy level. In our opinion, this is fully consistent with the energy trilemma.

The authors Mehmood, Tariq, Aslam, & Agyekum (2023) studied the impact of digitalisation, innovation, and the use of renewable resources on the development of the G8 countries in the period from 1990 to 2018. The review covers not only energy systems, but also the impact of digitalisation and innovation on human health and the economy of these countries.

The factors studied were the load factor (according to the Global Competitiveness Index (GCI)), digitalisation (GINI index, SWID), natural resources (according to https://data.worldbank.org), government stability (ICRG), economic growth (GDP growth), and financial development (according to https://data.worldbank.org). The assessment was carried out using autoregressive models with a distributed lag, which allows tracking trends over time. This study was mainly concerned with assessing the resilience of the economies of these countries to the impact of new factors. But in our opinion, these methods can be used to quickly obtain information based on the media.

The authors Liao, Qiu, Wu, Sun, Shen, & Li (2022) used linear regression analysis to assess innovations for corporate sustainability, and another study Chen et al. (2022) assesses the sustainable development of energy systems in individual regions and territorial units, which is a very relevant topic of many studies Bauknecht et al. (2020); Brugger et al. (2021), Doroshenko, Orlenko, & Harnyk (2023), Efimov (2020), Zhang et al. (2022).

Thus, our study allows us to assess the overall impact of innovative technologies on the sustainable development of energy systems using existing technical and environmental indicators. The comparison of technical indicators with environmental indicators is also reflected in the energy trilemma index, but our analysis provides a more visual and timely picture.

The works of other authors mainly consider the impact of innovative technologies through the prism of bibliographic analysis or regression methods of statistical analysis. In the latter case, the information obtained relates mainly to regional units or individual countries, and the picture of global trends using this methodology is considered somewhat blurred and more difficult to perceive.

We have considered the main indicators that can be used to make a qualitative assessment of the development of countries. In this way, we have identified the leading countries in terms of the number of innovative capabilities (the country's ability to innovate index), expenditures on innovative research and implementation of the latest technologies, especially those related to SMART Grid technologies, solar and wind energy producers, and the quality of energy produced. Natural factors and environmental efficiency of countries are considered, as well as countries according to the energy trilemma. Thus, this study has made it possible to clearly trace the interconnection of innovative implementations on the development of energy and environmental efficiency of countries and has shown the possibility of obtaining a certain picture using available materials without complex calculations.

Discussion is an analysis of the results obtained in the previous section, as well as their comparison with the research of other authors. The author needs to describe the results of the study and to reflect on these results not only within the framework of his/her own research, but also within the framework of the research of other authors. In this section, it is necessary to "discuss" your past performance indicators of energy systems and results with the results of other authors' works on the chosen topic: what is common in the results obtained, what are the differences, who considered other aspects of the problem, etc. It is necessary to compare the results of your research not only with the research of your compatriots, but also with the research of scientists from other countries.

## CONCLUSIONS

The fact that the world is currently in the process of restructuring its energy systems raises questions about the quality of assessment of the development of countries' energy systems depending on innovations.

The review allowed us to identify certain dependencies in the development of modern energy systems.

The paradigm has changed from producing as much as I consume to producing as much as I can, consuming when I want or need to. This happened due to a number of innovative solutions, both political and technological.

The political decision was to pursue a green energy policy.

Technical and innovative solutions include the following:

First, the transition to a distributed energy system, including microgrid;

Second, new energy storage technologies have emerged;

Third, the emergence of prosumers, who are both users and producers of electricity;

Fourthly, technologies have emerged that have led to improved quality and lower prices for solar energy converters and wind turbines.

Fifth, systems have emerged that can be used to manage the production and use of energy with the highest possible efficiency - SMART Grid technologies.

The sustainable development of power systems in different countries was assessed using a number of indicators. The country's ability to innovate was assessed by the GII index, the amount of money spent on the development of the SMART Grid system. Countries were assessed by global solar and wind energy production, the country's environmental efficiency was also considered, and the share of energy produced from renewable resources and the composition of these energies were assessed.

This comparison revealed the following:

The countries with the highest scores in terms of innovation capacity are also the ones most interested in the development of SMART Grid technology.

The largest producers of solar or wind energy are not necessarily the ones with the highest environmental performance (this is primarily true for the US, South Korea, China and India).

Countries with renewable resources that allow energy to be produced without significant fluctuations (mainly geo- and hydrothermal resources, bioresources) and that have a high innovation capacity index have a high share of green energy and a high environmental efficiency index.

Countries with a high GII score have a developed system of proxies that create balance sheet groups that can go beyond the borders of one country (for example, the EU).

The processes of globalisation and distribution require appropriate governance and security instruments.

The uneven distribution of renewable resources across the world, even within a single country, makes it difficult to create a single large-scale policy in this area.

It should be borne in mind that the presence of fuel and energy resources FERs in the current system of global economic management has become a lever of political influence. Currently, almost all countries in the world are pursuing energy efficiency policies, but with due regard to the level and conditions of their socio-economic development. For most countries, this is a matter not only of national security, but also of their very existence (primarily for industrialised but energy-deficient countries), as the absence or shortage of FERs threatens economic development.

This review examines the impact of innovative technologies on the sustainable development of power systems. It identifies the main factors that influence the nature of system development, as well as a number of technical and environmental indicators that accompany these changes.

## REFERENCES

A European Green Deal: Striving to be the first climate-neutral continent. (2019). European Commission. Retrieved March 4, 2024, from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

Abdolmaleki, S. F. & Bugallo, P.M. B. (2021). Evaluation of Renewable Energy System For Sustainable Development, *Renew. Energy Environ. Sustain*, *6*, 44. https://doi.org/10.1051/rees/2021045

Acosta, L. A., Zabrocki, S., Eugenio, J. R., Sabado R., Gerrard, Jr. S. P., Nazareth, M., & Luchtenbelt, H. G. H. (2020). *Green Growth Index 2020 – Measuring performance in achieving SDG targets, GGGI. Technical Report No.16,* Green Growth Performance Measurement Program, Global Green Growth Institute (GGGI), Seoul, South Korea. Retrieved from https://greengrowthindex.gggi.org/wp-content/uploads/2021/03/2020-Green-Growth-Index.pdf

Aydin, M. (2019). Renewable and non-renewable electricity consumption–economic growth nexus: Evidence from OECD countries. *Renewable Energy, 136,* 599–606. https://doi.org/10.1016/j.renene.2019.01.008

Bakhmachuk, S., & Bakhmachuk, P. (2018). *Decentralized Electroindustrial Heating System With Heat Acumulation As Tool To Overcome «Green-Coal Paradox» / Modern Problems of Economics and Entrepreneurship*. Kyiv: Igor Sikorsky Kyiv Polytechnic Institute, Polytechnic Publishing House. ISSN 2310-5534 // e-ISSN 2414-9306.

Bauknecht, D., Funcke, S., & Vogel, M. (2020). Is small beautiful? A framework for assessing decentralised electricity systems. *Renewable and Sustainable Energy Reviews*, *118*(109543), 109543. https://doi.org/10.1016/j.rser.2019.109543

Bozhkova, V., & Halytsia, I. (2022). Mechanisms to ensure the development of the economy of the future in the context of global change. *Futurity Economics&Law*, *2*(2), 4–13. https://doi.org/10.57125/FEL.2022.06.25.01

Brugger, H., Eichhammer, W., Mikova, N. & Dönitza, E. (2021). Energy efficiency vision 2050: How will new societal trends influence future energy demand in the European countries? *Energy Policy*, *152*, 112216. https://doi.org/10.1016/j.enpol.2021.112216

Buzugbe, N. P. (2023). The Energy Consumption-Economic Growth Nexus in Nigeria: What Evidence Exists? *Futurity Economics&Law*,*3*(4), 209 - 222. https://doi.org/10.57125/FEL.2023.12.25.13

Chaparro-Banegas, N., Escribano, A. M.I., Mas-Tur, A., & Tierno, N. R. (2023) Innovation facilitators and sustainable development: a country comparative approach. In *Environment, Development and Sustainability*, 1-29, Springer. https://doi.org/10.1007/s10668-023-03055-w

Chayka, O. (2023, July). *The end of an era. Renewable energy producers are abandoning the scandalous green tariff. Why does it no longer work?* Retrieved from https://forbs.ua/company/kinet-epokhi-virobniki-vidnovlyuvanoi-energii-vidmovlyayutsya-vid-skandalnogo-zelenogo-tarifu-chomu-vin-bilshe-ne-pratsyue-12072023-14741

Chen, J., Kong, Y., Yin, S., & Xia, J. A. (2022). Comparative Method for Assessment of Sustainable Energy Development across Regions: An Analysis of 30 Provinces in China. *Energies, 15,* 5761. https://doi.org/10.3390/en15155761

Child, M., Breyer, C., Bogdanov, D., & Fell, H.-J. (2017). The role of storage technologies for the transition to a 100% renewable energy system in Ukraine. *Energy Procedia*, *135,* 410–423. https://doi.org/10.1016/j.egypro.2017.09.513

Child, M., Kemfert, C., Bogdanov, D., & Breyer, C. (2019). Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe. *Renewable Energy*, *139*, 80–101. https://doi.org/10.1016/j.renene.2019.02.077

Doddamani, Y. N., & Kapale, U. C. (2019). A transition from manual to Intelligent Automated power system operation -A Indicative Review. *International Journal of Electrical and Computer Engineering (IJECE)*, *9*(4), 2274. https://doi.org/10.11591/ijece.v9i4.pp2274-2280

Doroshenko, T., Orlenko, O., & Harnyk, O.(2023). Mechanisms for ensuring the development of the future economy in the context of global changes. *Futurity Economics&Law*, *3*(2), 132 – 150. https://doi.org/10.57125/FEL.2023.06.25.09

Efimov, D. (2020). Flexibility of the power system: background, relevance, and categorization, *in E3S Web Conf. Volume 216*. 01025. https://doi.org/10.1051/e3sconf/202021601025

Entezari, A., Aslani, A., Zahedi, R., & Noorollahi, Y. (2023). Articial intelligence and machine learning in energy systems: A bibliographic perspective. *Energy Strategy Reviews, 45*, 101017. https://doi.org/10.1016/j.esr.2022.101017

Environmental Performance Index. (2022). Retrieved from https://epi.yale.edu

ESTAT:Eurostat, C.-B. (2019). *Sustainable Development in the European union: Monitoring report on progress towards the SDGs in an EU context : 2019 edition*. Publications Office of the European Union. http://doi.org/10.2785/44964

Eurostat Statistical Yearbook. (2022). Retrieved from http://ec.europa.eu/energy/publications/statistics

Eurostat Statistical Yearbook. (2023). Retrieved from http://ec.europa.eu/energy/publications/statistics

Gan, L., Jiang, P., Lev, B., & Zhou, X. (2020) Balancing of supply and demand of renewable energy power system: A review and bibliometric analysis. *Sustainable Futures, 2*, 100013 https://doi.org/10.1016/j.sftr.2020.100013

Green Deal: Clean energy (2019) Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/clean-energy_en

Hutt, R., & Breene K. (2019). *Scientists just got closer to making nuclear fusion work*. World Economic Forum. Energy transition. Retrieved from https://www.weforum.org/agenda/2019/05/nuclear-fusion-could-solver-the-world-s-energy-problems-and-scientists-just-got-closer-to-making-nuclear-fusion-work

International Energy Agency. (2022). *World Energy Outlook 2022*. Retrieved from www.iea.org

International Renewable Energy Agency. (2017). *Electricity storage and renewables: Costs and markets to 2030*. Retrieved from http://surl.li/ayceg

International Renewable Energy Agency. (2022). *Renewable energy statistics 2022*. ISBN: 978-92-926-446-2.

Kharrazi, A., Sreeram, V., & Mishra, Y. (2020). Assessment techniques of the impact of grid-tied rooftop photovoltaic generation on the power quality of low voltage distribution network—A review. *Renewable and Sustainable Energy Reviews, 120*, 109643. https://doi.org/10.1016/j.rser.2020.1096413

Khomenko, I. V., Plakhtii, O. A., Nerubatskyi, V. P., & Stasiuk, I. V. (2020). *Electric power industry of Ukraine: Structure, management, innovations: A monograph*. Kharkiv: NTU "KhPI", Planet-Print LLC. ISBN 978-617-7897-02-5

Kibik, O., Taran-lala, O., Saienko, V., Metil, T., Umanets, T., & Maksymchuk, I. (2022). Strategic vectors for enterprise development in the context of the digitalization of the economy. *Postmodern Openings, 13*(2), 384-395. https://doi.org/10.18662/po/13.2/460

King, C. (2023, November). Top 10: Countries using renewable energy. *Energy Digital Magazine*. Retrieved from http://energydigital.com

Klusactk, J., Drapela, J., & Langella, R. (2023). Revenue Metering of Unbalanced Prosumers in Energy Communities. *IEEE Open Access Journal of Power and Energy*, 1-11. https://doi.org/10.1109/OAJPE.2023.3243385

Komar, V., Lezhniuk, P., Lesko, V., Malogulko, Y., Netrebskyi, V., & Sikorska, O. (2022). Electricity consumption and renewable energy sources generation schedules coordination in electric networks for balance reliability increasing. In *Energy Facilities: Management and Design and Technological Innovations* (pp. 42–75). Privat Company Technology Center. https://doi.org/10.15587/978-617-7319-63-3.CH2

Kucheriava, I. M., & Sorokina, N. L. (2020). Renewable power industry in the word and in Ukraine for the year 2019 – at the beginning of 2020. *Gidroenergetika Ukrainy, 1—2*, 38 - 44. Retrieved from ISSN 1812-9277.

Kuznietsov, M., & Melnyk, O. (2020). The Influence of Instability Consumption on The Hybrid Energy System Balance. *Vidnovluvana Energetika*, *2*(61), 8-17. https://doi.org/10.36296/1819-8058.2020.2(61).8-17

Larsson, P., & Börjesson, P. (2018). *Cost models for battery energy storage systems* (R. E. Guédez Mata, Ed.). Retrieved from http://surl.li/awhib

Levytska, O., Mulska, O., Ivaniuk, U., (…), Vasyltsiv, T., Lupak, R. (2020). Modelling the conditions affectingpopulation migration activity in the eastern European region: The case of Ukraine. *TEM Journal*, *9*(2). 507-514.

Lezhniuk, P., Komar, V., & Kravchuk, S (2019). Regimes Balancing in the Local Electric System with Renewable Sources of Electricity. IEEE 20th International Conference on Computational Problems of Electrical Engineering, *CPEE,* 8949118. https://doi.org/10.1109/CPEE47179.2019.8949118

Liao, Y., Qiu, X., Wu, A., Sun, Q., Shen, H., & Li, P. (2022). Assessing the impact of green innovation on corporate sustainable development. *Frontiers in Energy Research*, *9*. https://doi.org/10.3389/fenrg.2021.800848

Matvieieva Y., Vakulenko I., Saher l., & Petryna V. (2022). Essential basis of innovative activity n he context of renewable energy development. *Bulletin of Sumy State University: Series "Economics"*, *2*, 17-29. Retrieved March 4, 2024, from https://visnyk.fem.sumdu.edu.ua/en/2-2022-2

Mehmood, U., Tariq, S., Aslam, M. U., Agyekum, E. B., Uhunamure, S. E., Shale, K., Kamal, M., & Khan, M. F. (2023). Evaluating the impact of digitalization, renewable energy use, and technological innovation on load capacity factor in G8 nations. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-36373-0

Melnyk, L. H. (2018). *Green economy (EU experience and Ukraine's practice in the world of the third and fourth industrial revolutions).* Sumy: University Book Publishing House. ISBN 978-966-680-841-0

Muratori, M., Jadun, P., Bush, B., Bielen, D., Vimmerstedt, L., Gonder, J., Gearhart, C., & Arent, D. (2020). Future integrated mobility-energy systems: A modeling perspective. *Renewable and Sustainable Energy Reviews*, *119*(109541), 109541. https://doi.org/10.1016/j.rser.2019.109541

New Energy Outlook 2022. (2022, November 27). BloombergNEF. https://about.bnef.com/new-energy-outlook/

Novak, A., Pravdyvets, O., Chornyi, O., Sumbaieva, L., Akimova, L., & Akimov, O. (2022). Financial and economic security in the field of financial markets at the stage bof European integration.

*International Journal of Professional Business Review, 7*(5) https://doi.org/10.26668/businessreview/2022.v7i5.e835

Our Word in Data (2022). *Solar (photovoltaic) panel price vs. cumulative capacity.* Ourworldindata.org. Retrieved March 4, 2024, from https://OurWorldInData.org/energy

Parol, M., Wójtowicz, T., Księżyk, K., Wenge, C., Balischewski, S., & Arendarski, B. (2020). Optimum management of power and energy in low voltage microgrids using evolutionary algorithms and energy storage. *International Journal of Electrical Power & Energy Systems*, *119*(105886), 105886. https://doi.org/10.1016/j.ijepes.2020.105886

Photovoltaic report. (2023). Fraunhofer Institute for Solar Energy Systems, 53. Fraunhofer.de. Retrieved March 4, 2024, from https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Poliak, A. (2021, August 10). Energy storage systems: is there a future in Ukraine. *Environmental policy*. https://ecopolitic.com.ua/ua/news/sistemi-nakopichennya-energii-chi-ie-majbutnie-v-ukraini/

Redko, K., Denyshchnko, L., Dobrovolska, O., Lukyanenko, N., & Kyryllova, Y. (2022). Development of green energy as a path to energy independence of the national economy. *Futurity Economics&Law*, *2(*4), 36-42. https://doi.org/10.57125/FEL.2022.12.25.05

Renewable Energy. (2022, February). *Renewable Energy Policies, Laws and Regulations* Retrieved from https://ppp.worldbank.org/public-private-partnership/renawable-energy

Ritchie, H. & Rosado, P. (2020). "Energy Mix". Ourworldindata.org. Retrieved March 4, 2024, from https://ourworldindata.org/energy-mix'

Senthil, R. (2022). Recent innovations in solar energy education and research towards sustainable energy development. *Acta Innovations, 42,* 27-49. https://doi.org/10.32933/ActaInnovations.42.3

Sukhodolia, O. M. (2022). A*rtificial intelligence in the energy sector: analytical report.* Kyiv: NISS. Retrieved from https://doi.org/10.53679/NISS-analytrep.2022.09

Suprunenko, S., Pylypenko, N., Trubnik, T., & Volchenko, N. (2023). Forecast of changes in the macroeconomic situation in Ukraine: SMART economy of the future. *Futurity Economics&Law*, *3*(3), 219 - 236. https://doi.org/10.57125/FEL.2023.09.25.13

Svitlak, I., &Huts, N.(2022). The legal charter of the company of the future: the order of creation. *Futurity Economics&Law*, *2*(1), 22-27. https://doi.org/10.57125/FEL.2022.03.25.03

The Global Innovational Index (2022). Retrieved from https://www.globalinnovationindex.org

The scientific project center for the development of the unified energy system of Ukraine (SPCD UES Ukraine). (2018). *Experience of the EU countries in improving energy efficiency, energy audit and energy management for energy saving in the economy.* Retrieved from https://ua.energy/wp-content/uploads/2018/01/Pidvyshhennya-energoefektyvnosti-v-YES.pdf.

The World Bank. (2020). *Economic analysis of battery energy storage systems.* Retrieved from http://surl.li/awhid

Tymoshenko, M., Saienko, V., Serbov, M., Shashyna, M., & Slavkova, O. (2023). The impact of industry 4.0 on modeling energy scenarios of the developing economies. *Financial and Credit Activity Problems of Theory and Practice*, *1*(48), 336–350. https://doi.org/10.55643/fcaptp.1.48.2023.3941

Vdovichena, O., Vidomenko, O., Tkachuk, S., Zhuzhukina, N., & Lukianykhina, O. (2022). The use of information in the world economy: globalization trends. *Futurity Economics&Law*, 2(4), 4 - 11. https://doi.org/10.57125/FEL.2022.12.25.01

Verkhovna Rada of Ukraine (2002). Law of Ukraine "On innovation activity", dated 04.07.2002 № 40-IV (2002). Retrieved March 4, 2024, from https://zakon.rada.gov.ua/laws/show/40-15#Text

Verkhovna Rada of Ukraine (2014). Association Agreement between Ukraine, on the one hand, and the European Union, the European Atomic Energy Community and their Member States, on the other hand: international document of 27.06.2014. Retrieved March 4, 2024, from https://zakon.rada.gov.ua/laws/show/984_011#Text

Verkhovna Rada of Ukraine (2019). Law of Ukraine "On Alternative Energy Sources" No 555-IV of 01.01.2024. Retrieved March 4, 2024, from https://zakon.rada.gov.ua/laws/show/555-15

Verkhovna Rada of Ukraine (2021). Law of Ukraine "On energy efficiency", dated 21.10.2021 No. 1818-IX. Version as of 01.01.2024, grounds — 3460-IX. Retrieved March 4, 2024, from https://zakon.rada.gov.ua/go/1818-20

Wierzbik-Stronska, M. (Ed.). (2020). *Youth involvement in civil society development: current state and prospective trends*. Poland, Katowice: Publishing House of Katowice School of Technology. ISBN 978-83-955125-6-8

World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press: New York, USA, 383. ISBN: 019282080X.77

World Energy. (2022). *Trilemma index*. Retrieved from https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2022

Yakymenko, I., Petrashko, L., Dyman, T., Salavor, O., Shapovalov, E., Galaburda, M., Nychyk, O.,& Martyniuk, O. (2022). *Sustainable Development Strategy: European Horizons.* Kyiv: NUFT. ISBN 978-966-612-275-29

Zhang, D., Tian, J., Goh, H.-H., Liu, H., Li, X., Zhu, H., & Wu, X. (2022). The key technology of smart energy system and its disciplinary teaching reform measures. *Sustainability*, *14*(21), 14207. https://doi.org/10.3390/su142114207