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Recovery of the energy system of Ukraine towards the development of renewable energy

Yevhen Terekhov*

Joanneum Research Forschungsgesellschaft mbH, Leonhardstraße 59, Graz, Austria
*Corresponding author's email: Yevhen.Terekhov@joanneum.at

Abstract

In view of the Europe-wide energy crisis and global climate change, Ukraine could contribute to the development of the entire European energy network if it rebuilds its energy system after the war in accordance with the principles of climate neutrality. The aim of the research was to identify options for the development of renewable energy in Ukraine as a prerequisite for the modernization of its energy industry towards climate neutrality. It was found that wind energy generation is the most cost-effective option for future green electricity generation in Ukraine after solar energy using the method of comparing electricity generation costs, investment needs and CO2 emissions of various energy sources, as well as analyzing the regional distribution of natural potential for generating wind and solar energy. Using the method of analyzing capacity factors of electricity generation from renewable energy sources, it was found that the share of renewable energy in Ukraine could increase to 65% in primary energy consumption and to 70% in electricity supply by 2050. Keywords: renewable energy, climate neutrality, reconstruction, energy system.

Keywords

Energy system recovery, Renewable energy development, Ukraine energy transition

Introduction

Russia's war against Ukraine has only reinforced the need to transition to renewable energy sources so that energy resources would not become a means of political influence [1], [2]. Substantial reconstruction efforts must be provided by the private sector if clear incentives and investment guarantees are created [3]. Reconstruction is intended to promote the necessary reforms in Ukraine [4]. Overall, the destruction of energy infrastructure in Ukraine amounted to 40% in 2022. To overcome this difficult situation in the energy sector, investments in green energy should be made, as the country has all the resources for cost-effective and climate-neutral energy supply [5].

The Ukrainian government has set the goal of increasing the share of renewable energy in primary energy consumption from 8% in 2022 to 25% in 2035 [6]. Various green energy technologies could contribute to this goal.

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In the study [7] a methodical approach to the pre-selection of technologies for energy generation from the perspective of availability, climate protection impact, acceptance and market volume is proposed.

The results of the research will present scenarios for the development of renewable energy in Ukraine, which will depend on the extent to which investments will be directed to the development of renewable energy and which energy sources will be the most promising in terms of their economic and environmental characteristics in the overall Ukrainian conditions. The study is aimed at determining options for the development of renewable energy in Ukraine that will ensure security of energy supply, cost-effectiveness of electricity production and the achievement of climate neutrality by 2050.

Methods

In order to understand the real scale of the war-related destruction of the energy infrastructure, a statistical method is used to collect data on the current state of energy facilities in Ukraine from secondary data sources, taking into account that currently about a fifth of the territory of Ukraine is occupied by Russia and there is no precise information on the scale of losses of the energy system in occupied territory. For each energy supply technology currently used in Ukraine, separate statistics for destroyed and occupied facilities were collected from the source [8] and presented in tabular form. As Ukraine strives for EU membership, a comparative analysis of the experience of EU countries in phasing out fossil fuels is of particular importance for the transformation of the Ukrainian energy sector in line with EU climate goals. The first comparison group was Germany and Austria, as EU countries with the greatest progress in the development of renewable energy, and the second comparison group was France, as a country that is developing nuclear power as a controversial option. Structures of primary energy consumption from official secondary statistical sources of each country selected for comparison were analyzed for the years 1990, 2000, 2010, 2015, 2019, 2022 – retrospectively, and for 2030, 2050 – prospectively [9], [10].

Oil, coal, natural gas and nuclear energy were classified as fossil energy sources. To determine the forecast share of renewable energy in primary energy consumption in Ukraine in 2030 and 2050, the data provided by the Ukrainian government as part of the 2022 Recovery Plan for the expansion of renewable energy according to an optimistic scenario (maximum electricity volumes) were used.

As a next step, all electricity generation technologies were classified as location-dependent and location-independent. The data on the productivity of renewable energy sources were determined for location-dependent technologies using the example of Ukraine, and for location-independent technologies using the example of Germany. Calculations of electricity generation volumes in Ukraine were carried out taking into account the capacity factors provided: 1) First factor - planned nominal capacities of each electricity generation technology in the Ukrainian Recovery Plan for 2040 and

2050; 2) Number of full load hours of each technology during which electricity can be generated (Full load hours (FLH) indicate the number of hours that allow the nominal power of a particular technology). The value of full load hours is not constant and changes not only due to natural phenomena, but also as a result of technology development, improvement of technical operation of equipment, etc. In calculations, an increase in full load hours of 1% per year was observed. By multiplying the nominal capacities of the respective energy plants and their average full load hours (coefficient), the electricity generation volumes of the respective plants can be determined. The studies of the variability of the full load hours were carried out [11], but not in connection with different scenarios of the expansion of renewable energies within the framework of the Recovery Plan of Ukraine.

Using the capacity factors mentioned above, values were calculated for total electricity production for the forecast period according to four scenarios (depending on maximum and minimum capacities of renewable energies and use and non-use of nuclear energy. In order to determine Ukraine's own electricity needs, it was assumed that electricity demand would fall by 1% annually by 2050 (linear reduction). The choice of green electricity production technology is based on the costs of its production, the required initial capital costs for the construction of generating capacities, and the annual productivity of the relevant technology.

The study presents various scenarios for the development of renewable energies in Ukraine in accordance with the Ukrainian government's plans to rebuild the country's energy sector.

Results and discussion

Results

The Ukrainian government needs about 47 billion US dollars (all energy sources) just to restore the damaged energy facilities in the country. However, these investments would not be appropriate for the construction of new coal-fired power plants, as coal will lose its importance as an energy source in Europe in 20 or 30 years, but the newly built coal-fired power plants are planned to operate for over 50 years.

Table 1. Losses of Ukraine's energy system for electricity generation as a result of the war (as of May 2023) [8].

Energy sources	Share of net electricity generation; % (2022)	Installed capacity, MW	Occupied, %	Destroyed, damaged or attacked, %
nuclear energy	60,8	13835	43	---
thermal power (hard coal, natural gas)	29,6	21500	78	100
Large hydropower	4,6	4700	5	100
Small hydropower	0,1	120	1	4
Solar	1,6	7600	13	8
Wind	3,3	1600	80	1

Reconstruction should take into account the transition to clean energy and at the same time ensure Ukraine's energy security. However, the expansion of renewable energies needs sufficient time and cannot immediately replace the loss of fossil fuels. Apart from the abundance of fossil fuels, their use is associated with harmful effects on the climate, which contradicts the goals of climate neutrality in Ukraine (Table 1).

Table 2. Economic and ecological assessment of various energy sources, globally (in the years 2019-2023) [12], [13], [14].

Energy sources	Levelized Costs of Electricity, LCOE	Global weighted average total installed costs (TIC) (2019)	Economic life (years)	CO2 intensity (g CO2 / kWh)
Renewable energy				
Solar Photovoltaik	0,047 USD / Kwh	995 USD/kW	25	27
concentrating solar power	0,182 USD / Kwh	5774 USD/kW	25	27
Onshore Wind	0,031 USD / Kwh	1473 USD/kW	25	13
Offshore Wind	0,077 USD / Kwh	3800 USD/kW	25	13
Hydropower	0,047 USD / Kwh	1704 USD/kW	30	2,2
Geothermal	0,073 USD / Kwh	3916 USD/kW	25	65
Biomass	0,066 USD / Kwh	2141 USD/kW	20	10…19
Nuclear energy	0,135 USD / Kwh	2000 USD/kW (BBEP-1000)	45…80	2,5
Conventional energies				
Brown coal	0,131 EUR/Kwh (2021)	2000 USD/Kw	45	1036
Hard coal	0,155 EUR/Kwh (2021)	2000 USD/kW	45	1060
Natural gas	0,08-0,13 USD / Kwh	1000 USD / Kwh	20	550

Furthermore, it is expected that fossil fuels (except nuclear power) will play an increasingly smaller role in energy supply in Ukraine, which is a general European trend. In response to the Russian attack, Ukraine stopped buying fossil fuels from Russia. In the first year of the war, hard coal consumption fell from 29 million tonnes in the previous year to 17 million tonnes (own production), and natural gas consumption fell from 28.8 to 18.5 billion m3.

According to the Recovery Plan of Ukraine [15], an increase in domestic natural gas production is planned by 2032. Overall, Ukraine's future energy mix will represent the options of natural gas, nuclear power and renewable energies. Natural gas use is seen as a bridging technology in the transition to renewable energies. Mainly from 2050 onwards, renewable energies and nuclear power will be combined in Ukraine's energy mix with a clear prevalence of nuclear energy. Such an energy mix corresponds to the goals of climate protection if nuclear energy is perceived as a safe energy source. Only from 2070 would it be possible to generate energy exclusively from renewable sources [16]. A faster exit from fossil fuels would be possible if energy consumption in the country were to decrease.

The comparison of the share of primary energy consumption in Ukraine and Germany, Austria and France is shown in Figure 1. Thus, the share of renewable energy sources in Ukraine during the period under review was inferior to the share in other comparable

countries. However, it was in Ukraine in 2016-2021 that the largest increase in renewable energy capacity was observed among other European countries.

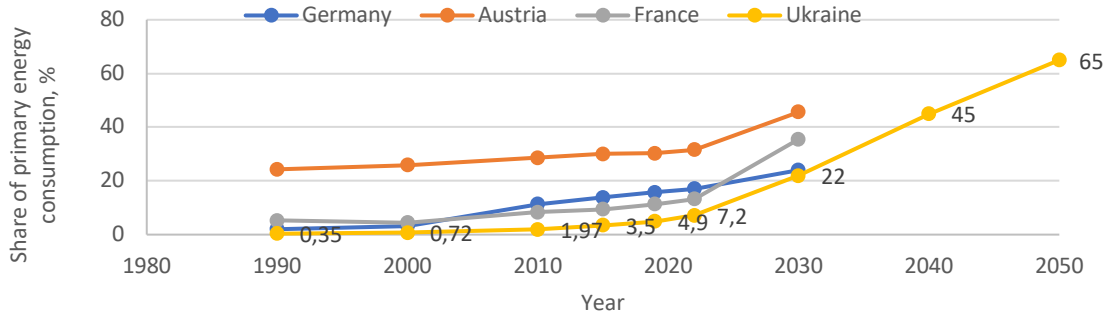

Figure 1. Share of renewable energy in primary energy consumption by country in % and its forecast for Ukraine until 2050 [17], [18], [19].

Based on Table 2, the highest efficiency projects will be for electricity generation from photovoltaics (global: LCOE 0.047 USD / Kwh, TIC 995 USD/Kw), onshore wind (global: LCOE 0.031 USD/ Kwh, TIC 1473 USD/Kw) and hydropower (global: LCOE 0.068 USD / Kwh, TIC 995 USD/Kw).

From the point of view of natural conditions in Ukraine, electricity generation from wind turbines would be particularly profitable. The coastline of Ukraine is about 2,700 km [20], where the wind speed at a height of 20 m reaches an average of 6.7-6.9 m/s. Wind farms can also be installed in shallow water at a depth of up to 50 m. Also, in Western Ukraine in Ivano-Frankivsk region (Carpathians), Chernivtsi region, Lviv region and Transcarpathia the wind speed is around 6.5 m/s. This means that not only southeastern Ukraine is attractive for the development of wind energy, but some areas in the west of the country (Figure 1).

Since renewable energies have a lower energy density per unit area compared to fossil and nuclear energy sources, more land is used for their production than for conventional energy production. To exploit the onshore potential, up to 7000 km2 of the country can be used for wind turbines, achieving a total capacity of 35GW.

According to [15], two scenarios for the development of energy production have been created, which assume the extent to which investments will actually be made in the expansion of renewables (see Table 3). The calculated ranges in the level of expansion of the respective renewable energies between optimistic and pessimistic scenarios determine areas of action for incorporating investments in increasing the capacity of green electricity generation.

From the point of view of planning the performance of renewable energies, it is important to take into account their productivity in electricity generation. The full load hours (FLH) indicate the number of hours that enable the nominal power of a particular technology. The number of full load hours depends on natural and operational factors.

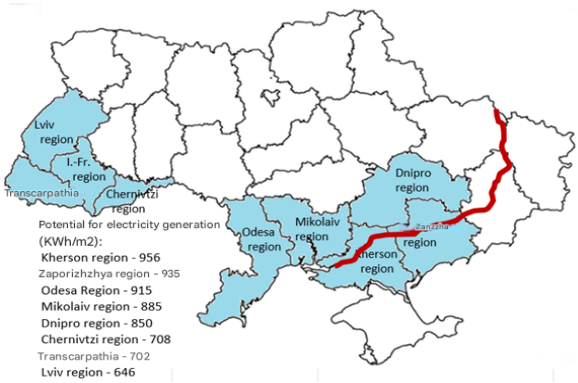

Figure 2. Most favorable regions of Ukraine forelectricity generation from wind energy [20]

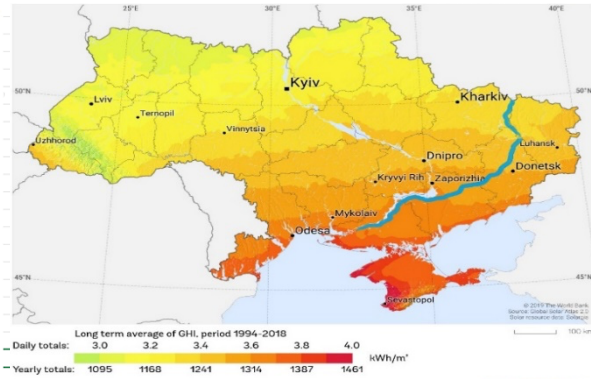

Figure 3. Solar radiation in Ukraine, KWh/m2 per year [20]

Table 3. Expected expansion of climate-neutral energies under the Project of the Recovery Plan of Ukraine, (capacities, GW) [15]

Scenario	01.01.2022	2023	2025	2030	2035	2040	2050
pessimistic							
PV	6, 3653	6,8	7,2	8,2	8,2	9,2	13
wind power	1,529	2,8	3,3	4,3	4,7	4,4	7
bioenergy	0,254	0,25	0,3	0,35	0,4	0,45	0,5
small HPP	0,1929	0,198	0,202	0,212	0,217	0,227	0,237
large HPP	---	6,79	6,79	6,79	7,25	7,25	7,25
nuclear energy	13,8	13,8	13,8	13,8	13,8	13,8	13,8
optimistic							
PV	6, 3653	8,25	9,2	12	18,5	35,3	58,6
wind power	1,529	3,5	5,2	8	11,7	20	32
bioenergy	0,254	0,3	0,9	2,4	3,9	5,2	7,9
small HPP	0,1929	0,198	0,207	0,227	0,247	0,257	0,297
large HPP	---	6,79	7,15	8,6	9,82	10,24	10,37
nuclear energy	13,8	13,8	13,8	>14,8	>17	>20,3	>20,3

Thus, based on global investments in the total output of renewable energy sources (see Table 2) and the electricity yield of each energy source in 2020, 2022 (see Table 4), PV had the best value of this indicator: only with an investment of 0.337 euros it was possible to produce 1 kWh of electricity during the year. To evaluate the productivity of energy facilities for green energy generation, which are planned to be built as part of the reconstruction of the energy sector in Ukraine, the static value of the average full load hours for 2020 is used (Table 4). Based on this indicator, a forecast for electricity generation in Ukraine until 2050 is made (see Figure 4).

To determine the volume of domestic electricity consumption in Ukraine, the dynamics of changes in electricity consumption in Ukraine for 1985-2021 were analyzed with the construction of a predictive regression model y=-0.2001x+407.12 of linear type (R2=0.8481).

Table 4. Efficiency of respective energy production technologies [21], [22].

Energy sources	Installed capacity, GW (nominal power)	Actual annual production of electricity, TW	Theoretical maximum annual production of electricity, TW (nominal power*8760)	Annual use rate (efficiency, % / full load hours)
location-independent technologies				
hard coal (De) 2022	18,523	49,29	162,261	30,37/2660
natural gas (De) 2022	30,27	91,94	265,165	34,67/ 3037
bioenergy (De) 2022	9,4878	46,5276	83,106	55,98/4903,8
nuclear power plants (UA) 2020	13,835	65,36	121,1946	58,79/5150
location-dependent technologies				
solar power plants (UA) 2020	5,194	5,684	45,49944	12,49/1094**
wind power plants (UA) 2020	1,11	3,271	9,7236	33,64/2947*
hydro power plants (UA) 2020	6,335	7,415	55,4946	13,36/1170

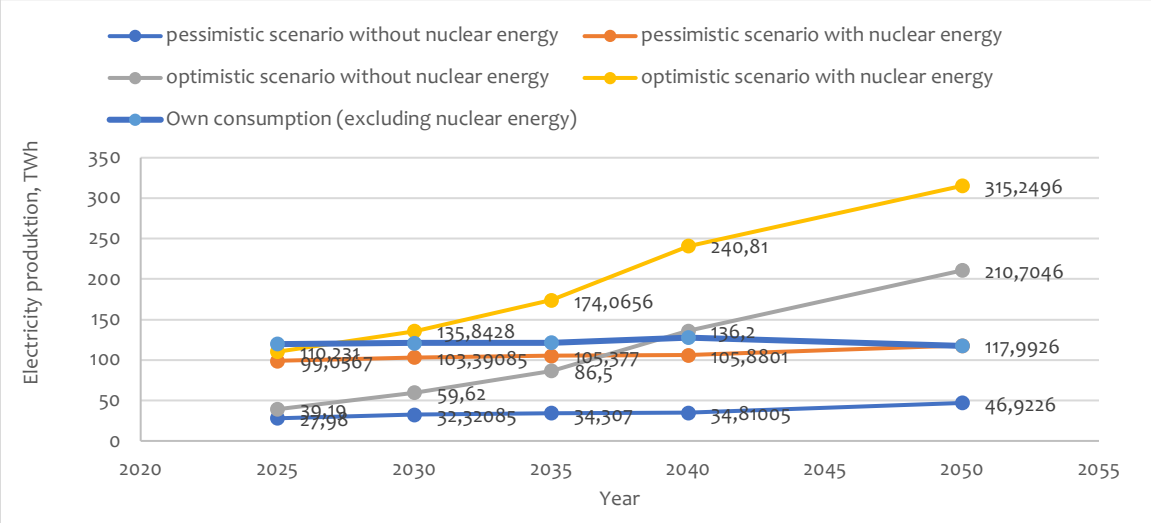

Figure 4. Electricity production and self-consumption from renewable energy sources in Ukraine (PS-Pessimistic Scenario, OS-Optimistic Scenario). Source: Own calculations based on Tables 3-4.

Discussion

The conducted studies confirm the statement [1] on the conditions of transition to energy changes, as well as the importance of freedom from energy dependence on authoritarian regimes [2]. However, a fundamentally new contribution of the study is the determination of the productivity of green electricity production technologies and the assessment of the level of domestic electricity consumption.

In contrast to [9] regarding the factors of choice of energy production technologies, taking into account the low share of renewable sources in the energy balance of Ukraine, it is determined to be more valuable to conduct a comparative characteristic of the costs of electricity production, initial investments and the productivity of the corresponding technology in the climatic conditions of Ukraine. However, it should be

taken into account that not all of the projected electricity production for export under the scenarios depicted will be delivered to foreign consumers in the form of electricity.

The export potential of green electricity from Ukraine will be derived from the decisions on which amounts of energy will be supplied as electricity and which as a secondary energy source, hydrogen. According to the Recovery Plan (see Table 3), 30 GW of the total capacity of renewable energies is intended for hydrogen production by 2050. From the average ratio between productivity and total capacity of energy plants in 2050, it can be concluded that 30 GW of capacity promises an average of 66.3 TWh of electricity for hydrogen production.

According to calculations [20], it was confirmed that natural gas and nuclear power are still used as a bridge technology for a complete transition to renewable energies. However, from a safety perspective, investing in the expansion of nuclear energy in Ukraine remains debatable. It is assumed that natural gas consumption in Ukraine will continue until at least 2050, and nuclear power until 2070. According to [20], the share of nuclear energy in the country's primary energy consumption will decrease to 20-25% in 2050. The consumption of hard coal for energy needs in Ukraine should be stopped by 2040. The use of these two technologies makes electricity production independent of the natural features of the areas where the facilities are located. However, according to Table 2, this will lead to an increase in hydrocarbon emissions into the atmosphere - about 500 g of CO_2 per 1 kWh if gas consumption is maintained after 2040 and to an increase in environmental risks and investment losses if nuclear power is continued.

Conclusion

It has been established that Ukraine has the best natural conditions for the production of electricity from wind energy. These power plants can be effectively used throughout the territory of Ukraine, but their location in the West and South of Ukraine is the most promising. The second most efficient technology for generating electricity is solar energy, the best natural conditions for which are formed in the South of Ukraine. An approach to the selection of electricity generation technologies is determined, which is based on taking into account the productivity of energy-generating equipment in the specific natural conditions of Ukraine, the costs of generating electricity, as well as the impact of these technologies on total greenhouse gas emissions. Accordingly, optimistic and pessimistic scenarios for the development of renewable energy sources in Ukraine have been defined, reflecting their overall productivity with and without the use of nuclear energy.

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