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Modelling the Energy Sector in Ukraine with RES Development Scenarios

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Abstract:

Purpose: *The aim of the article is to identify possible scenarios for RES development to meet the socio-economic and environmental requirements of Ukraine. The research question which the authors asked was about possibility and timeframe of RES development in Ukraine within the defined scenarios.*
Design/methodology/approach: *The research gap identified by the authors includes the development of scenarios for RES development as a component of the entire energy sector using the MARKAL/TIMES model. The paper presents the results of research conducted using a variety of research methods and tools, including a critical analysis of literature, an integrated MARKAL/TIMES model generator, scenario analysis based on an optimalisation model and a linear regression model. The research extends over the period 2018-2021.*
Findings: *The results confirmed that the development of RES according to the indicated scenarios, which assume the progressive substitution of non-renewable energy sources in Ukraine until 2050, will allow to meet the demand at different times and make the Ukrainian economy coherent with the low-carbon plans of the EU economies. However, it should be emphasised that the results obtained must be verified after the end of the war operations on Ukrainian territory, taking into account the existing situation of the energy sector infrastructure and potential changes in Ukraine's economic policy priorities.*
Practical implications: *Regarding Ukraine's aspirations for EU membership, there is a need to model the country's energy sector in terms of its ability to contribute to sustainable development.*
Originality/Value: *In practice, modelling for the energy sector and its actors and energy market stakeholders is sometimes used in the definition of the country's macroeconomic strategic objectives, which stimulate and are intended to help reform and transform economies in line with global trends and international law.*

Keywords: *Modelling scenarios, renewable energy sources, the energy sector.*

JEL codes: *O1, O2.*

Paper type: *Research article.*

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1. Introduction

Ukraine and the entire world have faced the climate change problem, which has been apparent since the mid-20th century, and which is a consequence of human activities. One of the solutions to this problem is rolling out of a full-scale energy transformation from fossil fuels to renewable energy sources. The development of science and advanced technologies has already opened real perspectives of the use of energy from renewable sources at a greater scale, and even of a full-scale transition of economies to RES.

The achievement of the objectives specified in the national strategies for the development of Ukraine's energy sector depends in many aspects on the country's socio-economic progress. There is a doubt as regards the development of the power system in the long-term perspective, and in particular in relation to the development of nuclear energy and RES.

Source literature applies the term of a sustainable energy system, which should be based on "a combination of renewable energy acquisition technologies, renewable fuels in transport, renewable heat, demand reduction, effectiveness of utilization, as well as cogeneration of energy production" (Mitchel, 2010).

An attempt to combine energy, economics, and environmental protection in the context of sustainable development, as stated by T. Mirowski. "contributed, among others, to an interdisciplinary approach of scientists and researchers in applied sciences, as well as to introduction of smart technologies, search for possible ways to improve energy efficiency in mature energy technologies, diversification of sources of procurement of raw materials of strategic significance, development of RES energy, and a greater care for natural environment. Political, economic, and sociological sciences have also gained an appreciation of the research scope of the impact of sustainable development policy on changes in economy and society" (Mirowski, 2022).

Optimization in energy sector research is one of the primary components supporting the decision process and sets out possibly the best direction for solutions while taking into account a specific criteria and a function of the objective, which most often is an economic, an environmental, and a social effect. Optimization aids in the selection of the best possible scenario for the system under investigation. The beginnings of the scientific debate on the interaction and the interdependence between energy and economy fall onto years 1973–1985.

Hogan and Manne (1979) would explain then the relationship between capital and energy, which consequently impacts the energy demand. Berndt and Wood (1979) suggested that capital and energy may be complementary on short-term basis, however Hudson–Jorgenson applied a desegregated research using a general equilibrium modelling for analysis of the impact of the increase of oil prices on the

(Bhattacharyya and Timilsina, 2010; Hudson and Jorgenson, 1978). The 1990s mark the beginning of the interest of scientists and energy market stakeholders in the interaction created by Energy and the natural environment, an in particular taking into account the topics related to the climate change. The majority of energy system models have attempted to capture the above topics.

The energy sector and its electric power subsector, which is the main subject of research, is one of the key sectors of economy in the majority of European Union Member States (Nagaj, 2016) and in Ukraine and is subject to *ex ante* regulations (Lyulyov *et al.*, 2021; Volchyn *et al.*, 2013).

Depletion of traditional types of energy raw materials and an increasing negative impact of the energy sector on natural environment have resulted in the tightening of environmental standards, significant fluctuation of energy prices, striving for enforcement of energy and economic security, politicisation of energy supplies and other factors brought about an urgent need to review the current state of affairs of the energy sector, to seek for possibilities of its modernisation, as well as to revisit the Ukrainian strategy within this scope.

Ukraine's dependence on imports of energy raw materials leads to major socio-economic problems. An extraordinarily high degree of depreciation of (energy) infrastructure, as well as an extremely low efficiency of energy raw materials utilization constitute the factors contributing to Ukraine's position among economies with high energy intensity indicators (Sabishchenko *et al.*, 2020).

Ukraine is a reservoir of non-renewable natural the energy sector resources including coal, natural gas, crude oil, and uranium, as well as it has a significant potential as regards biomass energy, hydroelectric energy, and other renewable energy sources. Since the onset of the war, Ukraine has also been the most important component of the power transmission infrastructure for the Russian natural gas exports into the European Union (Krawchenko and Gordon, 2022; Kudria, 2012; Chen *at al.*, 2020; Plėta *et al.*, 2018).

One of the primary challenges in shaping a country's energy policy and a model of functioning of the energy sector supporting its dynamic development is diversification of sources of energy, in particular if imports are necessary. This is a key aspect calling for the need to model the energy sector in the direction of achieving energy independence. The functioning of the energy sector in a developed state determines its civilisational development and a stable economic growth.

The technical potential of RES possible to generate within a year in Ukraine, according to the data provided by The State Agency on Energy Efficiency and Energy Savings of Ukraine, has been estimated at 68.9 million tonnes of oil equivalent (Mtoe) per year. It is currently utilised only in 5%, while its full use would enable replacement of nearly 50% of traditional fossil fuels (Czapliński and Kavetskyy, 2019).

During the last few years, there has been a noticeable development of the RES sector, however so far it has been playing only a marginal role of 2% in Ukraine's energy balance. Yet, the share of RES has been changeable and it depends on weather conditions (Iwański and Sarna, 2017). In the light of the data provided by OECD, the capacity of installations generating energy from biofuels and biomass increased in years 2018-2019 from 948.2 to 2640.4 MW, and in case of solar and wind power from 515.4 to 776.4 MW (Snapshot of Ukraine's Energy Sector, 2019).

Table 1. *The **r**egions in Ukraine with the highest share of RES in 2018 (installed capacity in MW)*

Region	Wind Farm/ Power Plant	Solar Farm/ Power Plant	Home Solar Installations	Other	Total
Kherson	337.7	406.0	33.2	3.9	780.8
Zaporizhzia	497.8	288.9	5.6	3.7	796.0
Odesa	32.7	430.0	21.1	1.2	485.0
Mykolaiv	118.9	592.6	16.3	13.6	741.4
Lviv	33.9	328.7	18.6	3.0	384.2
Vinnytsia	0.0	336.5	17.9	40.9	395.3
Khmelnytskyi	0.0	275.9	23.0	25.1	324.0
Dnipropetrovsk	0.0	1013.8	70.6	29.8	1114.2
Kirovohrad	0.0	298.4	31.9	19.3	349.6
Donetsk	13.5	0.0	9.4	5.5	28.4
Other	7.1	952.3	305.4	138.5	1403.3

Note: *Data excluding temporarily occupied territories of Crimea*

Source: *Own elaboration on the basis of (NEURC, 2021; UWEA, 2021, DTEK Group, 2021).*

According to official Ukrainian data, in years 2010–2017 the total installed capacity of RES increased almost 13 times, while the energy generated from these sources in year 2017 showed an increase of 765.2% as against year 2010 (Czapliński and Kavetskyy, 2019). Still in year 2014, the nominal power of RES in Ukraine was only 0.1 GW, which finds an explanation in the lack of interest in this direction of the energy sector development in the financial circles associated with President Yanukovych overthrown in year 2014, whose removal may be considered as the turning point in the development of RES in Ukraine.

In the same year the Ukraine's *National Energy Efficiency Action Plan until 2020* (State sites of Ukraine, 2021) was adopted, which sparked large investment projects, predominantly in Photovoltaics, which saw the most spectacular progress in terms of installed capacity. In years 2014–2020, EUR 6.1 billion was invested into RES in Ukraine, EUR 2.5 billion out of which constituted foreign investments. The "green boom" resulted in an increase in the nominal power of RES from 0.1 GW in year

2009 to 5.6 GW in year 2019 and by another 2 GW up to 7.1 GW in May 2020 (Czapliński and Kavetskyy, 2019).

If in year 2014 renewable energy accounted for only 2.5% of Ukraine's generated power, in year 2020 it was already 7.5% (Kost, 2021). The situation as regards RES is painted in a slightly different way in the light of the data provided by The Energy Community Secretariat (ECS), according to which the share of RES in the electric power generated in Ukraine increased from 3.1% in year 2009 to 7.0% in year 2018, with a forecast and a goal for 2020 of 11.0% (ECS, 2020).

An analysis of RES from the point of view of the installed capacity shows a visible strong and nearly a double increase of the photovoltaic capacity, which reached the level of 3555 MW, as well as nearly a double increase in the installed capacity of small hydroelectric power plants (< 10 MW) and wind farms, up to 185.4 MW and 1025 MW, respectively. The share of each type of energy in the total capacity of RES in year 2019 was as follows (Ukrainian Institute for the Future, 2020):

- Major hydroelectric power plants – 4624 MW;
- Solar energy – 3555 MW;
- Pumped-storage hydroelectric power plants – 1488 MW;
- Wind farms – 1025 MW;
- Small hydroelectric power plants – 185 MW;
- Biogas installations – 143 MW.

The key developmental factors for RES were: a conducive investment climate and effective programs and tariffs supporting the development of the renewable the energy sector, as well as technological development. The other important factor of growth was an active approach of Ukrainian national banks and international financial institutions within the area of RES project investments. In year 2019, the Ukrainian renewable energy market was entered by such companies as NBT (Norway), Guris (Turkey), Scatec Solar (Norway), TIU Canada (Canada), Modus Energy International (Lithuania), and EMSOLT (Turkey).

During the last five years, the Ukrainian government adopted a number of key reforms, including an important reform of public companies, which resulted in an increased accountability of the state for the energy sector. A significant part of reforms was a result of the international commitments that determined the international position of Ukraine in the energy sector or of the aspirations of the consecutive Ukrainian governments associated with European integration and the adaptation of internal solutions to globally approved standards, and in particular European Union standards.

An important vector of development is the assurance of energy security as part of the category of reformative actions as regards the limitation of the scope and the consequences of the consumption of energy as means of political pressure by The Russian Federation (Motowidlak, 2021). Electric power market reforms are not a one-time occurrence, but rather a long-term process during which errors and erroneous assumptions are being continually corrected (Doroshuk, 2020).

As part of the planned program of reforms and strategic documents, there is also a number of sector-specific in the area of electric power and natural environment. Ukraine possesses a collection of strategies, programs, regulations, and policies. The most important sector-specific strategic document for the energy sector is *The New Energy Strategy of Ukraine 2035 "Security, Energy Efficiency, Competitive Ability"* (Resolution of Vierchova Council, 2021). The Strategy was adopted by the government in year 2017 and it incorporates plans, sets out priorities of the government and the strategic goals of the state in the energy sector until 2035.

Listed as the priority in the Strategy is energy security, and in particular the energy independence from The Russian Federation, which has proven of such a paramount importance since the onset of the war (Nezhyva and Mysiuk, 2022; Ferriani and Gazzani, 2022). The strategy presents an outline of the entire scope of energy reforms in Ukraine, from energy efficiency through an efficient management of energy resources.

The implementation of the strategy has been divided into three phases, the purpose of which is to achieve the reform of the energy sector by year 2020, the development and the optimisation of infrastructure by year 2025, and a sustainable development in a long-term perspective by year 2035.

However, the choice of the community vector in the electric power sector reforms in Ukraine is questioned also by some Ukrainian experts. A. Bayramov and Y. Marusyk argue that community templates cannot be readily implemented in Ukraine, as they constitute finished solutions that have already been implemented in the EU and as such may not serve as an effective tool in solving energy-related problems in a country affected by a deep crisis not only in the energy sector, but also throughout its entire economy with a limited production potential and paralysed by deep contradictions of particular interest of various groups of influence and centres of political pressure.

The authors quoted above also emphasize the ambiguous approach towards reforms of the Ukrainian energy sector on the part of Ukrainian decision-makers and regulators. On one hand they declared a full acceptance for the European Union vector and swiftly implemented the proper energy-related legal regulations in compliance with the EU's *acquis communautaire* and on the other they did not give up the defence of the former interests deeply rooted in the previous system. The consequences are non-transparent rules of operation of the Ukrainian energy sector (Bayramov and Marusyk, 2019).

2. Materials and Methods

The completion of the aim of the article and the search for the answer to the formulated research question called for, apart from extensive study of source literature, empirical research to be designed and carried out. The research process was completed in 4 basic phases, which utilized a diversified methodological approach.

Table 2. *Research procedure*

Research Phase	Research Goal	Utilized Research Tools /Methods
I	Identification of the condition of the energy sector in Ukraine and goals and assumptions of the long-term policy for changes aimed at a sustainable development	Desk Research Analysis
II	Generation of RES development models in the Ukrainian energy sector	MARKAL/TIMES Model Generator
III	Simulation and modelling energy production forecasts taking into account RES	Scenario Analysis
IV	Verification of models of RES' participation in energy production in Ukraine	Linear Regression Analysis

Source: *Own elaboration.*

Among the various methods for modelling the energy sector identified in source literature (Szczerbowski, 2014; Kamiński, 2010) the simulation scenario method was selected, which may constitute a synthesis of the econometric method and the optimization method, as well as utilize their analytical tools.

Furthermore, it should be noted that due to the key importance of energy for the correct functioning of the entire economy, while taking into account a critical analysis of objectives leading to the completion of goals, which result from the energy sector development strategy adopted by Ukraine and international commitments, and in particular EU's *aqui communitare*, or from *backcasting* perspective, which accounts for the so-called *rebound effects* and macroeconomic *top-down* perspective, creation of an economic-energy-environmental model was assumed to be justified.

Apart from the decision as regards the selection of the correct approach to modelling the energy sector of significance is the choice of the proper tool for carrying out the abovementioned process. Among the many tool groups known and described in source literature (Krzemień, 2013), MARKAL/TIMES integrated generator was selected, which is the most comprehensive system utilized in 70 countries by 250 institutions globally.

MARKAL/TIMES is a generator of general purpose models, which are adapted to newly developed evolution scenarios of a specific energy-environmental system during a period of usually from 20 to 50 years. They may refer to a system at a global, regional, national, or a local community level. It should be noted that models generated by means of MARKAL/TIMES were also utilised in simulations of integrated policies of the European Commission concerning the use of renewable resources, alleviation of the effects of climate change, and improvement of energy efficiency and much more rigorous environmental goals than 30-30-30 in a longer perspective at the national and the European level.

The TIMES demand scenario components consist of a set of assumptions on the drivers (GDP, population, households, outputs) and on the elasticities of the demands to the drivers and to their own prices. For the global versions of TIMES, the main drivers are: population, GDP, GDP per capita, number of households, and sectoral outputs.

The second constituent of a scenario is a set of supply curves for primary energy and material resources. Multi-stepped supply curves are easily modelled in TIMES, each step representing a certain potential of the resource available at a particular cost. In some cases, the potential may be expressed as a cumulative potential over the model horizon (e.g., reserves of gas, crude oil, etc.), as a cumulative potential over the resource base (e.g., available areas for wind converters differentiated by velocities, available farmland for biocrops, roof areas for PV installations) and in others as an annual potential (e.g., maximum extraction rates, or for renewable resources the available wind, biomass, or hydro potentials). Note that the supply component also includes the identification of trading possibilities, where the amounts and prices of the traded commodities are determined endogenously (Loulou *et al.*, 2016).

The procedure of model generation for the energy sector in Ukraine by means of MARKAL/TIMES incorporated a creation of 3 scenarios, i.e., a reference scenario, the liberal RES scenario, and the revolutionary RES scenario.

The reference scenario is considered to be a hypothetical scenario, in which specifications of most energy technologies remain unchanged until year 2050, as against previous years and therefore there is no increase in the efficiency of the consumption of energy resources and only a small part of the RES potential is utilized the way it was taking place in year 2020. In this scenario, which may be also described as conservative, a gradual replacement of technologies happens only at the end of the so-called design lifespan of the existing installations or capacity.

This scenario served as a reference for comparison of the alternative liberal RES and revolutionary RES scenario. It is a reference for the effectiveness of a policy stimulating technological and pro-environmental changes in the economy and the energy sector. In the reference scenario, which may be also described as conservative, a gradual replacement of technologies happens only at the end of the so-called design lifespan of the existing installations and capacity.

The following scenarios were generated by imposing potential external limitations on a reference model, determined by national and international energy and environmental policies (for example the minimum share of renewable energy, the maximum emission level of greenhouse gases or the minimum level of energy security). Thanks to this procedure, the utilized tool enabled as a result the creation of various energy system models on the basis of a diversified energy mix, understood as diversified technologies and fuel types.

The basic indicators that constituted the discriminants for the generated scenarios (reference, liberal RES, and revolutionary RES) included: energy efficiency, prices of primary energy raw materials, RES resources, nuclear energy and environmental requirements.

The best scenario was selected as a result of optimisation analyses. However, it should be noted that the most frequently used optimisation criteria for energy sector models account for economic, environmental, and social impact (Krzemień, 2013; Pikoń, 2011). The mathematical optimisation model applied in the research, apart from the mentioned function of the objective, accounted for in this case the following variables: use of primary energy sources, generation of electric power, required investment outlays, emissions.

The final phase of the research of an attempt to verify the developed energy sector models with a share of RES, which was completed on the basis of the linear regression model.

It should be emphasised that the inaccessibility of current statistical data reflecting the situation in the energy sector in Ukraine due to objective reasons (Russia's military assault) precluded the necessary updates of the developed forecasts and scenarios. As a result, it should be noted that the conclusions from the conducted research refer to the pre-war situation and should be adequately corrected after the end of the warfare, the consequences of which will surely influence the priorities set in Ukraine's economic policy, along with its future national energy policy.

3. Scenarios of the Development of RES in Ukraine's Energy Sector

Scenario-based designs of long-term economic energy models are founded, in the case of Ukraine, in the overriding objective of reinforcing the national energy security, as well as major phenomena of global character, depletion of traditional types of energy resources, an increased negative impact of the energy sector on natural environment, major fluctuations of energy prices on international markets, and politicization of energy supplies.

This brought about an urgent need to review the current condition of the energy sector and to search for possible ways to modernise it, as well as to review the policy, which since year 2019 have been a subject of attention of numerous international research teams working in Ukraine and on European universities (Child *et al.*, 2017). An important impulse to update and improve the MARKAL/TIMES energy system for Ukraine is the selection and the quantification of the proper policy and the measures assuring the achievement of the objectives of the New Energy Strategy of Ukraine until 2035 (ESU2035).

In order to identify the possible scenarios of the development of RES in Ukraine, a reference scenario (Table 3) was adopted as the primary point of reference, which served as the basis for the following two RES development scenarios: the liberal RES scenario and the revolutionary RES scenario.

Table 3. *The total supply of primary energy in the reference scenario of Ukraine's energy mix by year 2050 (bln kWh)*

	2012	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Coal	42.71	27.34	50.04	60.98	68.97	75.46	80.99	86.01	90.02
Gas	43.01	26.05	33.94	36.51	38.54	41.05	43.66	43.81	42.76
Oil/ petroleum products	11.60	10.55	12.25	13.12	14.22	15.34	16.07	16.83	17.75
Nuclear energy	23.65	22.98	16.95	15.54	13.98	14.42	12.53	12.55	12.55
Electricity	-0.99	-0,12	-0.25	-0.30	-0.35	-0.39	-0.43	-0.42	-0.41
Hydroelectr icity	0.90	0.46	0.91	1.03	1.12	1.12	1.13	1.13	1.14
Wind energy	0.03	0.09	0.26	0.37	0.38	0.39	0.40	0.40	0.43
Solar energy	0.03	0.04	0.02	0.05	0.07	0.08	0.04	0.04	0.04
Biofuels	1.52	1.46	2.11	2.20	2.22	2.52	2.82	3.39	3.94
Total	**121.46**	**88.85**	**116.23**	**126.50**	**139.15**	**149.99**	**156.08**	**163.74**	**168.22**
The share of RES (%)	**2.04**	**2.31**	**2.84**	**2.89**	**2.72**	**2.74**	**2.81**	**3.03**	**3.30**

Source: *Own elaboration on the basis of (Institute for Economics and Forecasting…, 2019)*

For the purpose of development of a reference scenario, it was necessary to adapt identical baseline indicators for all scenarios: GDP, the price of primary energy raw materials, the size of population, and the cost of technology. The scenario analysis carried out was based on the following assumptions: average annual GDP growth between 2016 and 2050 will be 4% and will quadruple by 2050, the price of oil imports will increase from USD 96 to USD 129 per barrel (between 2014 and 2050 – growth by 35%).

The price of coal imports, after declining in 2014-2016, will oscillate around USD 55-70 per tonne in the following years (until 2050), while the price of natural gas will increase from USD 10 to USD 16 per MBt during this period, thus showing an increase of 60%. At the same time, the estimated population of Ukraine will decrease from 44.9 million in 2020 to 38.9 million in 2050. In addition, supposing that the cost and efficiency of new technologies replacing old solutions will reflect current trends, it was assumed that the cost of new technologies will decrease and technological efficiency will increase.

The scenario assumes that most of the existing technologies may still be used during the period of modelling (2012-2050), which is useful in evaluation of implications for carrying out alternative scenarios, in which a significant role is played by the effectiveness of the measures and the policy stimulating technological changes in economy. The basic requirements for the reference scenario are inscribed in the objectives of The New Energy Strategy of Ukraine until 2035, in which the share of RES in the total supply of primary energy was anticipated to reach 30% by year 2050, with an anticipated drop by year 2035 of the share of coal to 15% in the total supply of primary energy.

The results within the scope of the total supply of primary energy in Ukraine as part of the reference scenario and The New Energy Strategy of Ukraine until 2035 are similar due to an assumption of the same energy intensity of the economy during this time. Differences occur only in the composition of primary energy sources, as the reference scenario includes an expectation of a higher demand for coal, while the use of nuclear energy and renewable energy are higher than in The New Energy Strategy of Ukraine until 2035.

Taking into account the key conditions of development of the energy sector, as exemplified by the electric power sub-sector, it is possible to identify two main directions of development scenarios including decarbonisation of the sector and a scenario increasing the share of RES in the supply of primary energy and generation of electric power, in a division, as mentioned above, into the liberal RES and the revolutionary RES scenarios (Table 4).

***Table 4**. Electricity production in Ukraine by 2050-liberal and revolutionary RES scenarios (bln kWh)*

	2012	2015	2020	2025	2030	2035	2040	2045	2050
Liberal RES Scenario									
NPP (existing)	90	88	65	52	32	20	13	13	13
NPP (new)	0	0	0	7	14	14	20	20	20
TPP (existing)	79	58	42	19	2	0	0	0	0
TPP (modernized)	0	0	0.9	5	9	26	27	27	27
TPP (new, coal-fired)	0	0	18	29	39	39	39	39	39
TPP (new, gas-fired)	0	0	5	7	9	7	7	7	7
CHPE	18	8	26	28	31	32	34	36	33
HPP (large)	11	7	10	11	12	12	12	12	12
HPP (small)	0.3	0.2	0.5	0.5	0.6	0.6	0.6	0.6	0.6

WPP (onshore)	0.3	1.1	9	15	22	27	32	37	42
SPP	0.3	0.5	3	5	7	9	12	14	16
SPP (prosumers)	0	0	0.3	3	5	12	20	28	35
GPP	0	0	0.3	0.3	0.4	0.4	0.4	0.3	0.3
BPP	0	0.1	4	4	5	5	5	6	6
Total	**199**	**162**	**182**	**186**	**187**	**205**	**224**	**242**	**253**
The share of RES (%)	**6.0**	**5.4**	**14.7**	**20.9**	**27.7**	**32.7**	**37.0**	**40.9**	**44.7**
Revolutionary RES Scenario									
NPP (existing)	90	88	65	52	32	20	0.1	0	0
NPP (new)	0	0	0	0	0	0	0	0	0
TPP (existing)	79	58	42	20	2	1	1	1	0
TPP (modernized)	0	0	1	5	9	24	31	32	0
TPP (new, coal-fired)	0	0	19	25	26	26	26	26	0
TPP (new, gas-fired)	0	0	7	4	1	0	4	0	7
CHPE	18	8	18	18	20	21	23	25	19
HPP (large)	11	7	10	11	12	12	12	12	12
HPP (small)	0.3	0.2	0.5	0.5	0.5	0.5	0.6	0.6	0.6
WPP (onshore)	0.3	1.1	9	45	80	94	117	131	163
SPP	0.3	0.5	3	10	17	27	40	63	96
SPP (prosumers)	0	0	0.3	3	5	11	17	23	36
GPP	0	0	0.1	0.1	0.1	0.1	0.1	0.126	1
BPP	0	0.1	7	8	9	10	14	18	31
Total	**199**	**162**	**180**	**200**	**214**	**247**	**285**	**330**	**366**
The share of RES (%)	**6.0**	**5.4**	**16.2**	**38.5**	**57.8**	**62.9**	**70.4**	**75.0**	**92.9**

Note: *NPP-Nuclear Power Plants, TPP-Thermal Power Plants, CHPE-Combined Heat and Power Plants, HPP- Hydropower Plants, WPP-Wind Power Plants, SPP-Solar Power Plants, GPP-Geothermal Power Plants, BPP-Biomass Power Plants.*
Source: *Own elaboration on the basis of (Institute for Economics and Forecasting…, 2019; Henrich Böll-Stiftung, 2021*

All scenarios with respect to the reference scenario are directed towards making the Ukrainian economy more efficient and coherent with scenarios of a low-emissions economy and national economies of European Union Member States. At the same time, it should be noted that the liberal RES scenario may resemble the reference scenario, but on the other hand it possesses determinants that assume the perfect competitiveness on the national energy market of Ukraine and in its sectors, which, as demonstrated, will be very unlikely under the current and the future legislative conditions.

Of particular significance for research seem to be scenarios determined by processes, which have already been initiated with legislative changes and with adopted strategies and international agreements, i.e. scenarios of decarbonization and the revolutionary RES scenario.

In case of implementation of the perfect competitiveness according to the liberal RES scenario, it could be expected that by year 2050 the share of RES in the structure of the end consumption of energy may exceed 30%, while the demand for energy resources will decrease following an introduction of energy efficiency measures, which will bring about an economic growth. The results of this scenario demonstrate the potential of the renewable energy competitive potential as against traditional energy without the use of any additional incentives for RES development (Institute for Economics and Forecasting…, 2019).

In case of the liberal RES scenario, by year 2050 (during which there is an assumption of a free development of all technologies) it may be clearly concluded that electric power will be generated by means of all currently available technologies in Ukraine. However, their structure will be subject to a significant change, as the share of RES by year 2050 will increase significantly as against year 2012. This happens due to a quick improvement and decreasing costs of RES technologies. The demand for electric power will be significantly decreased as against the reference scenario due to the implementation of economically viable energy efficiency potential in the end consumption of energy.

The generation of electric power will probably decrease from 28% in year 2035 to 22% in year 2050, as against the analogical years of the reference scenario. The demand for generation of electric power may slightly exceed the indicator from year 2012 in year 2035 and equal 205 bln kWh, while reaching approx. 253 bln kWh in year 2050, which will exceed by 27% the indicator from year 2012. There will be a decrease of the share of nuclear energy from over 50% in year 2020 to 13 % in year 2050.

This is associated with high costs of the construction of new and, first and foremost, the maintenance of the old and the obsolete installations and blocks. There is also a discernible drop in the consumption of energy from coal from 40% in year 2021 to 27% in year 2050. The greatest growth as part of RES is anticipated for solar and wind energy, while the scenario assumes a deadlock in hydroelectric energy generation due to an insignificant potential of minor rivers and completely depleted potential of major rivers.

The total power generation potential will probably increase from 199 bln kWh in year 2012 to 253 bln kWh in year 2050, and the capacity of energy blocks during this time will increase almost 2.7 times from 53 GW in year 2012 to 143 GW in year 2050.

The total power generation potential will increase from 199 bln kWh in year 2012 to 253 kWh in year 2050, and the capacity of energy blocks during this time almost 2.7 times from 53 GW in year 2012 to 143 GW in year 2050 (Institute for Economics and Forecasting…, 2019).

In case of the implementation of the target policy of the development of the energy sector towards energy based predominantly on renewable sources of primary energy (a requirement of the reference scenario of "the energy sector transformation"), there are forecasts of a significant increase of the share of RES in the structure of electric power consumption. An increase of the share of RES in the end consumption is forecast by up to 90.6% in year 2050 and a decrease of the demand for energy resources by 42% as against the reference scenario, thanks to the implementation of energy efficiency measures and energy savings tools.

However, the assumptions of the primary stakeholder of the Ukrainian electric power market, Ukrenergo, should be also taken into account. Ukrenergo assumes, as part of own report from evaluation of the adequacy of the power generation capacity of (Ukrenergo, 2021) a moderate pace of the development of renewable sources of energy. The level of their consumption by year 2050 may not be, according to the report, greater than 7.2 GW and 10.4 GW of wind and solar power. If such conditions are applied in the reference scenario, the share of RES in the electric power generation will increase maximally by 41% in year 2050, whereas in year 2035 it will equal approx./ 31%, which is also a higher level than the level forecast by ESU2035.

One of the key conditions of the revolutionary RES scenario is a complete departure at the end of the exploitation period of the existing blocks of nuclear energy following the example of the German *Energiewende*. The second condition is a replacement of technology-based coal blocks by as much as 93% with renewable sources generation of electric power. Solar and wind power plants will cover in this scenario over 80% of the share of production.

The generation of electric power in the revolutionary scenario should be only 14% greater than in the reference scenario in year 2050, while the installed capacity will increase 3.6 times from 53 GW in year 2012 to 327 GW in year 2050. The low-emission society scenario is also a decarbonization scenario and as such it is complementary with the RES scenario of the energy sector of Ukraine.

It also aims at a reduction of greenhouse gas emissions by 80% in year 2050 as against the level from year 1990. This scenario is the closest to the policy for reduction of the effects of the climate change. Forecasts show that a transformation of an energy system along with the low-emissions society scenario through the decarbonisation scenario, which in year 2050 enables not more than a 20% increase in greenhouse gas emissions as against the level from 1990 (as part of the current objectives of EU), the generation of electric power must be almost 100% free from conventional sources of primary energy and also close to the revolutionary scenario of the Ukrainian energy sector by year 2050.

The most important difference is that the scenario does not exclude nuclear power, considering it to be “clean” or low-emission energy. The share of renewable energy and nuclear energy in this scenario equals nearly 90%, 28% out of which is nuclear energy, 26% is wind energy, 23% is solar energy, 7% is bio-generation and heat energy, and 5% are hydroelectric power plants.

The low-emission society scenario, assuming a significant reduction of carbon dioxide emissions as a derivative of carbon combustions and other greenhouse gases, requires a significant increase of investment outlays. Forecasts show that by year 2035 there will be a need to invest EUR 1-4 bln more annually than in the reference scenario, and in years 2040-2050 another EUR 4-6 bln more.

The results of modelling of scenarios of development of Ukrainian energy mixes by year 2050 clearly suggest that Ukraine has a sufficient potential of renewable energy, which may fully cover all and any future demands for energy resources and services, even if the high level of consumption of electric power by end users is maintained, and in particular the energy intensive branches of Ukrainian industry (metallurgy and chemical industry). With the required technologies being fully or at least partially generated internally, Ukraine may solve not only problems related to energy, environment, and climate change, but also socio-economic ones.

According to the assessment of The International Renewable Energy Agency (IRENA), Ukraine has an opportunity to become the leading state in the development of RES in Central and Eastern Europe thanks to the excellent potential of its natural environment. The average annual insolation of the Ukrainian territory is greater than in Germany, which is the leader of solar energy in Europe. The average wind speed encourages plans for the development of wind energy. The promising potential of Ukrainian agricultural and forestry sectors indicates the possible to utilize biomass and biogas (IRENA, 2021).

Ukraine has all the assets it takes to utilise its own renewable energy potential to reinforce its trade balance and create new workplaces during the time when the country is faced with major economic challenges, such as: increased dependency on energy imports, a potential loss of its position as a country of transit for gas, and an urgent need to rejuvenate the aging resources of energy capital and power generation capacity.

Nevertheless, the most important aspect and challenged facing Ukraine is its victory in the defensive war waged against The Russian Federation. This is the key issue impacting the independence of this country. Only after a victory will there be time for verification of all the various assumptions and strategies.

Unfortunately according to Ukrainian estimates 40% of the energy infrastructure has been destroyed or damaged including Kyiv, Lviv and many other cities. At the end of the October 2022 H. Halushchenko Minister of Energy of Ukraine, informed that about 90% of the installed capacity of windmills and about 45-50% of photovoltaics are out of operation (Elżbieciak and Zasuń, 2022).

Living up to the energy expectations of Ukraine will require comprehensive actions, and in particular ensuring environmentally sustainable scenarios. The most probable primary sources of renewable energy for Ukraine in the future will include: wind and solar energy, geothermal energy, developed side by side together with the efforts to maintain the capacity generated by nuclear energy.

The correct combination of the above options may ensure a reduction of a greater part of the total demand of Ukraine for natural gas in production of energy (Savchuk, 2014). RES scenarios include a clear reference to Ukrainian demand for natural gas from Russia and its consumption in the economy already in year 2030.

An important part of this process is introduction of new promising technologies, including energy storage systems, which will enable a transition of the national industry sector to consumption of energy from alternative renewable sources. Promising in this context for the metallurgical industry is the development of the electric furnace steel production method.

On the other hand, as much as over 70% of the total final energy con other compounds, and in particular in production of ammonia. Introduction to the abovementioned production processes of new technologies based on RES will contribute to their reduction by at least 20%. The average use of traditional energy in the pulp and paper industry fluctuates between 29 and 32 GJ/t of produced goods. At the same time, international experiences indicate that there is a possibility to replace conventional non-renewable sources of energy with renewable ones in the production of pulp and paper, and especially with biomass (up to 60% of total energy consumption) (EBOR, 2021).

The results of modelling show that the implementation of the liberal RES and the revolutionary RES scenario is characterised by positive macroeconomic results in a forecast of growth of Ukrainian GDP, especially in the medium-term and the long-term perspective, commencing in year 2025, and assuming an abrupt coming out of the period of a GDP drop in years 2019-2020.

Unfortunately, there are also specific barriers (not including the war), which may inhibit the process of a positive influence of RES on the economy. Overcoming these barriers starts with a better understanding of renewable sources of energy, their potential, costs, and benefits. The government must facilitate the permit issuance procedure and improve the access to the energy market for companies producing energy from renewable sources. is also a lack of mechanisms of refunds and clear procedures of connection to the power grid. Expertise as regards the limitations and the stability of the grid will also be important, in order to enable the identification of the best strategies of construction of RES power plants and storage systems.

The time frame of the existence of the national Ukrainian renewable energy (Table 4) enables drawing of the conclusions that the ambitious objectives identified in *The New Energy Strategy of Ukraine until 2035: security, energy efficiency, competitiveness* (NES, 2035; 2021) (25% of energy consumption in year 2035 from renewable sources of energy) prove hard to achieve.

The current dynamics of the RES energy share generated in Ukraine is insufficient in order for the identified objectives to be achieved. The time frame during which the 25% objective of identified in the strategic documents for year 2035 was estimated. All the calculations with the use of regression analysis and the confidence intervals of the forecast were carried out in Microsoft Excel and the obtained module parameters are presented in Table 5.

Table 5. *Linear regression model parameters*

	Factors	Standard error	t -Student	p-Value	Lower 95%	Top 95%
Split	-1062.71	88.78027	-11.9701	2.99E-07	-1260.52	-864.894
Year	0.53007	0.044071	12.02776	2.86E-07	0.431875	0.628265

Source: *Own calculations on the basis of data provided by (World Bank, 2021; Eurostat, 2021).*

From the model parameters presented in above mentioned table it may be concluded that they are statistically significant. This refers also to the entire model (Significance F at the level of 2.86E-07). The forecast of growth of the RES energy share in Ukraine (Table 6), according to the conducted regression model analysis, remains consistent with the annual report concerning the degree of implementation of the energy sector reforms in Ukraine (Ukraine Annual Implementation Report, 2020), which reflects the degree of achievement of the indicators and identifies the status of implementation of RES into the energy sector.

According to the report, the implementation of The National Action Plan Within the Scope of RES in Ukraine (National Efficiency Action Plan, 2020) was in year 2020 achieved only in 52%, and guaranteed access to the grid and integration with the electric power grid of major RES energy companies in 74%.

The energy efficiency objectives have been achieved to an advanced degree at the level of 67%, while The National Plan for Energy and Climate has been implemented only in 38%.

Table 6. *Forecasts of the RES share in electric power production according to Strategy 2035 and individual scenarios of the Ukrainian energy sector*

Scenario	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Strategy 2035	11	12	17	25	-	-	-
Liberal RES	15	21	28	33	37	41	45
Revolutionary RES	16	39	58	63	70	75	93

Source: *Own elaboration on the basis of data provided by (Institute for Economics and Forecasting…, 2019; Henrich Böll-Stiftung, 2021; Technical University of Denmark, 2021).*

The linear regression model was used as the basis for development of a growth scenario for the share of renewable energy generated from RES in Ukraine along with the lower and the upper confidence interval of this model. This analysis enables verification of the scenarios and forecasts discussed above (Table 7).

Table 7. *Scenarios of growth of the share of renewable Energy based on the linear trend estimation of the share of energy generated from RES in Ukraine*

	2025	**2035**	**2043**	**2052**	**2065**	**2071**	**2080**
Upper confidence interval (% RES)	13.05	19.95	25.11	30.76	38.73	42.36	47.78
Scenario (% RES)	10.8	16.08	20.31	25.08	31.96	35.13	39.90
Lower confidence interval (% RES)	8.54	12.22	15.53	19.41	25.19	27.91	32.03

Source: *Own calculations on the basis of data provided by (World Bank, 2021; Eurostat, 2021).*

The regression model analysis leads to a conclusion that the objective identified for year 2035 will not be achieved before year 2053. The objectives identified in Strategy 2035 will be achieved respectively as follows: 35% of the share of RES in year 2071, whereas the achievement of the objectives of the liberal RES scenario and the revolutionary RES scenario exceeds beyond the horizon of year 2080, during which the value of the share of RES in the Ukrainian energy sector may achieve only 40%. As a result, the achievement of the objectives of energy sector models for Ukraine and an adequate share of RES would be difficult without a revision of the energy policy, investments, and development of energy generation technologies.

4. Discussion and Conclusions

The key challenges and priorities of the Ukrainian energy sector, as part of the energy system transformation towards RES and decarbonisation in relation to the economic objectives consistent with national strategies until year 2035 and forecasts until year 2050 are the following according to the conducted research:

- achieving synergies in the development of the energy sector and in the economic development,
- ensuring completion of the transformation of the energy market and the

institutions of the energy sector and the electric power subsector,
- full integration with the EU electric power market and grid.

Ensuring continuation for clean and green Energy policy and Energy efficiency by:

- support and simulation of RES development,
- modernization of fixed assets used in traditional energy systems and implementation of innovative technologies,
- increasing energy efficiency and Energy savings of the economy and private households,
- reducing industrial emissions and pollutions,
- ensuring reliable supplies of clean and affordable energy,
- ensuring own storage systems for nuclear waste,
- development of energy storage systems (industrial batteries),
- expanding research, education, and awareness throughout the entire economy.

The greatest challenges facing Ukrainian economy as regards the achievement of the ambitious objectives of the energy and economic transformation in accordance with the projections based on national strategies by year 2035 and 2050, have been identified in the research as follows:

- defensive war with The Russian Federation,
- a weak investment climate,
- a low and uncertain economic growth,
- a small competitiveness on the energy market,
- high energy intensity and use of coal in GDP,
- obsolete energy generation capacity and infrastructure,
- a high level of dependence from imports of primary sources of energy and decreasing national production of fossil fuels,
- the necessity to purchase and supply RES technologies from abroad,
- imperfect legislative mechanisms for RES manufacturers,
- insufficient integration with EU energy markets,
- insufficient institutional capacities,
- insufficient predictability of legislation,
- delayed implementation of EU legislative achievements,
- the international conflict in the East of Ukraine (resulting in a high risk related to implementation of the project for investors everywhere in Ukraine),
- weakness of the assessment of the impact of economic policies and measures.

The first and foremost task in the policy of the Ukrainian government is to end the hostilities as soon as possible. Only then can appropriate steps be taken towards full integration into the European Union electricity grid, as well as supporting and stimulating further development of RES. The Ukrainian economy, including the energy sector and the stakeholders of the electric power market are still facing numerous challenges.

The energy sector, as a strategic sector, constitutes a special interest of the Ukrainian state and is subject to state control and regulations. An increasing role in the energy sector is being assigned to renewable energy, which occupies one of the leading areas of the interest of foreign investors in Ukrainian economy, is environmentally friendly, and reduces Ukraine's dependence on coal and natural gas, and therefore remains a vital component of energy security.

The development of systems, installations, and power plants relying on renewable energy dynamizes economic growth, which at the same time has a positive influence on natural environment and climate. On the other hand, investments generate new jobs, which reinforce economy and pave the way for the zero-emission future of Ukraine.

The primary lever of stimulation and development of renewable energy in Ukraine was the introduction of *the feed-in tariff*, according to which the state purchases electric power from RES. A valid allegation of the opponents of increasing the share of RES as a primary source of energy is the lack of stability associated with the changeability of the climate, weather conditions, and the day/night cycle.

A solution to this dilemma may be in the near future hybrid RES-based technologies incorporating two or more renewable sources of energy such as wind and solar power plants and energy storage systems for ensuring a greater efficiency of energy production by a combined system, characterized by a lower susceptibility to climatic conditions and the day/night cycle. They could provide additional manoeuvre capacities while ensuring stable supplies of energy.

In the event of temporary lack of insolation or wind, a combined system will continue to supply energy from batteries. If more electric power is generated than currently required, the control unit will transmit the surplus to a centralized electric grid in accordance with *the feed-in tariff*. Furthermore, if the anticipated lifespan of every RES installation equals 20 years, active operation in combination with other installations will guarantee as many as 25 years or more. Such systems will guarantee:

- reliability (use of surplus of technologies and / or storing energy);
- possibility to simultaneously improve the quality and the accessibility of electric power;
- operation of electric power and heat supply systems on the basis of RES by

means of various energy storage systems;
- a significantly lower level of toxic emissions as against traditional technologies based on coal, natural gas, and crude oil;
- achievement of sustainable energy supplies thanks to synergistic operation of the system.

In view of the above, the application of hybrid RES-based systems offers therefore sufficient energy independence, a profit from sales at *the feed-in tariff*, as well as generation of energy without any environmental impact.

In order to manage and improve the mechanisms of state regulation of stimulation of the development of hybrid RES-based installations and energy storage systems in Ukraine, there is a need for state-financial and budgetary regulation of stimulation of the development of renewable energy, including through the application of technologically diversified tools and the regulation of *the feed-in tariff*.

Critics of the excessively revolutionary approach to RES (Kytaier *et al*., 2020) as a source of primary energy and electric power generation claim that it has serious side effects for the functioning of the economy (Kost, 2021):

- deepening of Ukraine's traditional difficulties associated with the deficit of manoeuvring capabilities enabling balancing of the system depending on an abrupt decrease or increase of consumption during the day/night cycle (the problems including domination in RES structure of solar power plants that are not in operation during night hours, connecting nearly as much as 2.5 times more solar power to the grid than anticipated in The Action Plan, concentration of RES capacity in the southern circuits of the country);
- deepening of financial pathologies on the electric power market;
- nuclear power plants, hydroelectric power plants, and the operator of the transmission system were burdened financially in order to enable the development of RES, which is not conducive to creation of healthy market mechanisms;
- a faulty and not transparent structure of the cost circulation among market participants remains a source of indebtedness.

The result of the implementation of national scenarios of the development of the energy sector and of RES in year 2020 is Ukraine's rapid increase of its renewable capacity, which immediately led to technological and financial issues. Ignoring these issues could have led to serious consequences for the functioning of the entire electric power system. Nevertheless, in year 2020 the new government of Ukraine adopted an amendment of the act regulating the operation of RES companies.

Among the main provisions of the amendment are a reduction of *the green tariffs* for the existing solar power plants by the maximum of 15%, for wind power plants by the maximum of 7.5% (this should result in budgetary savings estimated by the Ukrainian Ministry of Finance at 6 bln Ukrainian hryvnia per year); introduction of the responsibility on the part of RES companies for balancing of the system, from January 1st 2021 at 50% of the value, and 100% from year 2022.

At the same time, the permissible deviations from forecasts were to equal 5% for solar power plants and 10% for wind power plants; a 5% increase of the power generated by Enerhoatom, which may be achieved in accordance with the market rules on the bilateral contracts market. Therefore, further research is necessary in order to further explore the issue of development of renewable energy, which will incorporate a comprehensive account of the mechanisms of the state's and the RES' impact on the national economy and the possible ways in which renewable energy could be further improved through an introduction of hybrid systems of renewable sources of energy.

An important aspect of the research carried out is the confirmation that the development of RES in the near and long term, will contribute to putting Ukraine on the path of sustainable development and towards green energy. Furthermore the utilisation of renewable sources of energy instead of conventional ones will increase Ukraine's energy security thanks to the possibility to achieve energy independence, which is the most important argument for the proponents of this direction of the development of the energy sector inscribed in the majority of long-term national strategies of Ukraine.

It is also a serious argument in the discussion concerning Ukraine's security in the broad sense (Müller-Kraenner, 2008) and its economic independence from the supplies of energy raw materials from The Russian Federation (Molo, 2008; Pronińska, 2012; Zięba, 2008), as well as limiting Russia's pressure on Ukrainian economy (Frankowski, 2008).

Unfortunately, the obtained research results will require yet another round of simulation and forecasts taking into account the major changes have occurred and will continue to occur due to the current warfare in Ukraine, as well as in the entire world's economy. There is reason to believe, then, that the war in Ukraine has led to a window of opportunity for new climate and energy policies in Europe centring on the accelerated deployment of renewable energy technologies, and on the accelerated phase-out of fossil energy use (Steffen and Patt, 2022).

At this time, it is hard to determine the scope of devastation in Ukraine's human resources and infrastructure, as well as provide a correct assessment of the consequences of the war from the point of view of Ukrainian economy and the global economy, as the situation on the frontlines remains dynamic and it is still difficult to anticipate a near-enough end of warfare. As a consequence, the presented results of the research may only provide a starting point for future forecasts and comparison to be carried out upon the cessation of war.

Based on the results obtained and the analysis conducted in the article, further possible research areas can be indicated. Further research efforts may for example, taking into account changes in infrastructure and energy demand as key drivers of electricity supply and demand and also use of other simulation tools and comparisons.

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