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METHODS AND MODELS OF ESTIMATING ENERGY TRANSITION ON THE EXAMPLE OF ZHYTOMYR UNITED TERRITORIAL COMMUNITY

The paper presents results of scenario modelling and assessment of energy transition to 2050 in the Zhytomyr territorial community (TC), which provides for a switching from fossil carbon based energy resources in the current TC energy system functioning to 100% use of renewable energy sources (RES) which meets all energy demands and supports the Sustainable Development of TC in accordance with the relevant UN goals. For this purpose, the optimizational economic and mathematical TIMES-Zhytomyr model (no analogues in Ukraine), based on the TIMES-Ukraine model, was developed. It includes 647 energy technologies that are currently available or may be presented in the coming years in Ukrainian market.

For the development of the TIMES-Zhytomyr model, a low-available local energy statistics was processed. As a result, the first energy balance by the form of the International Energy Agency for the large Ukrainian city and the basic energy-technological system of Zhytomyr TC were developed.

Using the TIMES-Zhytomyr model, based on foreign and Ukrainian experience, for the first time, four scenarios of Zhytomyr TC energy system development were designed and modelled, covering all economic sectors and household sector (population). The first one is the Baseline scenario, which displays the possible dynamics of the energy system development without a purposeful energy efficiency policy, the development of RES, etc. Three other scenarios are aimed at studying TC's transition capabilities by 2050 to 100% renewable energy and environmentally friendly technologies use.

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The results of modelling confirmed that the available renewable energy resource and technological potential allows Zhytomyr TC to perform the energy transition to 2050 in an economically feasible and socially acceptable way, significantly reducing energy and carbon intensity of the local economy, substantially eliminating GHG emissions, increasing the welfare of citizens and creating at least 10 thousand new workplaces. It will also significantly contribute to Zhytomyr TC to reach at least 10 of the 17 UN Sustainable Development Goals.

The research results presented, due to a significant novelty and large-scale relevance of the task, are essential in both the theoretical and practical significance. They can be used by scientists for their research and by authorities and experts for development of local, regional or national level strategies, plans or programs of economic, energy, transport, climate and ecology scope. It can also be considered as one of the first steps in preparation of a comprehensive strategy for the Zhytomyr TC development to achieve climate neutrality in accordance with the current objectives of the European Union.

Key words: *climate change, sustainable development, energy transition, renewable energy, modelling and forecasting, TIMES model*

Formulation of the problem. Since the end of the twentieth century, mankind has faced an extraordinary challenge - climate change, which has affected and continues to increase its negative impact on natural systems and directly on people in all continents. At the moment, rising temperatures of the atmosphere, oceans, and melting glaciers, together with abnormal and extreme weather (droughts, floods), as well as rising levels of World Ocean, are undoubted facts.

In 2015, 195 countries adopted the Paris Agreement, which recognizes climate change as an urgent and potentially irreversible threat to humanity and the planet, whose solution requires keeping the increase in average temperature on the planet well below 2°C compared to pre-industrial level and making efforts to limit this increase to 1.5°C [1].

During 1880–2012, the global average temperature of the surface of continents and oceans increased by 0.85 ° C. According to the report by the World Meteorological Organization "The State of the Global Climate 2020" [2] in 2020 - one of the three warmest years recorded - the average global temperature exceeded by 1.2°C the pre-industrial level, and there is a 90 percent probability that at least one year between 2021 and 2025 will be the warmest in the history of observations and a 40 percent probability that during this period the mark of 1.5°C will be surpassed.

The use of fossil energy resources, such as coal, petroleum products, natural gas, has a negative impact on global climate situation, because it is accompanied by the release of greenhouse gases (GHG) [3]. At the same time, by various estimates, 70-80% of energy is consumed in cities being the latter accountable for over 60% of total GHG emission [4]. This necessitates implementing policies and measures in the energy sector aimed at combating climate change and improving the environmental situation, not only at the level of the central government, but also local authorities [5].

Municipal energy sector is an important element in the country's energy system, because by providing energy services to population, local enterprises and organizations, it significantly affects the development of socio-economic relations in the regions and in the country as a whole. However, due to low energy efficiency, resulting primarily from moral and physical deterioration of equipment and networks, lack of funds for their modernization, both Ukraine's energy sector in general and municipal energy sectors in particular are unable to work efficiently and reliably, so they produce much more GHG emissions than in European countries hence they have a significant potential for decarbonization.

Guidelines for solving the problem. The most globally widespread program to support local decarburization is the Covenant of Mayors [6]. Due to its unique characteristics and capabilities, it is positioned as an exceptional model of broad movement and multilevel management, uniting local, regional and national forces with the support of national governments. It was launched in the EU in 2008 and is currently signed by over 7,000 local authorities far beyond Europe. Under the provisions of the Covenant of Mayors, local and regional authorities have made voluntary commitments to reduce CO2 emissions by at least 20% by 2020 and 40% by 2030 via implementing energy efficiency and energy saving measures and expanding the use of renewable energy sources (RES) thus contributing to low-carbon economic development or, in other words, **energy transition** and higher quality of life. One of the main tools for planning decarburization measures under the Covenant of Mayors is the Sustainable Development Action Plan (SEAP) until 2020 [7] and the Sustainable Development and Climate Action Plan (SECAP) until 2030 [8]. As of early 2021, 284 local governments in Ukraine joined the Covenant of Mayors, including major cities such as Kyiv, Kharkiv, Dnipro, Zaporizhia, Lviv and Zhytomyr.

Many cities do not limit themselves to committing to the Covenant of Mayors and set higher goals for decarburization, low-carbon energy use and energy efficiency. For example, the legislations of seven US states (including New York, Ohio, California, New Jersey and Rhode Island) provide municipalities with the opportunity to choose energy service providers. This opportunity is widely used, for example, in California, which is the most progressive state in RES terms, 42 cities and Santa Cruz county receive all their electricity from the suppliers of "clean" energy [9]. There are five more such cities in other states where lesser powers to choose suppliers are compensated by their own RES capacities. The number of municipalities and districts that declared their desire to achieve full electricity supply from RES in March 2021 were 173 and 6, respectively. The Ukrainian cities of Zhytomyr, Lviv, Kamianets-Podilskyi, Chortkiv, Trostyanets, as well as the Baranivka United Territorial Community (UTC) and the Association of Small Towns of Ukraine (ASTU) have also declared the goal to switch to renewable energy by 2050 [10].

Large international investment banks are redirecting their investments from fossil fuel into green projects. For example, the European Bank for Reconstruction and Development (EBRD) plans to invest 1 trillion euros by 2030 in projects to combat climate change and maintain environmental sustainability, including the construction of RES facilities [11]. The EBRD is the largest foreign investor in Ukraine since independence, so the demonstration of local governments' intentions to work towards low-carbon development will provide an opportunity to attract significant investment in the development of their communities.

The goal and objectives of the study. The urgency of the problem of decarbonization and new guidelines and conditions for the development of UTCs necessitate the search in Ukraine for new ways to increase the efficiency of decision-making in the development of local energy supply systems. Given the complexity of energy systems, and the large number of technical, socio-economic, spatial and environmental factors, as well as the long-term nature of the problem, it would be too difficult to complete the assigned tasks without the use of modern information tools and mathematical models.

Economico-mathematical models are the most common way to study the current condition and prospects for the development of energy functioning of the city or UTC. With their help it is possible to adequately display the UTC's entire energy system, representing energy processes as a detailed technological structure with certain economic and environmental parameters, as well as to make multivariate calculations of its development in different scenarios. Mathematical models can also focus on individual aspects of energy systems development (e.g., calculating the cost of electricity, estimating the number of new jobs and economic consequences, energy saving potential, energy demand, required investment, etc.) [12, 13].

In European countries and the United States, quasi-dynamic optimization models of energy systems used for strategic planning and forecasting of energy supply at the local, national, regional, interregional and global levels have gained great popularity. The most widespread of these are dynamic optimization models of type TIMES (The Integrated MARKAL-EFOM System), used in more than 70 countries by more than 80 research centers [14]. The objective function in such models is to minimize the power system's consolidated costs with a number of restrictions.

A model of the energy system of Ukraine has been developed at the Sector of Energy Development Projections of the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine [15]. More detail about the structure and methodology of TIMES-Ukraine model is given in [16, 17].

Based on the national model TIMES-Ukraine, a municipal model of the energy system of Zhytomyr UTC was developed and tested, which was supported by the non-governmental organization "350.org" and Zhytomyr City Council [18]. The purpose of this study is to model and assess the ways of energy transition in Zhytomyr UTC until 2050 in various scenarios. The main objectives of the study were to analyze the current state of energy sector in Zhytomyr UTC, data collection, direct development of the TIMES model and a number of scenarios and post-optimization analysis based on foreign and Ukrainian experience.

Analysis of research and publications. The relevance of modeling the energy transition in foreign municipalities is demonstrated by a number of studies conducted in recent years [19-22], in particular, using TIMES-models [23, 24]. For example, the study [22] is based on the toolkit EnergyPLAN, which simulates the entire energy system to develop a strategy for the transition to renewable energy in the city of Aalborg (with a population of 211 thousand people). The toolkit allows choosing the mode of economic or technical modeling, and the latter was chosen for this study, which means a priority to those energy generation technologies that have the highest conversion efficiency and use local energy resources, while their economic efficiency is sidelined.

The authors of [23] use the TIMES model to minimize the net present costs in predicting the low-carbon development of space heating and hot water systems in Sweden of three different types: individual, local and centralized. At the same time, the demand for these services is set exogenously, and so are the relationships between the simulated system and the sector of electricity, transport and housing. The article [24] on the example of the city of Oslo (population over 650 thousand people) shows how cities can make a sustainable energy transition. The study is based on the use of the TIMES optimization model for finding optimal ways to reduce GHG emissions and reduce energy consumption. As electricity in Norway is mainly generated by hydropower, the decarburization potential of the electricity sector is rather small, so the study is more focused on the transport sector, where decarbonization potential is more significant and can be realized via the widespread use of so-called e-fuels, including hydrogen, as well as via the development of cycling. The study also identifies cost-effective decarburization measures aimed at total phase-out of fossil fuels by 2050.

In Ukraine, economic and mathematical modeling of national energy systems is only becoming popular, but still is not very widespread, and the number of studies on modeling energy transition at the municipal or regional level is extremely low. However, the accession of Ukrainian cities to the Covenant of Mayors [6] has created certain demand for such research from local governments thus provoking a number of works on forecasting fuel and energy balances and GHG emission dynamics within the preparation of municipal action plans on sustainable energy development and climate by 2030

For example, the Municipal Energy Plan of the city of Zaporizhia for 2014-2030 [25] takes into account the key provisions of EU Directives and commitments under the Covenant of Mayors and provides for the creation of economical and green energy sector in this city via complete renovation of public and residential buildings, energy supply systems, etc. To develop this plan, its authors compiled the city’s fuel and energy balance as the sum of merchandise balances of major utilities, but excluding industry and road transport; calculations of forecasted consumption of fuel and energy resources and their cost are made based on the forecast model the city’s development. That is, the authors did not develop full-fledged model of energy flows in the city of Zaporizhia. For more detail about sustainable energy action plans of some cities until 2030 see http://seap.ecosys.com.ua/.

Among the scientific publications there are practically no comprehensive model based studies of the transition of all energy flows in Ukrainian cities or territorial communities. Instead, very common are publications providing the results of modeling transport and passenger flows [26, 27], the impact of transport flows on the city environment [28], forecasting the amount of municipal solid waste [29], and modeling individual aspects of sustainable urban development [30]. The problems of modeling the processes of regional energy sector development are studied separately [31].

Research methodology. In this study, the Zhytomyr United Territorial Community means the city of Zhytomyr and the village of Veresy (as of early 2020). In the same constant composition, this UTC is the object of study throughout the modeling horizon.

The initial task was to define the current state of the energy sector in Zhytomyr UTC, for which a relevant statistical base was developed [32-35]. The base year for modeling was 2017, because it was the last year with the most complete information. During the data processing, numerous discrepancies were revealed in the statistical reporting on the consumption of individual energy resources, as well as insufficient detail of statistical information, lack of data on consumption of motor fuel by the population and other consumers. Finally, after conducting the necessary calculations, based on the above mentioned statistical data sources, the authors compiled the energy balance of the city of Zhytomyr (Table 1), which was used in the subsequent stages of the study.

Besides, for the first time a scheme of the energy system of Zhytomyr UTC was developed (Fig. 1), which reflects the technological chain of production, transformation and consumption of energy resources. In Fig. 1, dotted line indicates promising technologies that may appear in the process of modeling the development of the energy sector in Zhytomyr UTC.

The TIMES-Zhytomyr model is an optimization model of energy flows of Zhytomyr UTC. The energy system in the model is represented by a single region and consists of six sectors (Fig. 1): the energy supply sector (production, imports, and production of secondary energy resources); production of electricity and heat; industry; transport; household sector (population); and trade and services. That is, the model's structure corresponds to the structure of Ukraine's energy balance [36] according to the IEA form, except for the absence of the agricultural sector. To date, the TIMES-Zhytomyr model takes into account 647 technologies, the model's database is updated until the 2017 data and calibrated for the same year.

The future development of energy sector in a city or country highly depends on socio-economic development. According to the projected industrial output, population, housing development, energy prices and other macroeconomic and demographic indicators, the need for energy resources will be determined, while the technological structure and structure of energy used will depend on economic, energy, environmental and other policies.

Table 1

Zhytomyr Energy Balance for 2017

SUPPLY AND CONSUMPTION	Coal and peat, *t*	Petroleum products, *t*	Natural gas, *ths.* m^3	Biofuel and waste, m^3	Electricity, *MWh*	Heat, *Gcal*
Primary production	-	-	-	-	-	-
Supply from outside of UTC	2943	31477	208450	24310	674270	-
Change in stock	-	-	-	-	-	-
Total energy supply	**2943**	**31477**	**208450**	**24310**	**674270**	**0**
Statistical differences	-	-	-	-	-	-
Power plants					361	-
Heat generation	-349		-71643			738900
Zhytomyrteplokomunenergo (*ZhHMEC*)		-	-68415	-	-595	
Other transformation facilities	-349	-8	-3227	2953	-	-
Distribution losses	-	-	-27950	-	-87525	-49307
Final consumption	**2594**	**31470**	**108857**	**21357**	**586745**	**689593**
Transport		30800	2269	-	14900	-
Automobile	-	30800	2269	-	-	-
Municipal electric	-	-	-	-	14900	-
Others	2594	176	106588	21357	586745	689593
Households (Residential)	-	-	78000	-	160746	517195
Industry	2594		22388	19004	242405	-
Commercial & public services	-	176	6200	2353	168695	172398
Non-energy use		**493**	-	-	-	-

Source: developed by authors.

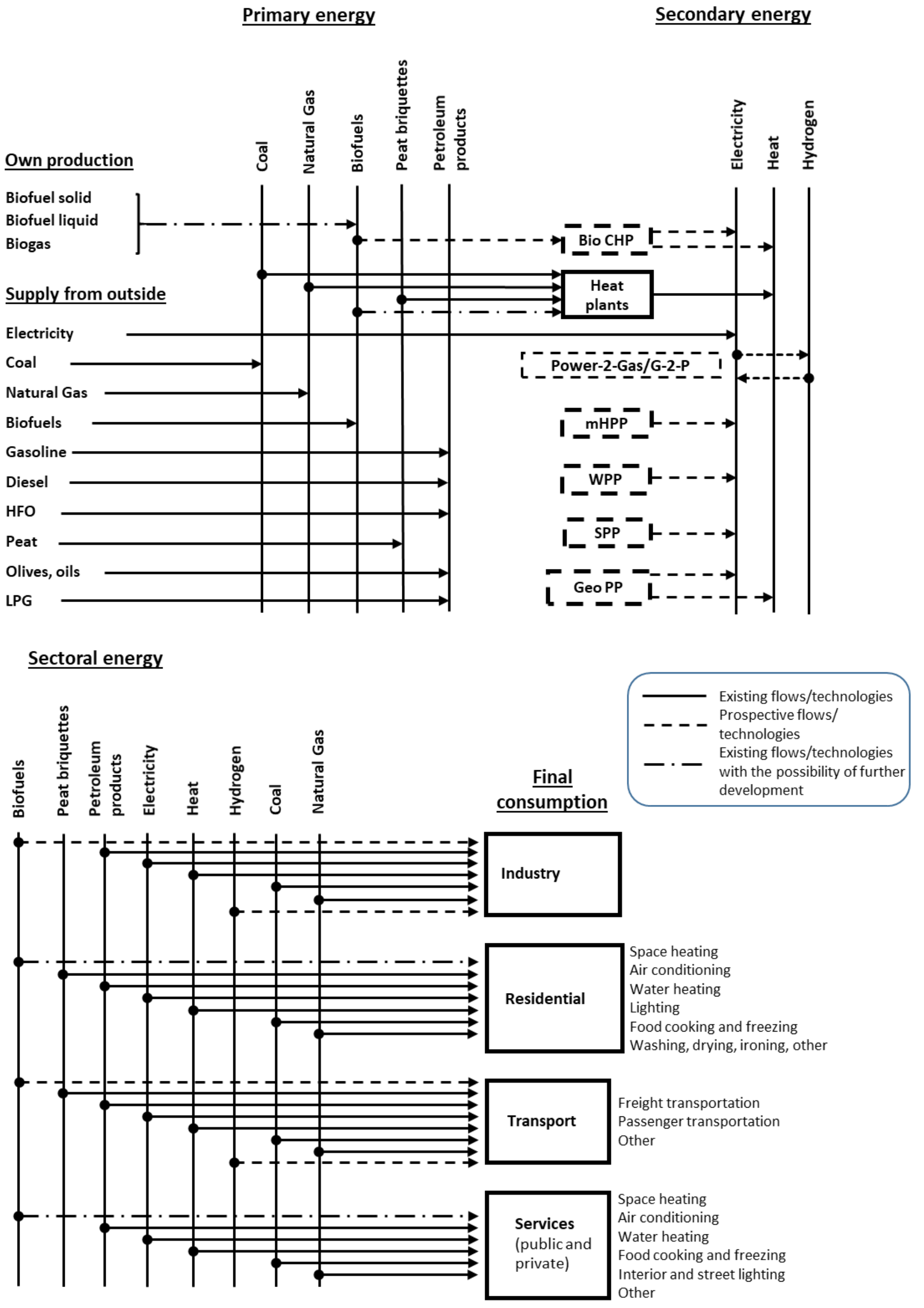

Fig. 1. Scheme of the energy system of Zhytomyr UTC in the TIMES-Zhytomyr model

Source: developed by the authors.

Due to the lack of long-term (until 2050) macroeconomic and demographic indicators of Zhytomyr UTC, which would determine the dynamics of the main drivers (control parameters of demand for energy services), the study used the relevant national indicators provided in [15][3]. Table 2 presents the forecast of Ukraine's GDP, developed in early 2019 and used to forecast the economic development of Zhytomyr UTC. The impact of the COVID-19 pandemic on the economy was not estimated, because the calculations were made before its emergence.

Table 2

Average annual growth rates of Ukraine's GDP in 2020-2050, *%*

Years	2020–2030	2031–2040	2041–2050
Ukraine’s GDP	3.8	3.5	3.2

Source: the authors’ calculations.

The demographic forecast is based on forecasted data of the MMM scenario, provided by the Institute of Demography and Social Research of the National Academy of Sciences of Ukraine [37], which is comparable to the corresponding forecasts of the UN Department of Social and Economic Affairs [38], which assume medium values of birth rate, life duration and net migration (Table 3).

Table 3

Forecasted population dynamics, *thousand people*

Number:	2017	2020	2025	2030	2035	2040	2045	2050
Current population of Zhytomyr	267.0	262.9	259.0	254.2	248.6	243.7	237.8	231.9
Population of Ukraine	44784	44396	43646	42766	41779	40816	39891	38915

Source: calculated by the authors.

This article develops ***four model scenarios***, the first of which is **the baseline scenario**, whose assumptions do not involve any fundamental change in the conditions of the Zhytomyr UTC power system, but it is necessary for comparison with alternative (target) scenarios. Alternative scenarios assume three different conditions for **the 100% energy transition to RES** by 2050, i.e. meeting energy needs (demand) in the final consumption sectors solely with RES, which should considerably strengthen the UTC’s energy self-sufficiency and climate resilience. At the same time, it should attain increased well-being, reliable energy supply and energy sufficiency; as well as economic, energy, environmental, food and other types of security. Table 4 summarizes the conditions and assumptions of all scenarios.

[3] The baseline macroeconomic scenario was prepared by the researchers of the Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine in 2016 within the project of the United States Agency for International Development (USAID) on "Municipal Energy Reform in Ukraine".

Table 4

Key scenario conditions and assumptions of achieving 100% RES in Zhytomyr UTC

BASELINE	A scenario does not imply ambitious energy and climate policy at the level of UTC.	UTCs energy is developing on the current principles. The level of energy efficiency implementation, the RES-measures corresponds to the present. New power generating capacities are not built. New technologies can't occupy a significant share in the market.
100% RES No 1	• 100% RES in heat generation and final energy consumption. • 50% of consumption is provided by local RES, other 50% – «green» electricity supply from other Ukrainian regions. • Possibility to conclude agreements on RES-electricity supply emerges since 2040.	The effective policy is pursued for the transition of final consumers and the transformation sector to RES. New RES plants are built. Maximal electrification, centralized heat supply preservation, transition to biofuels or energy from it. Annual power generation from RES in Zhytomyr and adjacent areas in 2050 is ***no less than 50% of UTC's consumption.*** Supply of electricity from RES in other regions of the country is at level ***not exceeding 50% of the UTC's needs***.
100% RES No 2	• 100% RES in heat generation and final energy consumption. • Power generation is of no less than total UTC's consumption. • Net-supply of electricity to/from other regions of country is zero. • Possibility to conclude agreements on RES-electricity supply emerges since 2040.	Conditions and assumptions of the scenario 100% RES No 2 practically coincide with a similar scenario RES No 1, except: • Power generation in the city and adjacent areas is ***no less than 100% of UTC's final consumption.*** • To ensure reliability and safety of UTC's power supply, electricity is also provided by countrywide RES generators. • Interchange with Integrated power system of Ukraine is performed to balance the UTC's grid.
100% RES No 3	• 100% RES in heat generation and final energy consumption. • Power generation is of no less than 30% of UTC's consumption.	In 2050 and further, Ukrainian power supply will consist of 70% of the RES according to the project of the Concept of the "green" energy transition*. Under such conditions for Zhytomyr UTC, consumption of electricity only from the IPS will result in achievement of 70% of low carbon electricity share in final power consumption. To achieve 100% of RES electricity share in final consumption, UTC has to possess such RES power generating capacities, which will produce ***no less of 30% of UTC's total power consumption.*** Thus, supplying this produced electricity to the IPS will compensate the "dirty" 30% share of original electricity mix from IPS. All other conditions and assumptions are similar to those in the scenarios 100% RES No 1 and No 2.

* Concept of the «green» energy transition of Ukraine till 2050. URL: https://menr.gov.ua/news/34424.html

Source: developed by authors.

The transition of the electricity sector to 100% use of RES (with the predominance of wind and solar generation) will require sufficient ***maneuvering capacities to maintain a balance between supply and demand for electricity***. Therefore, the development of energy sector should be accompanied by the development of technologies of accumulation (batteries), energy transfer (electrolytic "green" hydrogen) or balancing capacity (gas-piston power plants). Such measures require significant additional investments. For this reason, it was decided to develop three scenarios for RES development, so that each of which assumes reaching 100% RES in the final consumption of heat, electricity and other energy resources, but the electricity *output* in the UTC differs across the scenarios.

The TIMES-Zhytomyr model allows calculating for all scenarios the lowest total costs for energy system development, making corresponding estimates of the structure of energy supply and use by sectors and fuels, and GHG emissions by emitter category, defining the optimal technological structure of energy production and consumption etc.

In order to achieve 100% RES in the structure of energy consumption in Zhytomyr UTC, it is necessary to assess the RES potential, which should be sufficient to fully meet the energy needs of the UTC.

At the time of this study, there were no publicly available estimates of the ***potential of renewable energy*** of Zhytomyr UTC, so the authors made their own calculations of the potential of solar, wind and bioenergy, whose results are given in Table 5.

Table 5

Potential of renewable energy in Zhytomyr UTC, *MW*

Type of power plant / biofuel	Potential
Terrestrial industrial solar power plants (SPPs)	77.5 MW
Roof SPPs on building of private and communal enterprises and other service sector facilities	37.5 MW
Roof SPPs of individuals	303 MW
Wind power plants	100 MW
Biomass	1016.5 toe annually
Hydropower	5.5 million kWh annually

Source: the authors' calculations.

Estimation of the ***wind*** potential was performed using data from sources [39, 40], for ***bioenergy*** potential, data of the Regional Target Program were used [35]. The development of ***small hydropower sector*** is planned in accordance with environmental criteria, while the total potential is estimated at 5.5 million kWh per year. Cost characteristics of energy technologies are similar to the data of the national model TIMES-Ukraine [41]. An assumption is also made, similar to that used in the TIMES-Ukraine model, that for every 1 MW of SPP or WPP, no less than 100 kW of storage capacity (e.g. batteries) must be built.

The results of simulation. The implementation of ***energy efficiency and energy conservation*** measures (EE) plays an extremely important role in achieving 100% RES in the structure of final energy consumption. Investments in energy saving are economically feasible, because, according to the simulation results, thanks to them in 2050 the final energy consumption will only increase by 26% compared to 2017, while in the baseline scenario, in which EE measures are practically not implemented, the consumption will increase by 63% (Fig. 2).

Note that in all graphs of final energy consumption, the category "solar energy" only reflect the collectors for hot water heating and space heating. Electricity generated from rooftop SPPs is supplied to the national grid, so it is not a final energy resource and is included in the electricity generation sector.

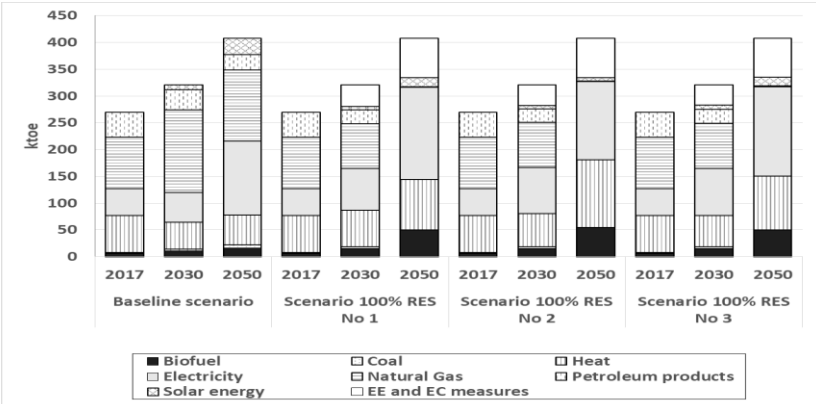

Fig. 2. *Final energy consumption across the scenarios,* thousand toe

Source: constructed by the authors

In the structure of final energy consumption (Fig. 3), the share of ***industry*** will increase. It is assumed that the energy needs of new types of industrial production can be met only via renewable sources. At the same time, new carbon-neutral technologies and electrification of industrial processes will make it possible to displace fossil fuels from final consumption in industry. Non-energy use of fossil energy resources as raw materials was not taken into account.

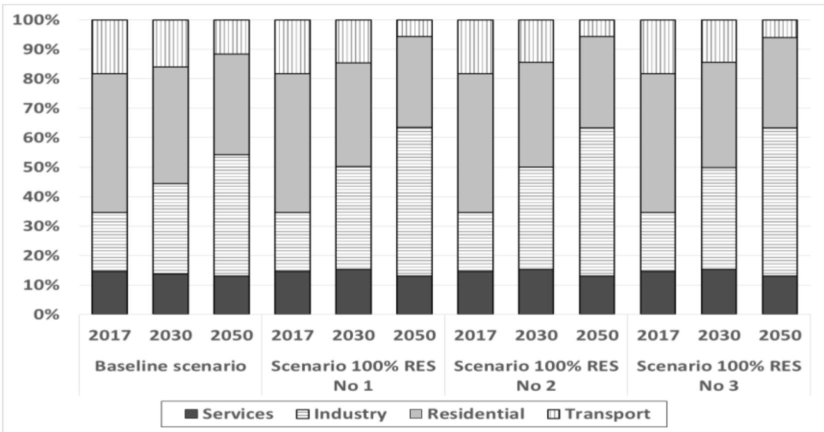

Fig. 3. Structure of final energy consumption, *thousand toe*

Source: constructed by the authors.

The population and the housing and communal sector have one of the greatest potentials for increasing EE. In 2050, energy efficiency measures can reduce energy consumption in all alternative scenarios by almost 428 million kWh. High prices for natural gas, further reduction in the cost of RES technologies, and electrification will contribute to gradual phasing-out of the use of natural gas. According to the scenarios of 100% RES No1 and No3 in 2050, the population will stop consuming natural gas thanks to full electrification of cooking, autonomous space heating and hot water supply. At the same time, 92% of ***space heating*** will be provided by highly efficient district heating, and the remaining 8% - by autonomous electric heating in private houses. In the scenario of 100% RES No 2 in 2050, district heating accounts for 89%, and instead of autonomous electric heating, 11% of the demand is covered by biomass boilers in private houses. ***Demand for hot water*** in the 100% RES scenarios varies. Thus, in the scenario of 100% RES No 1, 66% of hot water is more profitable to obtain from domestic electric boilers, 12% - from district hot water supply (DHW) and 22% - from roof solar collectors on private houses. In the scenario of 100% RES No 2, 90% is accounted by DHW, 7% - by roof solar collectors in private houses and only 3% - by electric boilers. In the scenario of 100% RES No 3, the distribution is as follows: 48% - electric boilers, 30% - DHW and 22% - solar energy. These simulation based calculations can be used in developing a municipal strategy for district heating.

Demand for air conditioning more than doubles by 2050, which is completely offset by thermal rehabilitation of buildings, due to which residential buildings will be heated much less during the day. This result is rather mixed, but it once again confirms the efficiency and relevance of implementing energy efficiency measures.

The model features the concept of more intensive use of ***public transport*** instead of private pransport within the city. Thus, while in the base year the passenger turnover for cars in the city is 387.2 million passenger-kilometers, and that of public transport (buses, taxis, trolleybuses and trams) - a total of 645 million passenger-km, which is 38% and 62%, respectively, then in 2050 it is projected to have 558 and 1451.7 million passenger-km, respectively, which will be 28% and 72%. Demand for freight transportation will also double by 2050. In all the three scenarios of 100% RES, a complete decarbonization takes place at the expense of displacement of cars with internal combustion engines (ICE) by electric cars, electric buses and biofuel trucks. In the process, total energy consumption in the transport sector will decrease by 40 and 35%, respectively, for the scenarios of 100% RES No 1–3. At the same time, hydrogen transport, according to current characteristics, still remains inferior to electric vehicles with batteries and to biofuel vehicles.

The potential for raising energy efficiency in the ***services sector*** (commercial and public) is somewhat lower than in the residential sector, but still allows by 2050 to reduce energy consumption compared to the baseline scenario by 17%, thanks to which it only increases by 10% compared to the base year. In the structure of consumption by resource type, the largest share will be accounted fot be centralized supply of heat produced from biomass, and electricity is in second place.

In general, 100% RES scenarios develop similarly with only minor differences. For the scenarios of 100% RES No 1 and No 2, on the condition that electricity supply starting with 2040 is provided by RES producers from other regions of the country, the share of clean energy in final consumption in 2050 reaches 99.71%. For scenario No 3, it will be 100% if the total share of electricity from RES in the UES of Ukraine is no less than 70%. A key role in the transition to RES will be played by electricity generated in centralized and distributed photovoltaic facilities, wind power plants, and solar energy for water heating and space heating. Biofuel CHP plants will operate in cogeneration mode and together with biofuel boilers will supply thermal energy for the vast majority of consumers. At the same time, due to the electrification of all sectors, the need to use natural gas and oil products virtually disappears.

In the baseline scenario, electricity generation directly in Zhytomyr UTC is practically absent, except for the existing small hydropower plant. Therefore, Figure 4 only shows the simulation results for the 100% RES scenarios.

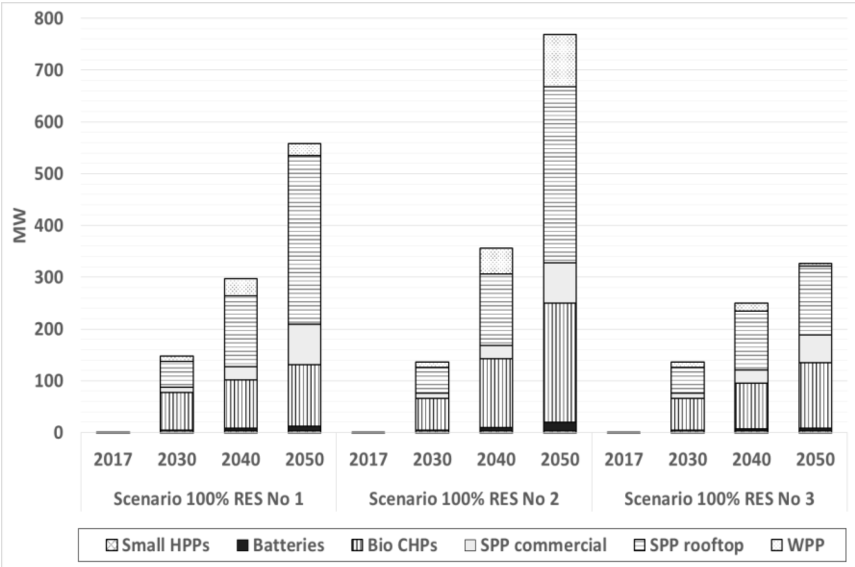

Fig. 4. Installed capacity of power generation facilities, *MW*

Source: constructed by the authors.

The scenario of 100% RES No 2 assumes 768 MW of installed capacity of RES facilities in 2050, with the domination of solar power plants, whose capacity is the maximum possible, given the above described assumptions. The scenario of 100% RES No 1 assumes the construction of new capacities of 558 MW, and the scenario 100% RES No 3 - 326 MW. In order to successfully implement any of the 100% RES scenarios, in the period from 2020 to 2022, it is necessary to introduce electricity generation facilities of at least 39.5 MW. The leader in terms of cost-effectiveness among photovoltaics is the industrial SPPs with tracking technology, which raises their efficiency and capacity factor, although they are more expensive.

Due to its insufficient research in Ukraine, this study does not consider the Vehicle-to-grid concept[4], which involves the use of electric vehicles connected to electricity grid as dispatched participants in the electricity market.

Total electricity output in the scenarios of 100% RES No 1, No 2 and No 3 (hereinafter less the share of supplies from outside the UTC) is 1075, 1845 and 795 million kWh, respectively. The structure of electricity generation (Fig. 5) slightly

[4] Vehicle-to-Grid (V2G) explained: What it is and how it works. URL: https://www.ovoenergy.com/guides/electric-cars/vehicle-to-grid-technology.html

varies across to the scenarios, but the main producers of electricity in all scenarios are biomass CHP plants.

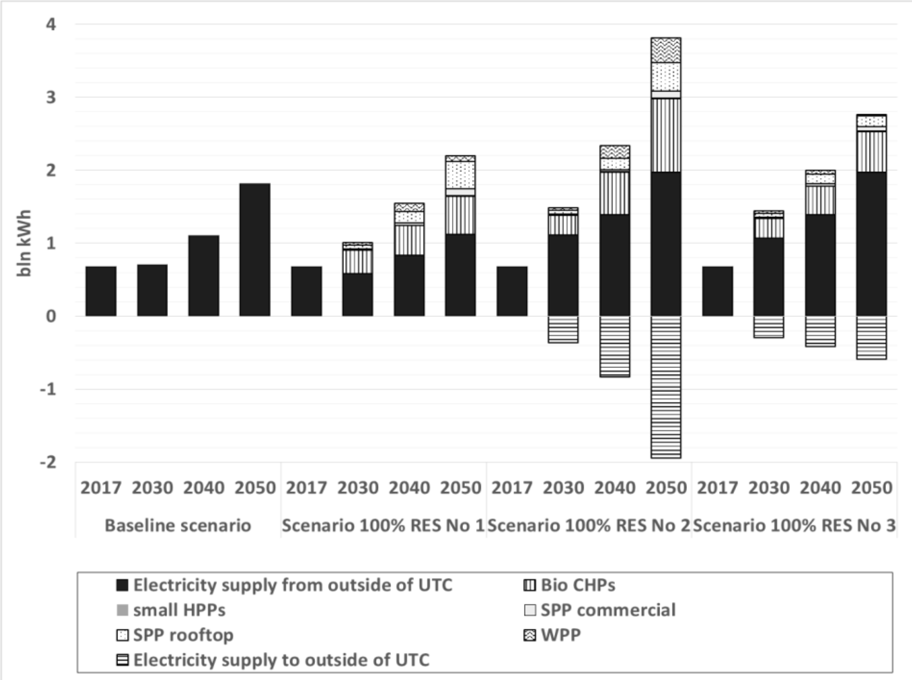

Fig. 5. Electricity output (supply), *million kWh*

Source: constructed by the authors.

In the sector of ***district heat supply***, a significant increase is observed in heat generation at the expense of gradual abandonment of fossil fuels by the industry and the transition to consumption of thermal energy generated by biofuel CHP plants (67% of total in the 100% RES scenarios No 1 and No 3, and 97% - in the scenario of 100% RES No 3) at the district and local heat-only plants (Fig. 6). At the same time, with the increase in heat generation, the total installed capacity of heat generating equipment is reduced almost four-fold in the scenarios of 100% RES No 1 and No 3 and by more than a half in the scenario 100% RES No 2. This is due to thermal modernization measures and because the existing heat-only plants still having a sufficiently high efficiency (according to municipal company "Zhytomyrteplokomunenergo" *(Zhytomyr Heat Municipal Energy Company, ZhHMEC)*), have not been used at full capacity for a long time. In 2017, their capacity factor averaged 20%, which is an extremely low figure that significantly affects profitability. Therefore, the heat-only plants that are not used at full capacity or have exhausted their resources should be closed. According to the scenarios of 100% RES No 1 and No 3, by 2050 it will be enough to have about 200 MW of heat generating capacities with high efficiency and capacity factor. The scenario of 100% RES No 2 requires larger biofuel CHE plants.

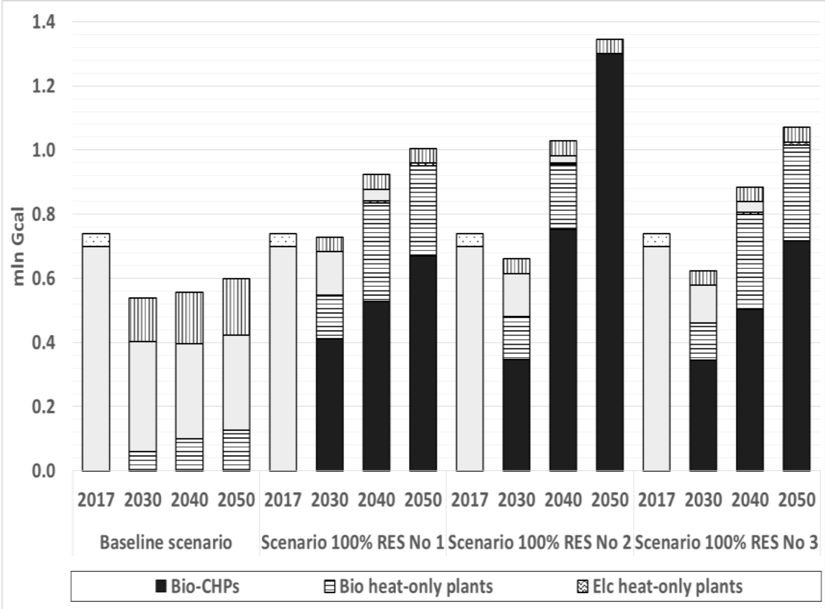

Fig. 6. Output (supply) of thermal energy, *thousand Gcal*

Source: constructed by the authors.

This study does not consider the implementation of measures to reduce heat losses in the networks, which, according to ZhHMEC, were 6.7% in 2017. Heat storage technologies are not considered either. Reducing losses and using innovative technologies could reduce the cost of energy transition to 100% RES for Zhytomyr UTC.

Investing in new construction and maintenance of energy facilities would help to create new jobs, and according to some international estimates, the installation of each megawatt of rooftop SPPs can employ up to 24 workers, i.e., implementing alternative scenarios can create from 3.6 to 9.2 thousand new jobs. Industrial SPPs and WPPs could additionally provide about 400 more jobs[5]. Bioenergy also has a considerable potential for job creation in the supply of raw materials, design and construction of power plants and in their maintenance - a total of about 3.5 full working months per 1 MW of newly installed thermal capacity, i.e. another almost 800 jobs[6].

Carbon dioxide emissions in all the scenarios of 100% RES in 2050 compared to 2017 are reduced by 308 times: from 555.1 thousand tons of CO_2 up to 1.8 thousand tons of CO_2. They may remain in small quantities in transport and industry. Total *GHG emissions* (not only CO_2) in 2050 may be reduced by 94% compared to the baseline scenario: from 525 thousand tons of CO_2-eq. to 31.4-46 thousand tons of CO_2-eq. (Fig. 7).

[5] Powering jobs growth with green energy. URL: https://www.nrdc.org/sites/default/files/jobs-growth-green-energy.pdf

[6] UK jobs in the bioenergy sectors by 2020.URL: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48341/5131-uk-jobs-in-the-bioenergy-sectors-by-2020.pdf

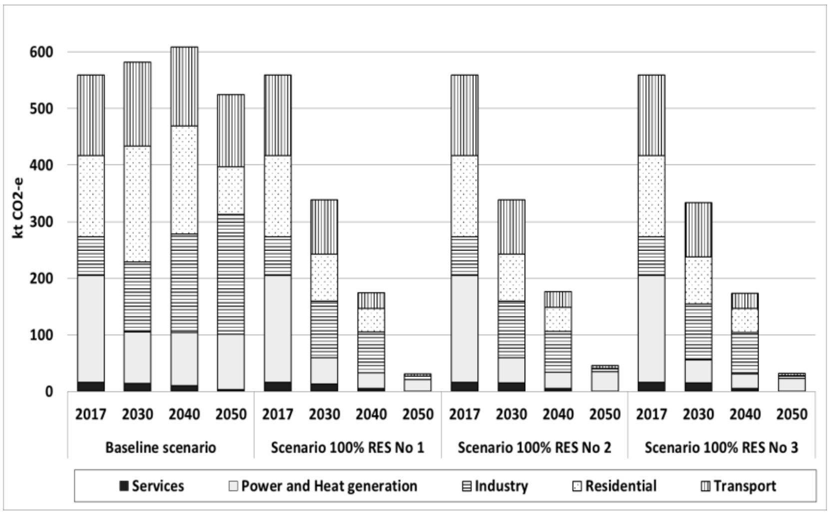

Fig. 7. Greenhouse gas emissions by sector, *thousand tons of CO2-eq*
Source: constructed by the authors.

Note that the volume of emission of such ***greenhouse gases*** as CH_4 and N_2O increases from 4.3 thousand tons in 2017 to 30-44 thousand tons in 2050 due to a significant increase in biomass combustion and the use of biofuel. Although the use of biofuels in the energy sector is conventionally considered carbon neutral, the combustion of biomass causes air pollution with fine and ultrafine particles (PM_{10}, $PM_{2.5}$ and less than 100 nm), so *filtration units must be installed on the chimneys of combustion bio-plants*. Otherwise, having almost completely stopped influencing the climatic situation, we can spoil the environmental component throughout the city. In addition, due to the harmful effects of dispersed particles on the human body there is a risk of increasing the level of diseases of the respiratory tract and circulatory system [42]. In the TIMES-Zhytomyr model, the capital costs for new biomass plants include the costs for filter units that meet the highest standards.

In the structure of ***total annual costs for the operation of the energy system*** (Fig. 8), which include investments in energy technologies (modernization, and purchase of new ones), operating costs, costs of the purchase, transportation and supply of fuel, the bulk will be the investments in energy end-use technologies. (household equipment, vehicles, lighting devices, etc.), because the latter have a much shorter service life compared to, for example, the technologies of electricity and heat generation, so their number is incomparably greater. However, with the exception of municipal vehicles, and appliances for urban facilities and the costs of financing energy efficiency measures, investment in end-use technologies are to be funded by city dwellers. In the long run, the existing generating capacity must be replaced by new ones, so capital investments will not be avoided, although in the baseline scenario, only heat-only plants will be built of the new generation. As a result, capital expenditures on generating capacity in the baseline scenario are much lower than in the alternative scenarios, but fuel costs in 2050 will be twice as high.

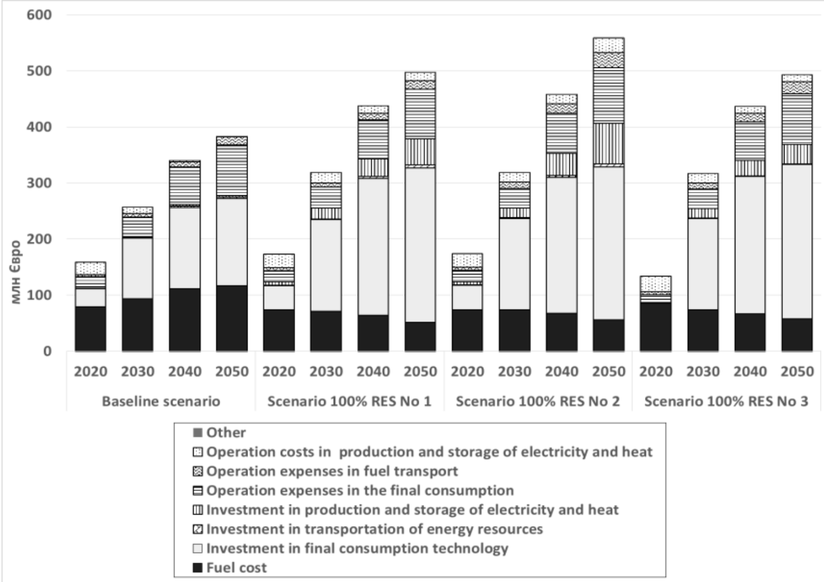

Fig. 8. Annual costs of the operation of the energy system, *million euros*

Source: constructed by the authors.

Figure 9 shows the difference between the costs in the baseline scenario and those in the alternative scenarios. The negative section of the cost axis shows the savings made compared to the baseline scenario.

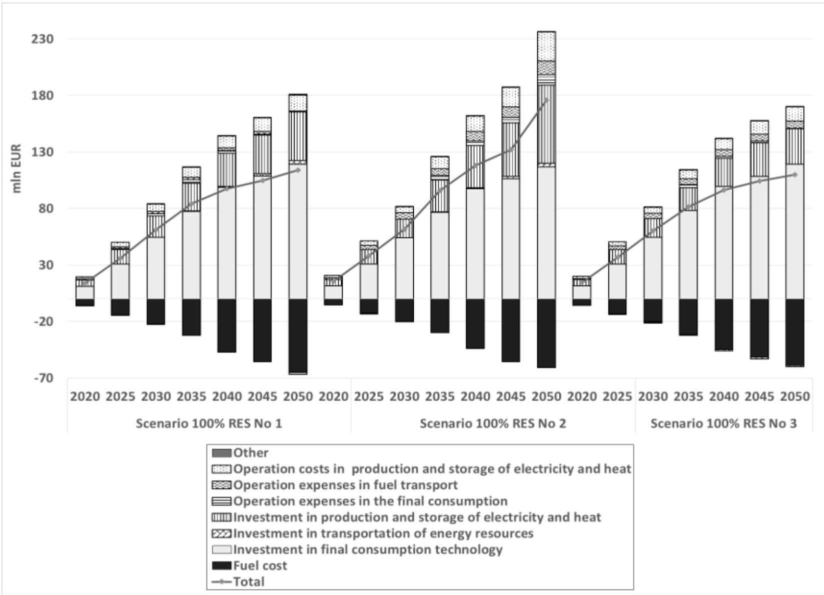

Fig. 9. The difference between the annual costs of the operation of the energy system between the RES scenarios and the baseline scenario, *million euros*

Source: constructed by the authors.

Total cumulative costs (2.152 billion euros under the baseline scenario and 2.655 billion, € 2.790 billion and € 2.656 billion euros under the 100% RES scenarios No 1, No 2 and No 3 respectively) for the development of a carbon neutral energy system for the period from 2020 to 2050 in the scenarios of 100% RES No 1 and No 3 are *by 23%*, and in the scenario 100% RES No 2 – *by 30%* higher than the costs in the baseline scenario. At the same time, the difference in ***capital investments*** (Fig. 10) for the whole period is 45–47%, being the lowest value scenario that of 100% RES No 3.

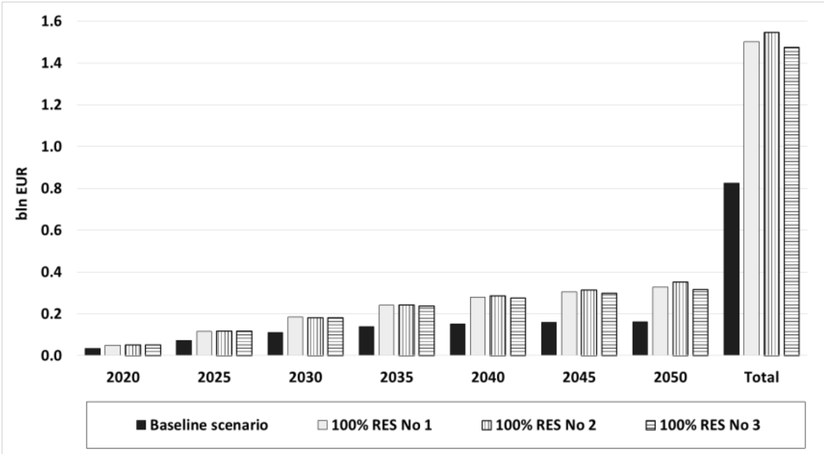

Fig. 10. Capital investments by 5-year periods, *million euros*

Source: constructed by the authors.

Conclusions

In the absence of an effective policy to encourage energy efficiency measures and intensify the use of RES (baseline scenario) in Zhytomyr UTC final energy consumption in 2050 will increase by 63% compared to 2017. At the same time, under the same socio-economic conditions, *the implementation of any of the ambitious scenarios of transition to 100% RES would allow to effectively and economically limit the above mentioned increase in energy needs to only 26%.* At the same time, there will be a cardinal reduction in GHG emissions, which in 2050 may be kept at no more than 6% of the level of 2017, or 0.14-0.20 tons per capita.

Recommendations for achieving the above mentioned targets are as follows:

– large-scale implementation of energy efficiency and energy saving measures;

– introduction of new carbon-neutral technologies both by energy production and energy consumption, as well as intensified electrification of industrial production and transport;

– stopping the degradation of district heating and increasing its share in meeting the heating needs of the population living in apartment buildings, as well as the budget funded sector up to 90%;

– electrification and/or transition to the use of biofuels for individual space heating;

– electrification of individual hot water supply, by maximizing the use of electricity from rooftop solar panels together with the development of solar energy powered rooftop collectors in private houses, which would cover the demand by 20-25%;

– implementation of the concept of more intensive use of clean public transport instead of individual transport within the city with a complete displacement of vehicles powered by internal combustion engines by electric cars, electric buses and biofuel trucks (hydrogen transport is another possible solution, but in this study it is not sufficiently investigated).

A key role in the transition to RES will be played by electricity generated by centralized and distributed photovoltaic and wind power facilities, as well as solar energy for water heating and space heating. Biofuel CHP plants will operate in cogeneration mode and together with biofuel heat-only plants will supply the vast majority of consumers with thermal energy. At the same time, due to the electrification of all sectors, the need to use natural gas and petroleum products will virtually disappear.

In 2050, the need of new electricity generating RES capacities is estimated at 326-768 MW, and that of heat generators with high capacity factor and efficiency - at 200-350 MW, which could potentially create up to 10.5 thousand new jobs and the funds involved in their construction would contribute to social development.

Cumulative costs for the operation of the energy system of Zhytomyr UTC in 2020-2050 in the baseline scenario are by 23-30% lower than in alternative scenarios, in particular due to the lower (by 45-47%) need for capital investment. However, fuel costs in the baseline scenario in 2050 could be twice as high as in the alternative scenarios.

The results of the study once again confirm that saving energy resources (in terms of energy efficiency and energy conservation) is the cheapest way to meet the energy needs of the population and the economy as a whole, while the related investments are more economically justified than those needed to produce additional energy resources to meet the same demands.

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МЕТОДИ ТА МОДЕЛІ ОЦІНКИ ЕНЕРГЕТИЧНОГО ПЕРЕХОДУ НА ПРИКЛАДІ ЖИТОМИРСЬКОЇ ОБ'ЄДНАНОЇ ТЕРИТОРІАЛЬНОЇ ГРОМАДИ

Представлено результати сценарного моделювання та оцінка здійснення енергетичного переходу до 2050 р. у Житомирській об'єднаній територіальній громаді (ОТГ), що передбачає зміну сьогоднішньої, заснованої на викопних вуглецеємних енергоресурсах, моделі функціонування енергетики ОТГ на найсучаснішу – таку, що на 100% використовує відновлювані джерела енергії (ВДЕ), задовольняючи при цьому усі енергетичні потреби і сприяє сталому розвитку ОТГ згідно з відповідними цілями ООН. Для цього вперше розроблено оптимізаційну економіко-математичну модель TIMES-Житомир (аналогів в Україні немає), що базується на національній моделі TIMES-Україна і включає 647 енергетичних технологій – уже наявних або таких, які найближчими роками можуть бути представлені на вітчизняному ринку.

Для розробки моделі TIMES-Житомир було опрацьовано малодоступну місцеву енергетичну статистику, за результатами якої за формою Міжнародного енергетичного агентства вперше сформовано енергетичний баланс для великого міста України – Житомира, а також побудовано базову енерго-технологічну систему Житомирської ОТГ.

Із використанням моделі TIMES-Житомир уперше розроблено та змодельовано чотири сценарії розвитку енергетичної системи Житомирської ОТГ, що охоплює усі економічні сектори, у т.ч. домогосподарства. Перший сценарій – базовий – показує можливу динаміку розвитку енергетичної системи без проведення цілеспрямованої політики з енергоефективності, розвитку ВДЕ тощо. Три інших сценарії націлені на дослідження можливостей переходу ОТГ до 2050

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року на 100% відновлюваної енергетики та використання екологічно-чистих технологій.

Результати моделювання підтвердили, що наявний ресурс відновлюваної енергетики та технологічний потенціал дозволяє Житомирській ОТГ здійснити енергетичний перехід до 2050 р. в економічно доцільний та соціально прийнятний спосіб, суттєво скоротивши енергоємність і вуглецеємність місцевої економіки, практично усунувши викиди парникових газів (ПГ), підвищивши добробут громадян та створивши щонайменше 10 тис. нових робочих місць. Це також суттєво сприятиме Житомирській ОТГ досягнути щонайменше десяти із сімнадцяти Цілей сталого розвитку ООН.

Представлені результати дослідження завдяки своїй новизні та актуальності поставленого завдання можуть бути використані науковцями в рамках їхніх досліджень, органами влади та експертами при розробленні стратегій, планів, програм економічного, енергетичного, транспортного, кліматичного, екологічного та іншого характеру не тільки на локальному, а й на регіональному та національному рівнях. Також їх можна вважати одним із перших кроків у підготовці комплексної стратегії розвитку Житомирської ОТГ, спрямованої на досягнення кліматичної нейтральності відповідно до сучасних цілей Європейського Союзу.

Ключові слова: *зміна клімату, сталий розвиток, енергетичний перехід, відновлювана енергетика, моделювання та прогнозування, модель TIMES*