Final Report

Long-term Energy Modelling and Forecasting in Ukraine:

Scenarios for the Action Plan of Energy Strategy of Ukraine until 2035

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Executive summary

This report presents the key input data, methodology and results of the project "Long-Term Energy Modelling and Forecasting in Ukraine: Scenarios for the Action Plan of Energy Strategy of Ukraine till 2035", as part of the Development Engagement: “Sustainable energy enabling environment”, currently being conducted under the Energy Partnership Programme between Ukraine and Denmark. The project was carried out from October 2018 to April 2019 with the main objective to support the implementation of the New Energy Strategy of Ukraine till 2035 (ESU2035) through the application of energy modelling tools and scenario analysis practices. This objective has been achieved through updating and improving TIMES-Ukraine energy system model for elaborating future energy scenarios, and through selection and quantification of the relevant policies and measures to achieve the goals of the Energy Strategy of Ukraine till 2035 [1]. The results of this project can support the development of the Action Plan for the implementation of ESU2035. Furthermore, the modelling results of this project can contribute to the development of the National Energy Efficiency Action Plan after 2020 (NEEAP), the National Action Plan for Renewable Energy after 2020 (NREAP), and the National Energy and Climate Change Plan for the period 2021-2030 (NECP).

During the project, conditions and assumptions for a number of scenarios were formulated together with the main stakeholders - the Ministry of Energy and Coal Industry, the Danish Energy Agency and the Ukrainian-Danish Energy Centre.

The Reference scenario considers the optimal development of the energy system of Ukraine under the goals of ESU2035. It is based on the targets specified in the strategy, including:

- Energy intensity of GDP
- Renewable share of Total Primary Energy Supply (TPES)
- Minimum renewable share of electricity
- Addition of 1GW nuclear power capacity in 2025

Multiple sensitivity scenarios assess either possible deviations from the targets or the influence of alternative sets of technologies. The *Low Renewable Growth* scenario assumes future low development of renewable energy as in UkrEnergo’s development pathways [2] for hydro, wind and solar power generation. *No New Nuclear in 2025* analyses the effects of a delay until at least 2030 of the new nuclear power generation capacity. In the scenario *New Balancing Techs*, new technologies that can provide balancing under increasing share of renewable generation are considered; while the *Green-Coal Paradox* scenario focuses on the effects of refurbishment of the existing coal-based power units to extend their lifetime and use these for balancing. *Optimise Balancing* provides insights into the effects a forecasting system (and a reduced balancing requirement) could have.

Additional scenarios put the goals of ESU2035 into a wider context (both national and international). *National Strategies* adds other national targets and measures from strategic documents (i.e. National transport strategy of Ukraine till 2030; National Strategy for Waste

Management in Ukraine till 2030; Concept of realisation of the state policy of heat supply; and Ukraine 2050 Low Emission Development Strategy) in addition to those described in ESU2035. *Low Carbon Society* further expands the previous scenario by considering a path to an 80% GHG emission reduction for Ukraine in 2050. This scenario is closer to the climate mitigation policy adopted in the EU. Finally, *Frozen Policy* considers only those policies, measures and targets that were adopted until 2015 (i.e. no policies, measures and targets from ESU2035 and other strategic documents) and is provided for comparison purposes.

To ensure validity of the results, the TIMES-Ukraine model was calibrated with the latest statistical data, and its database was updated in accordance with current macroeconomic and demographic forecasts, projections of global prices for energy commodities, updated data on resource potentials, and technical and economic characteristics of future energy technologies.

The results of the analysis for the *Frozen Policy* scenario show that in the absence of energy policy measures aimed at achieving a transition of the energy system (i.e. without stimulating the implementation of the potential of energy efficiency and renewable energy (RE), and the introduction of environmental restrictions), primary energy supply and final energy consumption will grow towards 2050. However, it is unlikely they will exceed 2012 levels. Under such conditions, the structure of the energy system will depend, first of all, on the projected fuel prices and the changes in the value of energy technologies. At the same time, coal will remain the dominant resource both in the fuel supply of power plants, and, in general, to meet the energy needs of the economy.

The *Reference* scenario, which reflects the conditions and main targets of the Energy Strategy of Ukraine until 2035, maintains the energy consumption at the level of 2015, while simultaneously increasing the use of RE by reducing the consumption of coal and natural gas. However, ESU2035 holds some uncertainty about the development of the energy sector after 2035. In particular, the development of nuclear energy (i.e. decommissioning, lifetime extension or commissioning of new units) after 2035 can lead to a drastic change in electricity generation and the dynamics of GHG emissions.

The results of the *No New Nuclear 2025* scenario show that once the objectives of ESU2035 are achieved (in particular a significant reduction of the energy intensity of the economy and a significant increase in the use of RE) the existing nuclear units will not be operating at full load, resulting in the postponement of the construction of the Unit #3 at the Khmelnytska plant from 2025 to not earlier than 2030-2035. At the same time, the generation from other power facilities will not differ from the *Reference* scenario.

In a scenario of moderate growth of renewable electricity production (*Low Renewable Growth*), as proposed in the Report on the conformity assessment (adequacy) of the generating capacity of the State Enterprise "NEC" Ukrenergo for 2018 [3], the total share of RE in the power generation will increase only to 41% in 2050 (compared to 63% in the *Reference* scenario), but in 2035 it would be about 31%, which is more than ESU2035 suggests. Replacing the generation of electricity from renewables with more expensive thermal generation after 2035 will affect the total cost of electricity in the system, which in the end can reduce the consumption of electricity by 5-7%, compared to the *Reference* scenario.

Currently, the balancing of power stations is mainly performed through the polluting coal generation, which causes the emergence of the so-called "Green-coal paradox". According to the model calculations (scenario *New Balancing Techs*), the use of modern balancing capacities and manoeuvring technologies will reduce capital investment by 13 billion euros in the period 2020-2050, while achieving the stated renewable energy target. In addition, the use of advanced precision forecasting systems (scenario *Optimise Balancing*) will further reduce investment needs by an additional 11.5 billion €, while increasing production of electricity from renewables.

The inclusion of targets from existing sectoral program documents to ESU2035 will not radically affect the future development of the energy system - the deviation of the basic aggregated energy balance indicators from their values in the *Reference* scenario is observed at 2-5%. However, particularly in the transport and residential sectors, energy consumption patterns differ significantly from those in the *Reference* scenario. In addition, there may be a certain redistribution of investment resources and individual fuel types across sectors. This indicates the potential for improvement of the existing practices by means of harmonisation of sectoral policies, as well as the need to update the indicators of ESU2035.

The analyses have also shown that achieving ambitious targets for decarbonising the Ukrainian economy (*Low Carbon Society* scenario) will in fact only require the continuation of the policies and measures initiated by the ESU2035, although this will require stepping up the investments. The relaxation or complete abandonment of the implementation of the decarbonization policy can quickly offset the achievements, in particular the reduction of energy intensity, GHG and pollutant emissions.

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1. Introduction

Background

In August 2017 the Cabinet of Ministers approved the new Energy Strategy of Ukraine till 2035 “Security, energy efficiency and competitiveness” (ESU2035) [4]. The goal of ESU2035 is to address the needs of the society and economy of Ukraine in supplying the fuel and energy in a technically reliable, safe, economically efficient and environmentally friendly way in order to guarantee the improvement of social well-being.

ESU2035 includes ambitious targets for Ukraine till 2035:

- More than halve energy intensity of GDP by 2035.
- Increase the share of renewable energy in the Total Primary Energy Supply (TPES) up to 12% in the short- and mid-term period till 2025, to 17% till 2030 and not less than to 25% till 2035 (including all hydropower capacities and thermal energy).
- Preserve the current share (ca. 50%) of electricity generation from nuclear power plants (NPP) until 2035.
- Achieve compliance of large thermal power generation with the Industrial Emissions Directive (2010/75/EU) [5].

According to ESU2035, achieving these objectives will require advanced technological decisions, considerable investments, updated legislation and structural changes in the economy, which should be based on a variety of modelling calculations.

The strategy notes that, *"… due to the absence of a long-term forecast for the social and economic development and the high political and economic uncertainty in the country at the moment of the Energy Strategy development, it will be necessary to further adjust the estimated TPES figures in course of the Energy Strategy implementation based on current practice and predictive modelling methods used in the EU countries*". In addition, ESU2035 states that *"… at the next stage the high-quality energy balance forecasting model will be developed with assistance of leading experts (including from EU). This will allow getting reliable data to be used for the implementation of the Energy Strategy or adjustment thereof, if necessary*". The need for advanced modelling tools to support the implementation of ESU2035 forms the background for the development of TIMES-Ukraine within this project.

Objectives of the project

The main aim of this project has been to support the Ministry of Energy and Coal Industry of Ukraine in developing tools for long-term modelling and strategic planning of Ukraine's energy system. These modelling tools are required to revise conditions and assumptions of ESU2035, as well as to develop a range of scenarios to assess optimal pathways of the Ukrainian energy system, in accordance with the goals of the Strategy (till 2035) and the future perspective (till 2050).

This has been achieved through the application of the TIMES-Ukraine model [6], as well as:

- updating and improving TIMES-Ukraine model
- selecting and quantifying policies and measures to model the pathways for achieving the goals of the Energy Strategy of Ukraine till 2035
- analysis of energy and climate policies
- providing a quantitative assessment of the scenarios for achieving the main targets of the Energy Strategy of Ukraine till 2035
- development of MS Excel toolkit and a Web-platform to analyse and visualise the modelling results

The results of this project can be used for the development of the Action Plan for the implementation of the Energy Strategy of Ukraine till 2035. Additionally, they can also be used to contribute to the development of the National Energy Efficiency Action Plan after 2020 (NEEAP), the National Action Plan for Renewable Energy after 2020 (NREAP), the National Energy and Climate Change Plan for the period 2021-2030 (NECP).

Participants of the Project

The project has been carried out by the project team in a close collaboration with the main stakeholders. Overall 5 workshops took place in the period from October 2018 to March 2019, during which the expectations and needs of the stakeholders where discussed, clarified and taken into account. The list below provides an overview of the main participants of the project (stakeholders and the project team).

Ministry of Energy and Coal Industry of Ukraine (Stakeholder)

- Olga BUSLAVETS, General Director, Directorate for Energy Markets
- Oleksandr MARTYNIUK, PhD, Head of RES Development Expert Group

Danish Energy Agency (Stakeholder)

- Aisma VITINA, Special Advisor
- Giada VENTURINI, PhD, Advisor
- Gregers LARSEN, Advisor

Ukrainian-Danish Energy Center (Stakeholder)

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Technical University of Denmark (International Consultants)

- Olexandr BALYK, PhD, Researcher
- Mikkel SIMONSEN, MSc., PhD Candidate

2. Energy system of Ukraine: current status, challenges and trends

Description of the current energy system

The current state of the generating capacities

The total installed power generation capacity of Ukraine by the end of 2017 (excluding power generating facilities of the Crimean Electric Power System and the Uncontrolled Territory of the Donbas Electricity System) is 51,7 GW (Figure 1), 59% of which belongs to thermal power plants (TPPs, CHPs, block stations), 26.7% - nuclear power plants, 12% - hydro power plants and hydro storage power stations (PSPs), 2.3% - power plants, working on renewable energy sources – wind, solar, biomass.

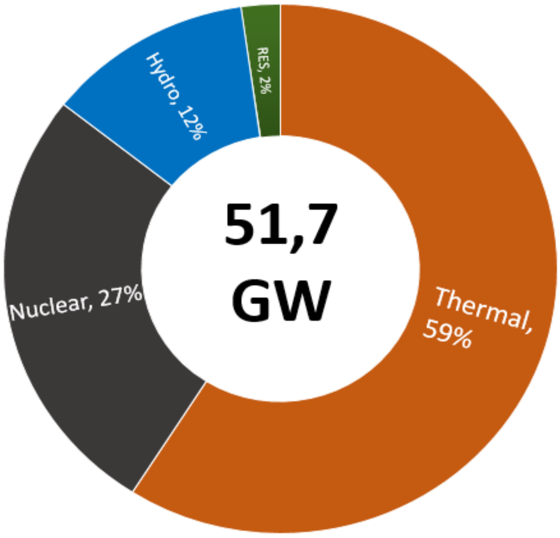

Figure 1. The total installed power generation capacity of Ukraine in 2017

The main generating capacities (as of 1st November 2018) are concentrated on:

- four nuclear power plants (15 power units, of which 13 with capacity of 1000 MW and 2 with capacity of 415 and 420 MW);
- cascades of 8 hydro power stations on the Dnipro and Dniester rivers with a total number of 103 hydro units, as well as 3 hydro accumulating (storage) stations (11 units with capacity from 33 MW to 324 MW);
- 12 thermal power plants with units of 150, 200, 300 and 800 MW capacity (75 units in total, including 6 with capacity of 150 MW, 31 with capacity of 200 MW, 32 with capacity of 300 MW, as well as 6 units and 3 turbine generator with capacity of 800 MW), as well as 3 large thermal power stations with units of 100 (120) MW and 250 (300) MW.

Distribution of energy sources in the total supply of primary energy

In the energy balance of Ukraine for 2017, the total supply of primary energy amounted to 89.6 million tons of oil equivalent, which is 5.0% less than in 2016 (Figure 2).

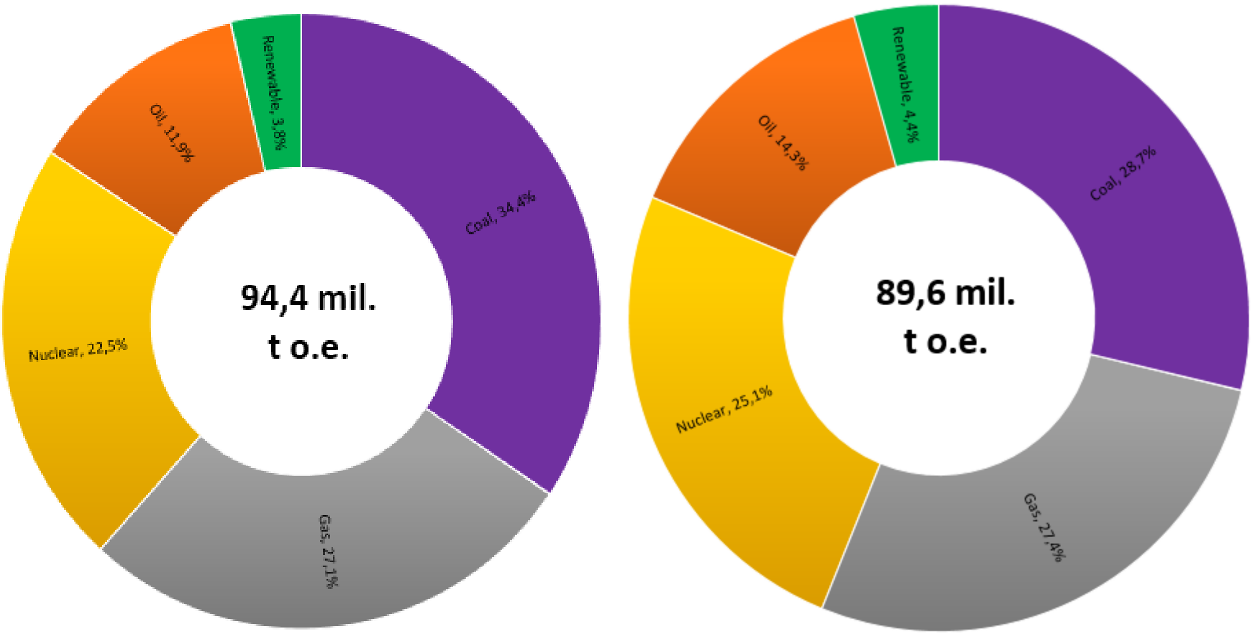

Figure 2. The energy balance of Ukraine in 2016 (left) and 2017 (right)

Final Consumption

Among the final energy sources used in 2017, natural gas holds the highest share (29.9%), while electricity has a share of 20.2%, and crude oil and petroleum products of 20.1% (Figure 3).

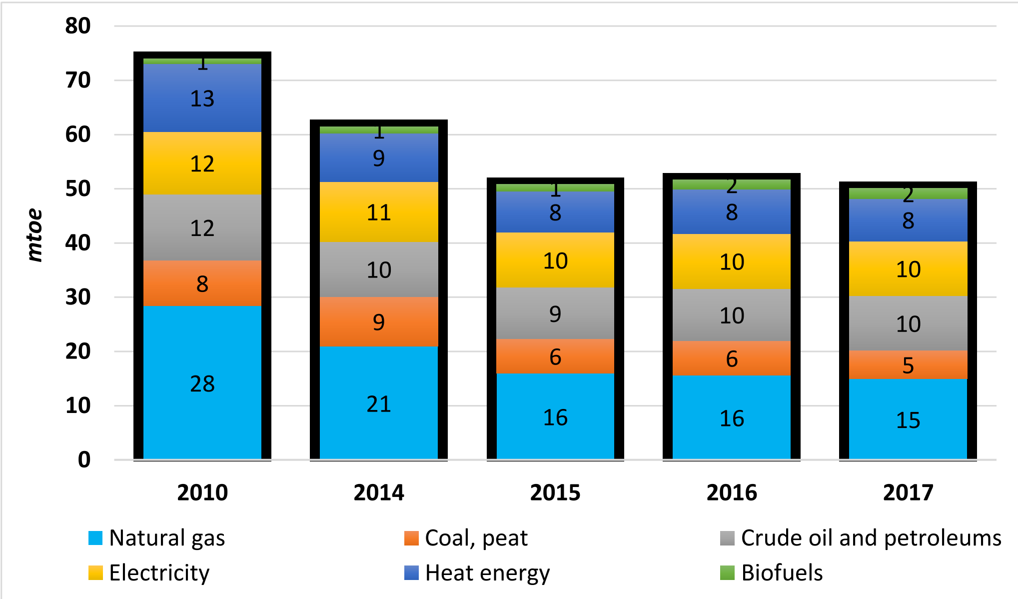

Figure 3. Final consumption by sources in Ukraine

The largest final consumers of fuel and energy in 2017 were the residential and industry sectors, which accounted for 32.8% and 30.2% respectively (Figure 4).

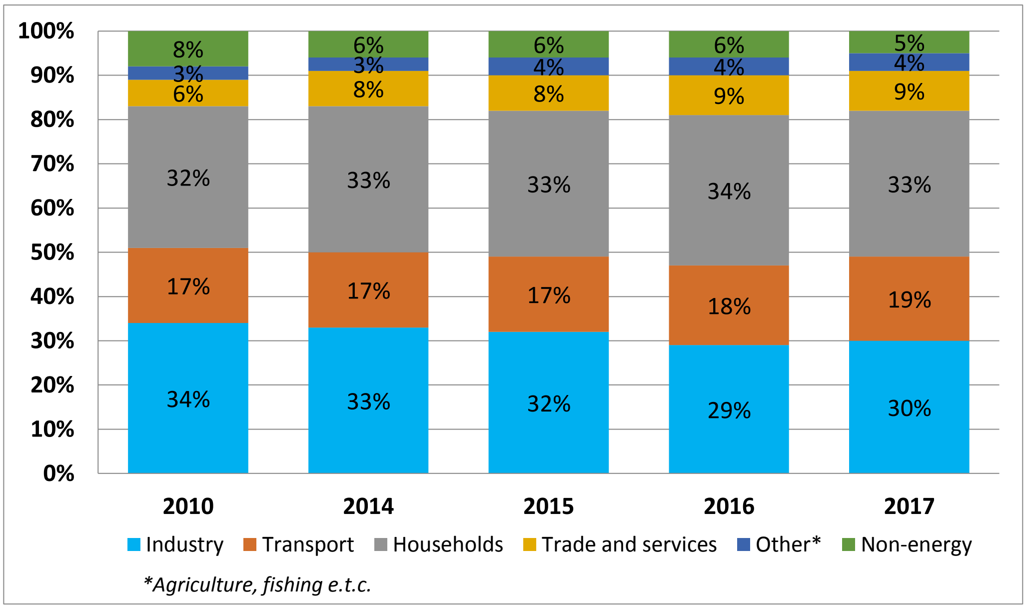

Figure 4. Structure of final consumption by sectors in Ukraine

Non-energy consumption in 2017 amounted to 2.5 million tons, of which 1.2 million tons was used as raw material for industry.

Overview of the challenges

Energy intensity

Appendixes 1 and 2 to ESU2035 contain key performance indicators comprising energy intensity, energy independency, reliability, security and environmental friendliness of the energy system, as well as composition of TPES and an electricity generation forecast until 2035. However, most challenges seem to be associated with meeting the indicators represented in Table 1.

Table 1. Some Key performance indicators of ESU2035

Indicators	2015	2020	2025	2030	2035
Primary Energy Intensity, toe/thousand USD GDP PPP	0.29	0.20	0.18	0.15	0.13
Share of RE (including hydro and thermal energy) in TPES, %	4%	8%	12%	17%	25%
Share of RE (including large hydro) in electricity production, %	5%	7%	10%	>13%	>25%
Share of wind and solar in electricity production, %	0.1%	1.2%	2.4%	5.5%	10.4%
Addition of nuclear capacity, GW			1		
Share of coal plants complying with Directive 2010/75/EC	<1%	<10%	<40%	85%	100%

Based on TPES and primary energy intensity, one can estimate the underlying assumptions made in ESU2035 regarding the average GDP PPP increase (Figure 5): 5.6% in 2015-2020, 4.4% in 2021-2025, 4.5% in 2026-2030, and 4.4% in 2031-2035.

However, taking into account the actual dynamics of GDP in 2015-2018, the average GDP growth in 2019-2020 would need to be not less than 9.1% to reach energy intensity of 0.2 toe per $1K GDP PPP 2011. Reaching the targets for energy intensity in the period 2025-2035 will require GDP growth of 3.3% in 2021-2025, 4.7% in 2026-2030 and 4.0% in 2031-2035 (Figure 6).

The Ministry of Economic Development and Trade forecasts GDP growth to be 2.8% in 2019, 3.8% in 2020, 4.1% in 2021, and 4.5% in 2022 [7]. The macroeconomic forecasts used in this project correspond to those expected by the Government, as specified in section 3 (Input data and key assumptions). According to those forecasts, GDP of Ukraine will grow on average 2.8% annually in the period 2016-2020.

Based on the above considerations, achieving the energy intensity target specified in ESU2035 for 2020 does not seem feasible. Nevertheless, the corresponding targets for 2025-2035 may well be achieved. Moreover, as seen in Figure 5, even the ambitious target for energy intensity for Ukraine in 2035 will be above the current level of the EU.

Therefore, it would be reasonable to reconsider the energy intensity target for 2020 (i.e. adjust the target to the current situation), as well as for 2030-2035 (i.e. set more ambitious targets). Consideration should be given to both policies and measures to increase the energy efficiency of the whole economy, and to support GDP growth.

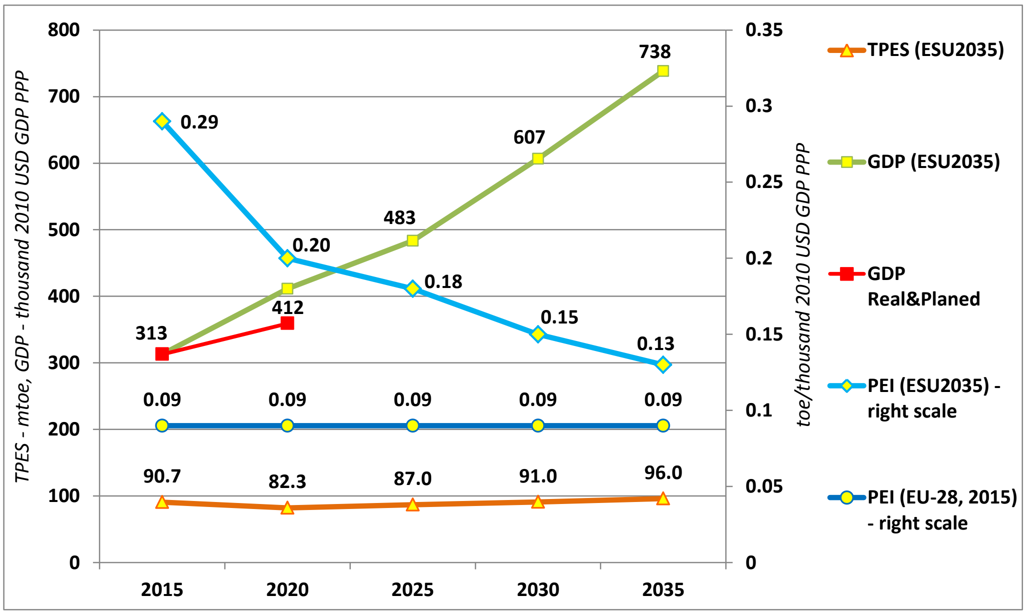

Figure 5. Dynamics of some key economy and energy indicators (TPES – Total Primary Energy Supply, GDP – Gross Domestic Product, PEI – Primary Energy Intensity)

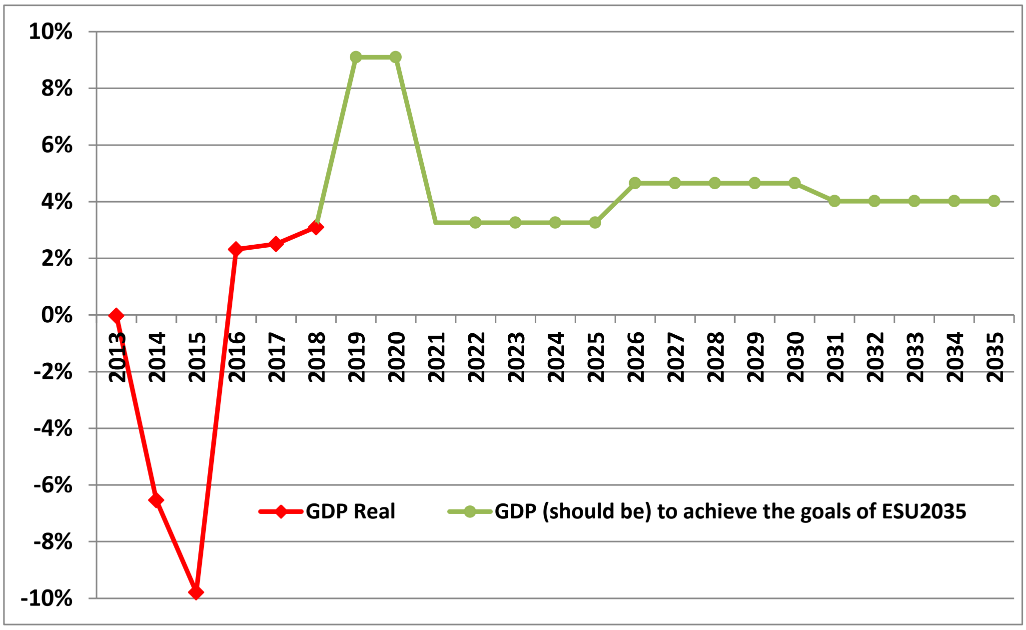

Figure 6. Growth of GDP to achieve the goals of ESU2035

Renewable energy expansion

A drastic increase of the RE share in the energy system is another important challenge, i.e. the 25% RE share (including hydro and thermal energy) in TPES in 2035 as indicated in ESU2035. Reaching 25% share of RE (including large hydro) in electricity generation will not suffice to satisfy the target; ambitious RE targets are needed for the end-use sectors. However, ESU2035 does not include any details on final energy consumption, which constitutes 50-55% of TPES. Therefore, on one side it is important to ensure the reliability of the power system under a rapid increase of RE (especially variable renewable energy), which has been expanding without the necessary development of manoeuvring and balancing capacity and other measures. On the other side, it is important to consider policies and measures that would allow increasing RE in final energy consumption, as well as to analyse what effect such an increase will have on the whole energy system of Ukraine.

Electricity demand has been growing only slowly in Ukraine. At the same, the availability factor of nuclear power plants is around 70%. Therefore, the addition of an extra nuclear unit (1GW) to cover electricity demand of Ukraine for baseload generation does not seem timely, especially considering the significant investments required for its completion.

The implementation of the Directive 2010/75/EU [5], which requires significant reduction of emissions for combustion units larger than 50 MW (all coal thermal units in Ukraine), is another important challenge for the energy system of Ukraine. The root of the problem lies in the old age of the existing coal units and the absence of any economic mechanisms (e.g. market-based) for the plant upgrade according to the new requirements. At the same time, there is a need to evaluate the technical feasibility of installing the cleaning equipment on the old units.

3. Methodology

Model description

TIMES-Ukraine is a linear optimisation energy system model, belonging to the MARKAL/TIMES model family [8,9], which provides a technology-rich representation of the energy system (bottom-up framework) for the estimation of the energy dynamics in the long-run [6]. The Ukrainian energy system is divided into seven sectors in the model (Figure 7). As such, the structure of the TIMES-Ukraine model complies with methodological approach of the State Statistics Service of Ukraine [10] (harmonized with Eurostat and IEA methodology) on energy statistics, with more than 1.6 thousand technologies currently represented.

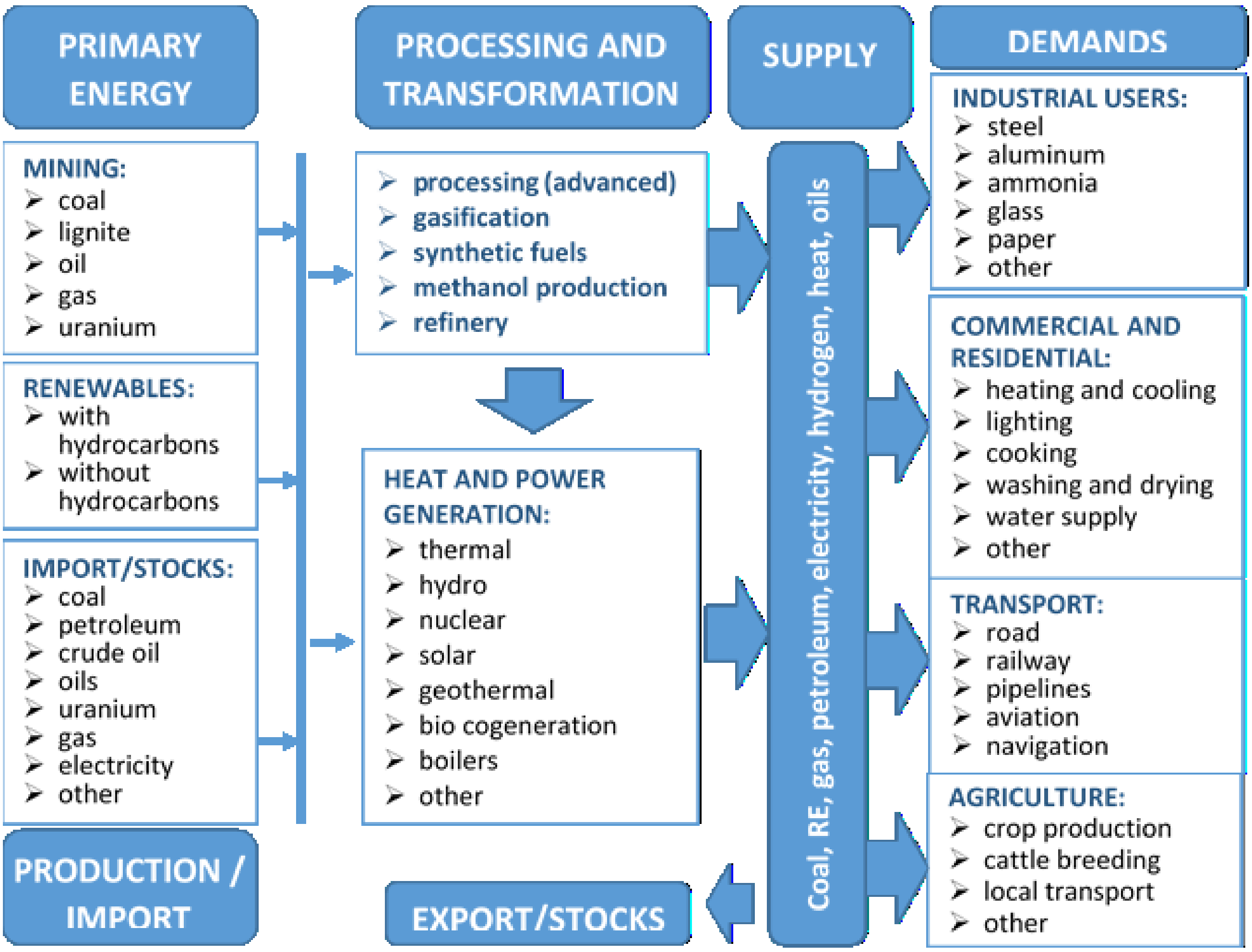

Figure 7. Representation of the energy system in TIMES-Ukraine model

Prior to the project, the model database was populated with economic and energy statistics for 2005-2012, and the model was fully calibrated for the years 2005, 2009 and 2012 (except for parametrisation of processes, other model parameters were also properly estimated in order to reflect the energy balance; as such, any of these years could be used as a base year for calculations). Within the project, the model database was fully populated with data for 2013-2015, which made it possible to revise the parametrisation of energy technologies. Moreover, some key input data such as energy production, international trade, performance of power plants and boilers was also provided for 2016-2018. Although the model was not fully calibrated with a new base year (2015), the accuracy of the calculated energy balance for 2015 comparing to the reported document is quite high. The calibration (to 2015) can be performed with relatively moderate efforts, as no additional input data would be required.

Industrial users are further disaggregated into two categories depending on the level of energy intensity. Energy-intensive subsectors are represented by product-specific technologies. For other industrial subsectors, a standard representation is adopted according to the four types of general processes: electric engines, electrochemical processes, thermal processes and other processes.

Energy consumption by households and commercial sector is determined by the most energy intensive categories of consumer needs, such as heating and cooling of dwellings, water heating, lighting, cooking, refrigerating, clothes washing and drying (ironing), dishwashing etc.

The transport sector is represented by the types of transportation: road, railway, pipelines, aviation and navigation. The energy services, which are provided by technologies of road and rail transport, are transportation of passengers and freight.

The agriculture sector is divided into crop production, cattle breeding, local transport and other.

Energy system models, like TIMES-Ukraine, are usually applied for long-term analysis of energy system development pathways. By changing the assumptions on useful energy demands, technologies, prices or other exogenous variables, scenarios can be analysed. As a first step, scenarios without measures (baseline scenario) are developed. In the next step, policy scenarios are designed by imposing additional constraints or targets on the energy system as to assess the effect of different policies. The result of the modelling is an assessment of the least-cost solutions for the entire energy system under given conditions and restrictions.

The TIMES-Ukraine model satisfies the methodological recommendations of international organizations for the development of energy and environmental forecasts. In particular, the recommendations of the Secretariat of the United Nations Framework Convention on Climate Change concerning the development of national communications [11].

Based on the previous applications, TIMES-Ukraine model is particularly suited to perform the following tasks:

- estimation of the optimal technological structure of the power system under the criterion of minimisation of the total discounted system cost [12–15]
- analysis of the structure of energy, material and financial flows in the system, taking into account resources trade [16–18]
- assessment of the potential of energy savings, renewable energy sources, new types of energy and fuels, and investment prioritisation based on a least-cost optimisation [19–22]

- forecasting the dynamics of greenhouse gas emissions [23–25]
- identification of possible threats to the energy supply of the country and determination of measures for their prevention [26–28]
- assessment of the impact of energy, economic, environmental, climate, industrial, agriculture, transport, innovation and other policies on energy development [29]
- investigation of the advantages and risks of integration processes and international obligations in the energy, ecological, climate and other spheres [30]

Model improvements

Within the project, the TIMES-Ukraine model has been vastly improved owing to the combined efforts of the experts from the Institute for Economics and Forecasting, NASU, and Technical University of Denmark.

Revision and verification of the model database and structure

The TIMES-Ukraine model largely relies on the national statistical classifications [31] which are consistent with NACE [32], CPA [33] and CN [34] that have been tangibly updated from the last calibration of the model upon 2012. Feeding the database with a new data for 2013-2015 compiled under new editions of statistical classifications in most of the cases required the revision of processing algorithm of primary data on energy resources, materials and economic activities, to align it with a topology of reference energy system (RES), as well as with methodological approach of Eurostat for energy statistics [35]. Besides, primary statistical forms of the State Statistics Service of Ukraine on energy production and use [36] were also changed comparing to 2012 version: the coverage of energy resources by type was expanded, while specification of energy flows like unit energy consumption by fuel for production of goods and services was shortened.

Moreover, some of the updates in the statistical reporting format also required revision of the reference energy system (RES), such as the incorporation of new energy commodities and processes (technologies) with respective adjustment of parameters of existing technologies. This mainly concerned the production/consumption of heat, and solid and liquid biofuel. The 11-mtp primary statistical form [36] provides now detailed information on electricity and heat auto-production by generation type for each sector, as well as sectoral use of electricity/heat split by origin of supply. As heat supply systems are not integrated and the share of heat auto-production is still growing, modelling experts considered it reasonable to adjust the topology of heat supply.

Demands and drivers

A new long-term macroeconomic projection was developed and implemented in the TIMES-Ukraine model with an updated set of macroeconomic drivers. According to this new baseline scenario, the recovery of the Ukrainian economy will prevail, which will ensure the growth of production, mainly in the food, textiles and pharmaceutical industries. The development of information technology will accelerate the growth of computer and electronic equipment production. The need for modernization and restoration of infrastructure will accelerate the growth rate of construction. Due to the slow growth of gross fixed capital, low investments and innovation activity, it is expected that renovation of productive capacities and optimisation of the structure of the economy will be low. The main development drivers will be the agriculture, food and pharmaceutical industries, while machinery and services (i.e. information technologies, research, education and health) will accelerate their development by end of the next decade. Growth rates by sector are summarized in Table 5.

The list of demands, corresponding drivers and functional relationships (calibration series) was discussed within the team in detail, and new approaches for demand-driver composition in the transport sector and for heating demands were proposed. However, owing to the lack of time and available and reliable information, such as estimation of the passengers' time budget or breakdown of residential buildings by EE performance, those suggestions were not implemented.

Improved representation of storage

Storage technologies were represented in the TIMES-Ukraine model originally, albeit in a simplified manner. There was a single storage technology for all technologies of the type "PV Plant Size" and another one for all technologies "Wind Onshore". During the project more storage technologies were added: three storage technologies for the Power Sector (high, medium and low voltages) and four storage technologies for the end-use sectors (industry, residential, commercial and agriculture). Investment cost of storage technologies are shown in Table 8, while technical characteristics are found in Table 2.

Table 2. Characteristics of storage technologies

Starting Year	Efficiency	Annual Availability Factor	Lifetime
2020	92%	33%	10 years

Incorporation of prosumers

Prosumers in end-use sectors (industry, residential, commercial, agriculture) have been incorporated in the model. Prosumers in the TIMES-Ukraine model are electricity consumers that are able to produce more electricity than they consume (through installed solar PV rooftop) and feed the excess electricity into the grid. Basically, this type of consumers utilises two technologies: solar PV rooftop panels and storage. The investment cost of solar PV is shown in Table 8, while their technical characteristics are found in Table 3.

Table 3. Characteristics of solar PV rooftop panels

Commodity Input	Commodity Output	Min shares of outputs	Efficiency	Annual Availability Factor	Lifetime of Process
Solar energy	Electricity to grid	60%	92%	13%	20 years
	Electricity for own consumption	10%			

Construction and decommissioning time and costs

In the project, the characteristics of the technologies within the power sector in the TIMES-Ukraine have been expanded by specifying the construction time for the new power plants (i.e. ILED parameter). Additionally, decommissioning costs of power plants have been updated. Table 4 shows the average construction time and decommissioning costs for every technology by fuel type.

Table 4. Average construction time and decommissioning costs for power plants by fuel type

Power Plants	Construction time (years)	Decommissioning costs (% of CAPEX)
Gas	2.0	2.0%
Oil	2.0	2.0%
Coal	2.0	5.0%
Biomass	2.0	1.5%
Wind	1.5	1.0%
Solar	1.0	1.0%
Geothermal	1.5	1.0%
Hydro	3.0	3.0%
Nuclear (extended)	2.0	0.0%
Nuclear (new)	7.0	10.0%

Input data and key assumptions

The database of the TIMES-Ukraine model includes the following data:

- statistical observations of the State Statistics Service of Ukraine
- data of the Ministry of Energy and Coal Industry; Ministry of Economy, Ministry of Environment, Ministry of Internal Affairs, Ministry of regional development, construction and housing and communal services, SAEE, power generating and supply companies, etc.
- data from the IEA (in particular ETP, E-TechDS), DIW Berlin, IAEA, OECD, DEA and others (used to identify promising energy technologies and their technical and economic characteristics)
- data from specialised associations (Bioenergy Association of Ukraine, Ukrainian Wind Energy Association, Ukrainian Association of Renewable Energy Sources and other) and companies (Energoatom, Ukrenergo, DTEK, Naftogaz, etc.)
- the structure of demand in the end-use sectors (corresponding to the models structure of other European countries)

- long-term macroeconomic development indicators that are based on data from the IEF NASU, international financial, rating agencies and other organizations (IMF, World Bank, Standard & Poor's, etc.), as well as data of the Ministry of Economic Development and Trade
- forecast of prices for the main energy resources (based on World Bank data)
- forecasts of demographic dynamics in Ukraine (based on data from the Institute of Demography and Social Research of the National Academy of Sciences of Ukraine and the Department of Economic and Social Affairs of the United Nations)
- GHG emission factors (based on the National Inventories data on anthropogenic emissions from sources and removals by sinks of greenhouse gases in Ukraine)

The basic macroeconomic scenario used in this project was prepared by the Institute for Economics and Forecasting in 2016 within the framework of the USAID project "Municipal Energy Reform in Ukraine". It has been updated with the recent changes in the economy of Ukraine. The macroeconomic scenario is shown in Table 5.

Table 5. Average annual growth rates of Ukraine's GDP for the period 2018-2050

Sectors/Years	2018-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Agriculture, forestry and fisheries	3.1%	3.8%	4.4%	4.0%	4.5%	4.5%	4.5%
Mining and quarrying	2.2%	2.0%	2.7%	2.2%	2.0%	2.0%	2.0%
Manufacturing industry	4.4%	4.0%	4.2%	3.9%	3.3%	3.3%	3.3%
Supply of electricity, gas, steam and air conditioning	3.7%	3.5%	4.5%	4.1%	4.1%	4.1%	4.1%
Construction	5.0%	4.9%	5.3%	5.1%	5.1%	5.1%	5.1%
Services	2.8%	3.5%	4.3%	3.9%	4.0%	4.0%	4.0%
GDP	3.0%	3.4%	4.4%	4.0%	4.0%	4.0%	4.0%

The forecast of prices for the main energy resources for Ukraine until 2050 is based on World Bank forecasts to 2030 [37] (see Table 6). By extrapolating data, a corresponding forecast for 2035-2050 prices was made.

Table 6. Commodity prices forecasts in nominal U.S. dollars

Commodity	Unit	2015	2016	2017	Forecasts					
					2018	2019	2020	2021	2025	2030
Coal, Australia	$/mt	58.9	66.1	88.5	108.0	100.0	90.0	86.4	73.5	60.0
Crude oil, average	$/bbl	50.8	42.8	52.8	72.0	74.0	69.0	69.1	69.5	70.0
Natural gas, Europe	$/mmbtu	7.3	4.6	5.6	8.0	7.5	7.0	7.1	7.5	8.0

Population projections for 2020-2050 (Table 7) are based on the Institute of Demography and Social Research of the National Academy of Sciences of Ukraine (IDSR), which are in line with the projections of the UN Department of Social and Economic Affairs (UN DSEA). For the purposes of this project, only one demographic scenario (IDSR – Scenario CCC) was used, which predicts average birth rates, average life expectancy and average net migration in Ukraine.

Table 7. Demographic scenarios for Ukraine (million people)

Scenarios	2012	2015[1]	2020	2025	2030	2035	2040	2045	2050
IDSR - Scenario CCC	**45.3**	**42.7**	**44.4**	**43.6**	**42.8**	**41.8**	**40.8**	**39.9**	**38.9**
IDSR - Scenario BBB			45.1	45.1	45.1	45.1	45.2	45.4	45.6
IDSR - Scenario HHH			43.4	41.6	39.7	37.8	35.8	33.9	32.0
IDSR – Sustainable scenario			44.1	42.7	41.1	39.5	37.8	36.1	34.3
IDSR - Scenario CCH			44.3	43.3	42.1	40.8	39.5	38.3	37.1
IDSR - Scenario BHB			44.3	43.5	42.7	41.8	41.1	40.7	40.3
IDSR - Scenario HBH			44.2	43.2	42.1	41.0	39.8	38.5	37.0
Scenario UN DSEA			43.7	42.4	40.9	39.3	37.8	36.4	35.1

Table 8 shows the estimated cost of capital expenditures (CAPEX) for the construction of power plants (PP) and electricity storages.

Table 8. Capital cost of future energy technologies for Ukraine (EUR/kW)

Technologies	2020	2025	2030	2035	2040	2045	2050
Wood biomass	2800	2800	2600	2500	2400	2200	2000
Biomass from waste of agro-industrial complex, etc.	2900	2800	2700	2600	2500	2300	2100
Biogas	4400	4300	4200	4100	4000	3900	3800
Gas (combined cycle)	1000	1000	1000	1000	1000	1000	1000
Gas (gas turbine)	600	600	600	600	600	600	600
Gas (steam turbine)	920	920	920	920	920	920	920
Coal (combustion in a circulating boiling layer)	1000	1000	1000	1000	1000	1000	1000
Coal (combustion in a circulating boiling layer)	1700	1700	1700	1700	1700	1700	1700
Coal (integrated gasification combined cycle)	1800	1800	1800	1800	1800	1800	1800
Coal (combustion on undercritical parameters)	1600	1600	1600	1600	1600	1600	1600
Coal (combustion on above-critical	1300	1300	1300	1300	1300	1300	1300

[1] Excluding the territories temporarily occupied by Russian Federation.

Technologies	2020	2025	2030	2035	2040	2045	2050
parameters)							
Joint combustion of coal and biomass (on undercritical parameters)	2050	2050	2050	2050	2050	2050	2050
On shore wind power plants	1500	1500	1440	1350	1300	1250	1250
Industrial solar power plants with a tracker	900	825	750	670	600	550	500
Industrial solar power plants without a tracker	700	675	650	580	520	475	440
Geothermal power plants	4362	4362	4362	4281	4119	3958	3877
Unit №3 at the Khmelnytska NPP	1581	1581	1581	1581	1581	1581	1581
Unit №4 at the Khmelnytska NPP	1510	1510	1510	1510	1510	1510	1510
New nuclear power plants	5328	5328	5328	5328	5328	5328	5328
Extension of the existing NPP for 10 years	135	135	135	135	135	135	135
Small hydro	2940	2926	2911	2882	2853	2824	2796
Large Hydro	3000	3000	3000	3000	3000	3000	3000
Battery Storages (EUR/kWh)	900	875	850	800	750	700	600

4. Scenarios

Scenario description

Within the framework of this project, four scenarios (*Frozen Policy scenario, Reference scenario, National Strategy scenario, Low Carbon Society scenario*) and a set of sensitivity scenarios designed as variations on the Reference scenario have been developed. The Matrix of the modelling scenarios is shown in Table 9.

Table 9. The Matrix of Scenarios

	Key scenario conditions	*Frozen Policy scenario*	*Reference scenario*	*Sensitivity scenarios*	*Scenario national strategies*	*Low Carbon Society Scenario*
Energy Strategy of Ukraine till 2035	Significant reduction in energy intensity		+	+	+	+
	Significant increase in the share of RE in the TPES and the structure of electricity generation		+	+	+	+
	47% of nuclear in the power generation in 2035		+	+	+	+
	Completion of Unit #3 at KhNPP in 2025		+	+/–	+	+
	European ecological requirements for TPPs		+	+	+	+
	Existing balancing technologies	+	+	+/–		
New balancing technologies				+/–	+	+
Qualitative system of forecasting electricity generation from solar and wind power plants				+/–	+	+
Green tariff up to 2030 according to the current legislation		+	+	+	+	+
Low development of RE (Ukrenergo scenario)				+/–		
The goals of other national strategies and plans					+	+
GHG emission reduction by 80% in 2050 compared to 1990 level						+

Frozen Policy scenario – assumes no changes in energy policy after 2015 (i.e. before adoption of the ESU2035). This scenario was made for comparison purposes.

Reference scenario – defined based on the main objectives and indicators of the Energy Strategy of Ukraine till 2035: reduction of the energy intensity of GDP; growth in the share of renewables in TPES; electricity generation structure, that preserves the dominant role of nuclear power as well as building unit #3 at Khmelnytska Nuclear Power Plant (KhNPP); and achieving European environmental requirements of the operation of large combustion plants. The same goals and restrictions are used for the period 2036-2050 (i.e. after ESU2035) as in 2035.

Sensitivity scenarios – are based on the Reference scenario and differ only in one of the constraints or conditions. In particular, opportunities to use new balancing capacity, availability of quality power generation forecasting system for Solar and Wind, or delayed construction of KhNPP unit #3 or renewable energy (according to the terms of the scenario presented in the Report on conformity assessment (adequacy) generating capacities (SE "NEC "Ukrenergo"). This group of scenarios was especially directed towards the needs of the Ministry of Energy and Coal Industry. The Matrix of the Sensitivity scenarios is presented in Table 10.

National Strategies scenario – includes targets from other national strategies and plans in addition to the conditions and constraints of the Reference Scenario, including Low Emission Development Strategies in Ukraine till 2050, the National Transport Strategy till 2030, Concept of state policy in the field of heating supply and others.

Low-Carbon Society scenario – aims at reducing the greenhouse gas emissions by 80% in 2050 with respect to 1990 levels. This scenario is closer to the climate mitigation policy adopted in the EU.

Table 10. The Matrix of the Sensitivity scenarios

Conditions	Names of Sensitivity scenarios				
	No New Nuclear in 2025	Low RE Growth	Green-Coal Paradox	New Balancing Techs	Optimise Balancing
Conditions of the Reference Scenario	+	+	+	+	+
High potential for development of RE in Ukraine (no more than 20 GW of wind, 12 GW of roof solar panel and 36 GW of solar plant size power by 2050)	+	–	+	+	+
Low development of RE (Ukrenergo scenario: no more than 7.2 GW and 10.4 GW of wind and solar power by 2050)	–	+	–	–	–
Completion of unit #3 at Khmelnytska power plant in 2025 (strict condition for the model)	–	+	+	+	+
Free conditions for competing unit #3 at the Khmelnytska power plant after 2020 (model chooses the year of completion)	+	–	–	–	–
Using all available existing power plants as balancing and maneuvering capacities	+	+	–	–	–
Using only existing coal power plants as balancing	–	–	+	–	–

Conditions	Names of Sensitivity scenarios				
	No New Nuclear in 2025	Low RE Growth	Green-Coal Paradox	New Balancing Techs	Optimise Balancing
and maneuvering capacities					
Introduction of new balancing and maneuvering technologies (Li-ion storages (battery), hydro, gas power plants (in particular, fast-response gas power plant)), excluding existing coal power plants	–	–	–	+	+
Wind and solar power plants work without an accurate forecasting system	+	+	+	+	–
An accurate system of forecasting electricity generation from large solar and wind power plans	–	–	–	–	+

Energy and climate policies in the scenarios

Energy and climate policies and measures used in the scenarios are based on Low Emission Development Strategy of Ukraine till 2050 [38], which takes into account ESU2035 and provides a list of policies and measures that were discussed in numerous working groups and included a wide range of stakeholders, including the Ministry of Energy and Coal Industry. Policies and measures that were taken into account in the project are given below.

Energy Efficiency

Energy efficiency (EE) policies include measures which aim to increase efficiency in the use of energy resources and the implementation of energy savings, accompanied with enhanced quality in energy services and energy resources supply. In order to achieve the targets of ESU2035, the following measure where represented:

- thermal insulation of building stock
- introduction of cogeneration at new and existing power plants
- increase efficient use of fossil fuels in heat generation (i.e. through refurbishment and technology substitution)
- advanced energy efficiency technologies in industry
- new farming technologies to reduce fossil fuel consumption (through refurbishment)
- increase in resource efficiency of production sector outputs (through technology substitution)
- lowering the share of carbon intense energy resources use by production sector (through technology substitution)

Renewables

Renewable energy policy includes measures which aim to support and stimulate the renewable energy development in Ukraine. Substantial intensification of RE will make a significant contribution to the EE measures, which aim to decarbonise the energy sector. The following measures were evaluated and included in the model into order to comply with the ESU2035 targets on the RE share in TPES and electricity generation:

- wind, solar, hydro, geothermal, bio- technologies in power sector
- biomass heat generation technologies
- increase in sustainable production of biomass for energy supply purposes
- production of electricity and heat generation from municipal and industrial waste
- production of liquid and gaseous biofuel from agriculture and forestry materials
- production of liquid and gaseous biofuel from municipal waste
- biogas production from manure and other by-products
- generation of energy from biogas coming from SHW landfills

Modernisation and innovation

Modernisation and innovation policy include measures which aim to modernise the existing energy technologies and implement innovation technologies, in particular:

- modernisation (retrofitting) of existing power plants
- decommissioning of inefficient technologies
- lifetime extension of existing NPPs
- use of transport vehicles that utilise additional types of motor fuels (e.g. addition of the possibility to use LPG to an existing gasoline vehicle)
- expansion of high-speed trains for passengers
- introduction of energy accumulation (storage) technologies
- hydrogen technologies in transport

Transformation of the market and institutions

Market transformation and institutions policy include business measures, regulatory and management practices, standards and codes, public awareness measures, policy on education, science and technology development. The following measures were included in this study:

- setting ambitious goals for reducing greenhouse gas emissions by 2050
- enabling consumer access to energy suppliers

5. Results

Detailed modelling results

Frozen Policy Scenario

In this baseline scenario the modelling results indicate:

- The total primary energy supply (TPES) will not exceed the level of 2012 throughout the forecasted period, even if the economy is restored and is growing.
- Renewable energy share will increase, albeit at a slow rate, even without targeted policies towards energy saving, renewable energy sources and environmental and climate restrictions.
- The coal industry has a hypothetical high growth rate, with the restoration of all existing mines and the return of them to the subordination of the official government of Ukraine and the construction of new mines.

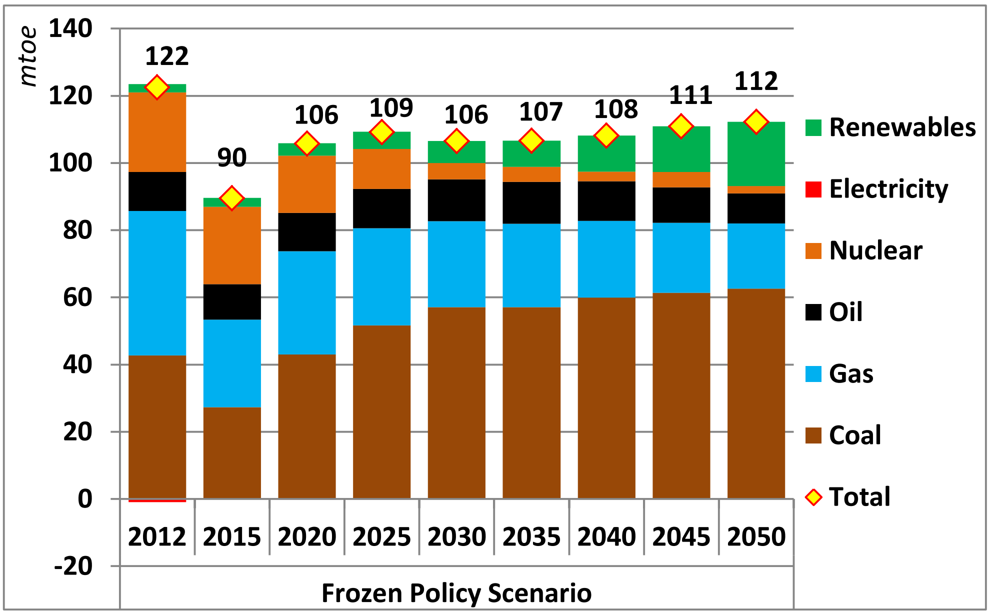

Figure 8. Total Primary Energy Supply in Frozen Policy scenario

- In the final energy consumption (FEC), the share of RE will increase to 3% in 2035 and 15.1% in 2050 due to biomass and solar energy.
- Without the targeted policy of stimulating the RE (especially in the building sector), the share of RE in the FEC will be 3% in 2035 and approx. 15% in 2050.
- Renewable share in electricity generation will experience a growth in the future; 18%, 24% and 28% in 2012, 2035 and 2050, respectively.
- The proportion of gas and heat supplied centrally will be significantly reduced.

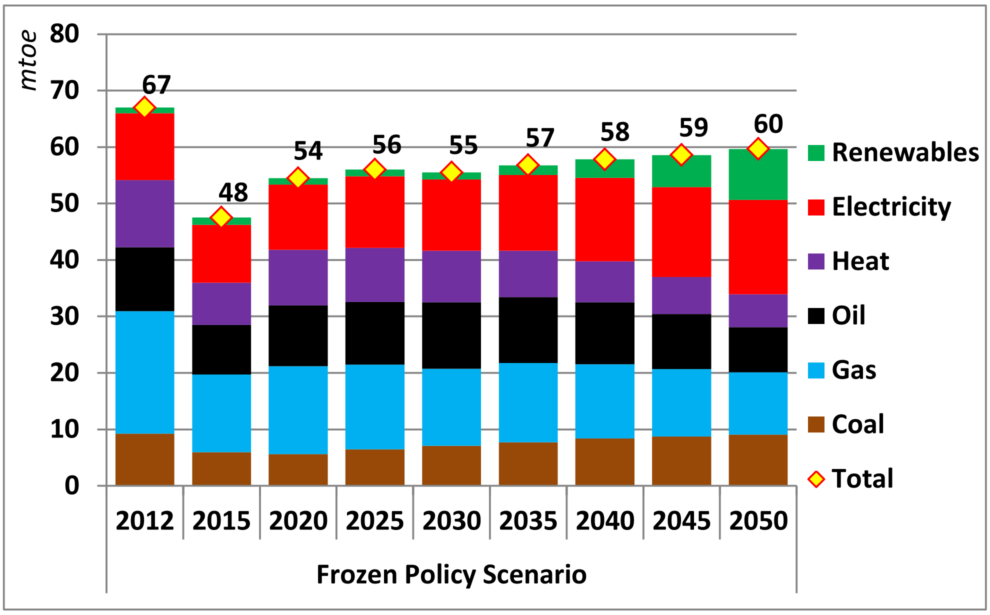

Figure 9. Final Energy Consumption in Frozen Policy scenario

- In the electricity generation, the share of coal thermal power plants will exceed 50% in 2035-2050.
- The share of RE may increase to 23% in 2035 and almost 30% in 2050.

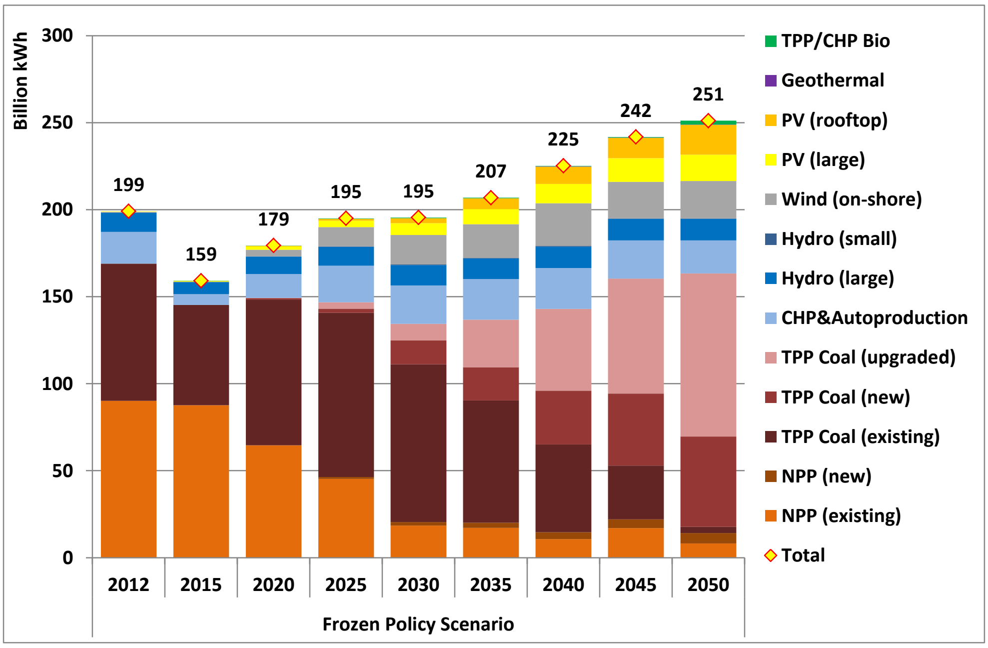

Figure 10. Electricity Generation in Frozen Policy scenario

- GHG emissions in the Energy and Industrial Process sectors will grow due to an increase in coal consumption. The growth is especially high in the Electricity and Heating sector. The share of GHG emissions will rise from 30% in 2012 to 35% and 40% in 2035 and 2040 respectively.
- Simultaneously, the share of GHG emissions in the Residential sector will fall from 10% to 7% and 4% in 2035 and 2050, respectively.

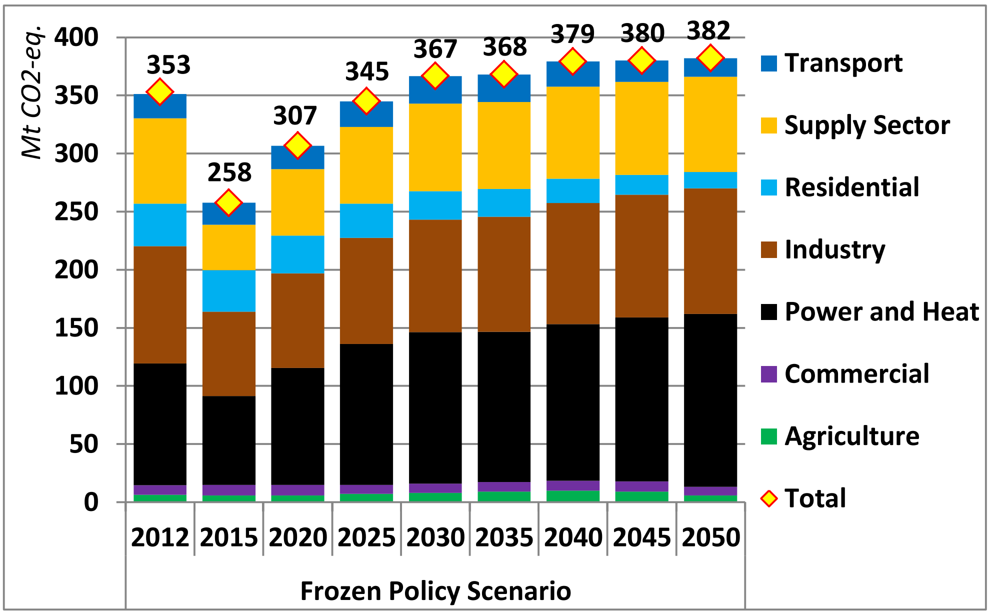

Figure 11. Greenhouse Gas Emissions in Frozen Policy scenario

Reference Scenario

- In the Reference scenario (based on ESU2035), TPES will remain at 2015 level throughout the forecasting period, provided that economic recovery, growth and unconditional restoration of sovereignty takes place.
- The share of renewables in TPES will correspond to the goals of ESU2035 by 2035, with renewables contributing up to one third of TPES by 2050.
- The share of coal may fall to 15% by 2035. However, it may reach the 2015 level again due to decommissioning of nuclear PPs.

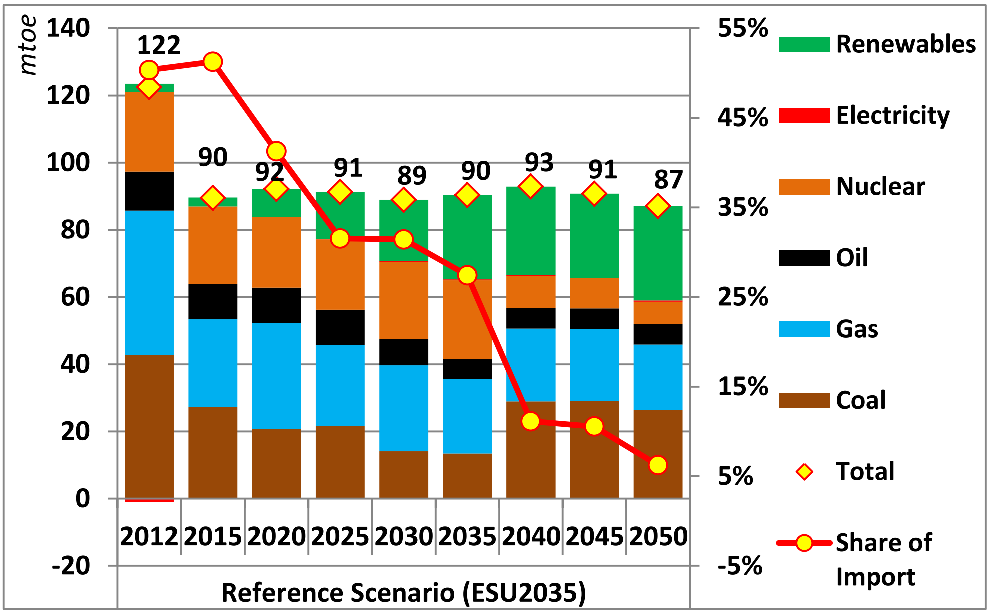

Figure 12. Total Primary Energy Supply in Reference scenario

- The results in terms of TPES under the Reference scenario and the Annex to the ESU2035 are similar, as the same energy intensity has been assumed.
- The composition of TPES is somewhat different. Under the Reference scenario, higher coal demand is expected, while nuclear and renewable usage is higher in ESU2035.
- However, in both cases the goals of ESU2035 with regards to renewables, energy intensity, and share of imported energy in TPES are met.

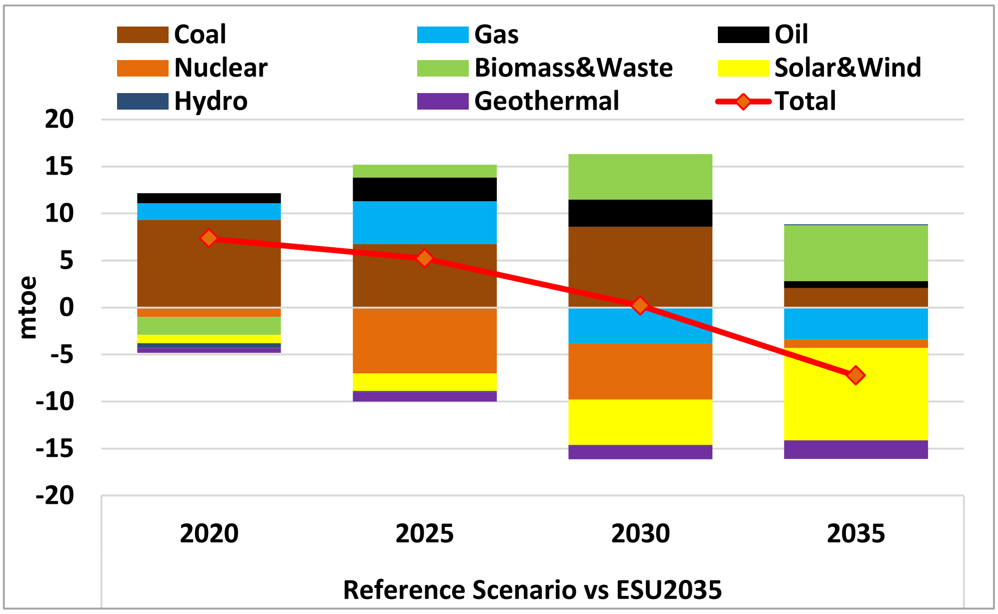

Figure 13. Differences in Total Primary Energy Supply

- Final energy consumption (FEC) will stabilise around 55-56 mtoe by 2020 due to energy saving measures.
- Share of renewables in FEC will reach 20% in 2035 due to dedicated policies, but it may fall again until 2050 unless the policies continue.
- The share of gas in FEC will fall from 32% in 2012 towards 18% in 2035, respectively. While electricity consumption will rise from 18% in 2012 to 24% and 30 % in 2035 and 2050, respectively.

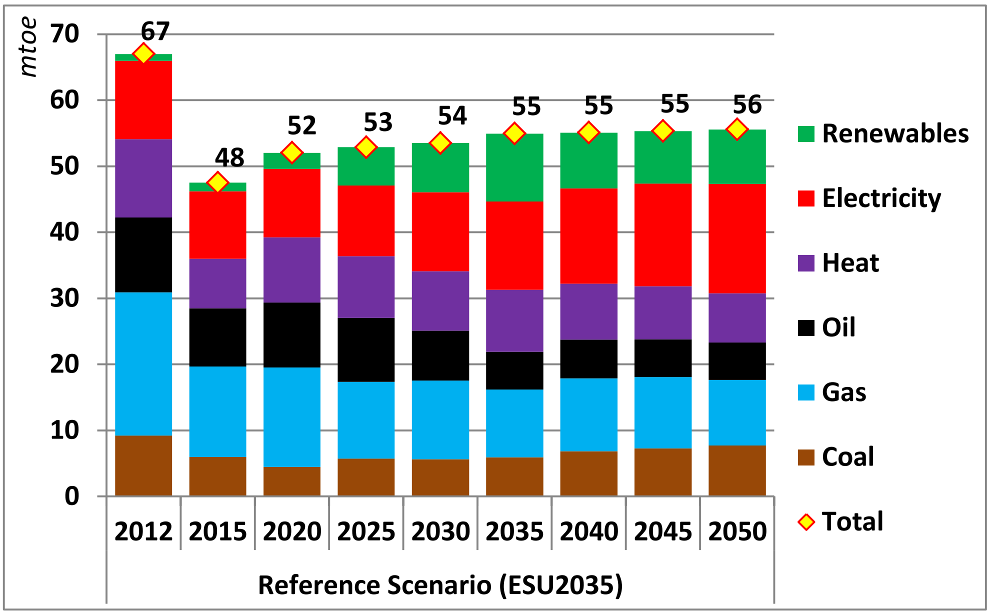

Figure 14. Final Energy Consumption in Reference scenario

- The shares of renewables in electricity in the Reference scenario expands up to 39%, indicating that generation may exceed the share of 25% foreseen in ESU2035 significantly. Overall the shares of renewables in electricity may exceed 60% by 2050.
- Nuclear energy will preserve its dominating role under the goals of ESU2035, however new nuclear units appear to be less competitive due to lower costs and technological improvements in renewable energy technologies.

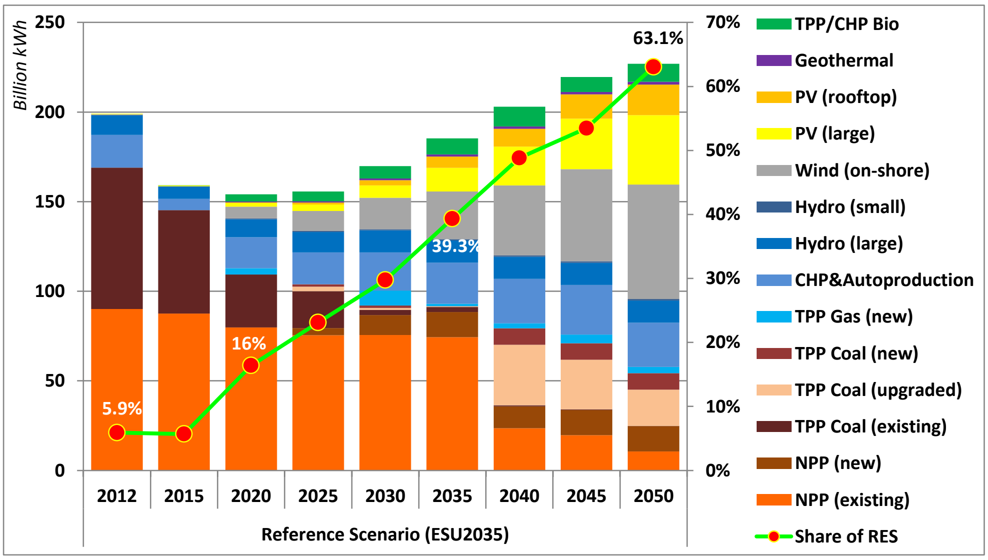

Figure 15. Electricity Generation in Reference scenario

- Implementation of ESU2035 will allow to significantly reduce GHG emissions from Energy and Industrial Process sectors. However, unless the policies are continuously updated, GHG emissions may rise again after 2035 due to retirement of nuclear and increased electricity generation from coal thermal power plants.

- Nevertheless, the most significant share of GHG emissions will remain in the industry sector, due to the lack of decarbonisation measures.

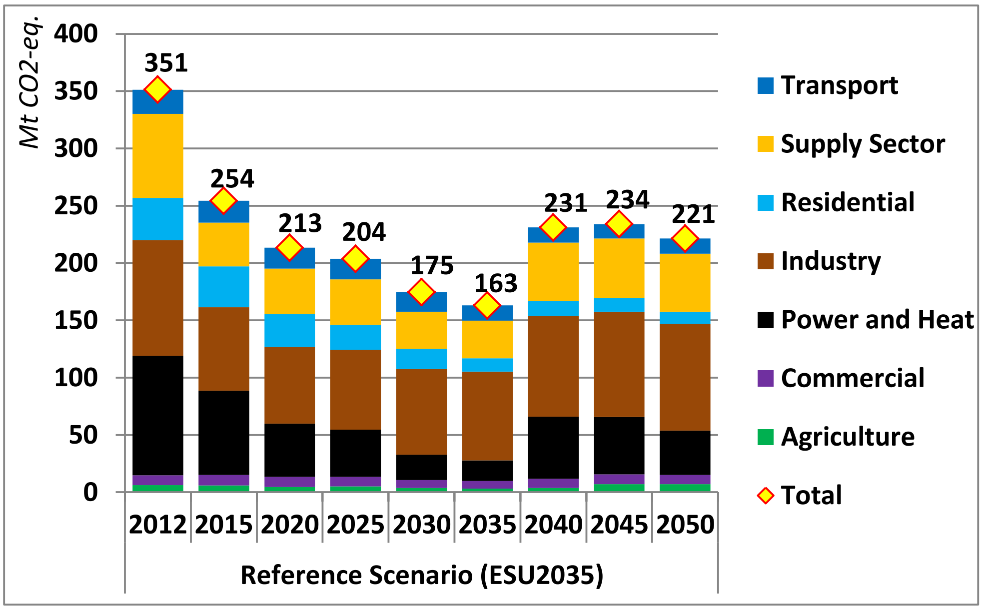

Figure 16. Greenhouse Gas Emission in Reference scenario

- Implementation of ESU2035 will allow for a reduced carbon intensity of GDP by 3.4 times in 2035 and 3.6 times in 2050 by improving the energy system.
- Compared to 2015, energy intensity of GDP will decrease by a factor of 2.2 and 3.2 in 2035 and 2050, respectively.

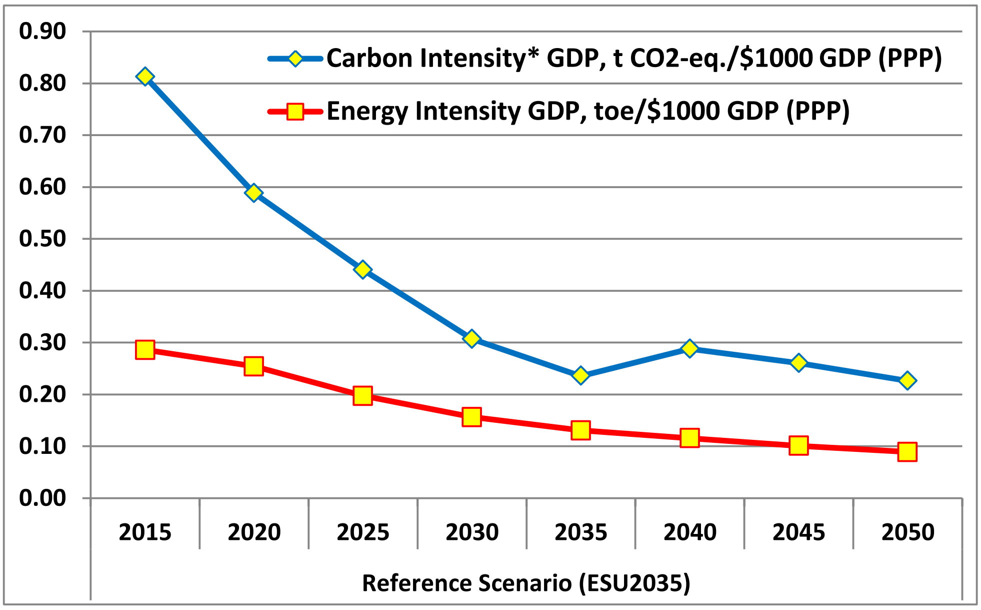

Figure 17. Carbon and Energy Intensity in Reference scenario

- Capital and operational expenditures will have to increase significantly in order to achieve the goals of ESU2035; however, two thirds of the expenditures will comprise the costs connected to the end-use energy consumption technologies. The share of Electricity and Heat sector in the total system cost will only be 15%.

- Compared to the Frozen Policy scenario, energy system costs will increase by 20% on average (or about 10 billion euro) until 2035, and by 9% on average (or about 7 billion euro) after 2035.
- The fuel costs will be lower by 1-2 billion euros compared to the Frozen Policy scenario.

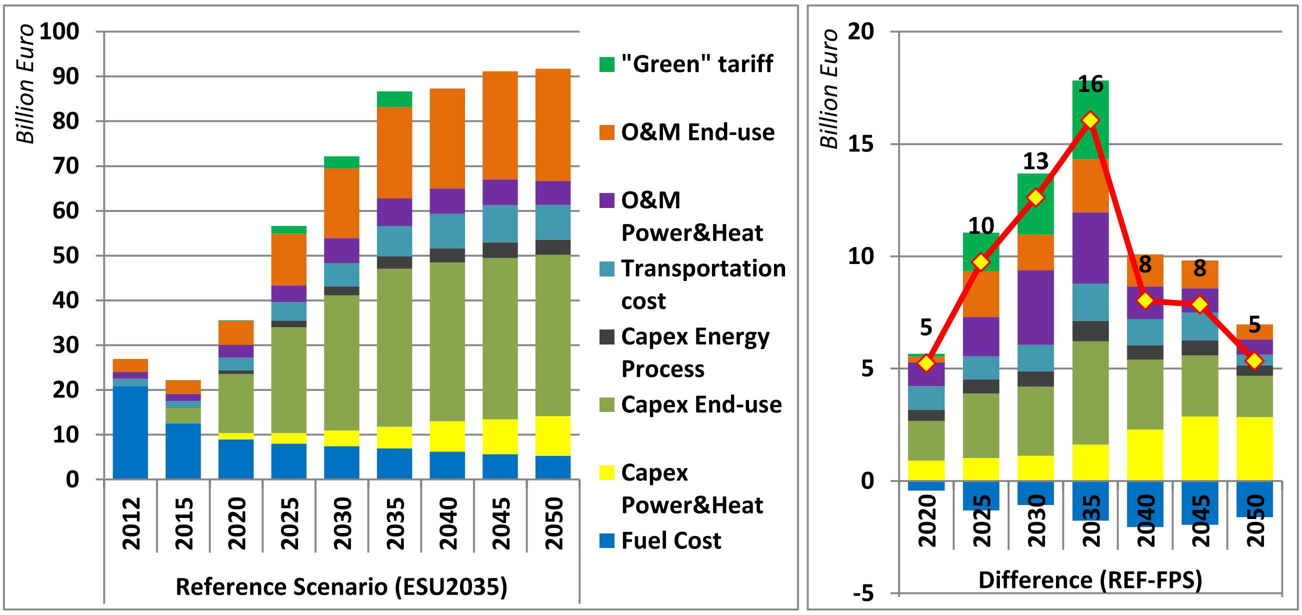

Figure 18. Total Operation System Cost in Reference scenario and difference with Frozen Policy scenario

Sensitivity Scenario: Low Renewable Growth

- The Report on the assessment of adequacy of generating capacities (DP "Ukrenergo") [3] considers scenarios with moderate rates of development of variable renewables, in which there can be no more than 7.2 GW and 10.4 GW of wind and solar power by 2050.
- If such conditions are applied to the Reference scenario, the share of renewables in electricity generation will increase to a maximum of 41% in 2050, while in 2035 it will amount to about 31%, which also is higher than anticipated by ESU2035.

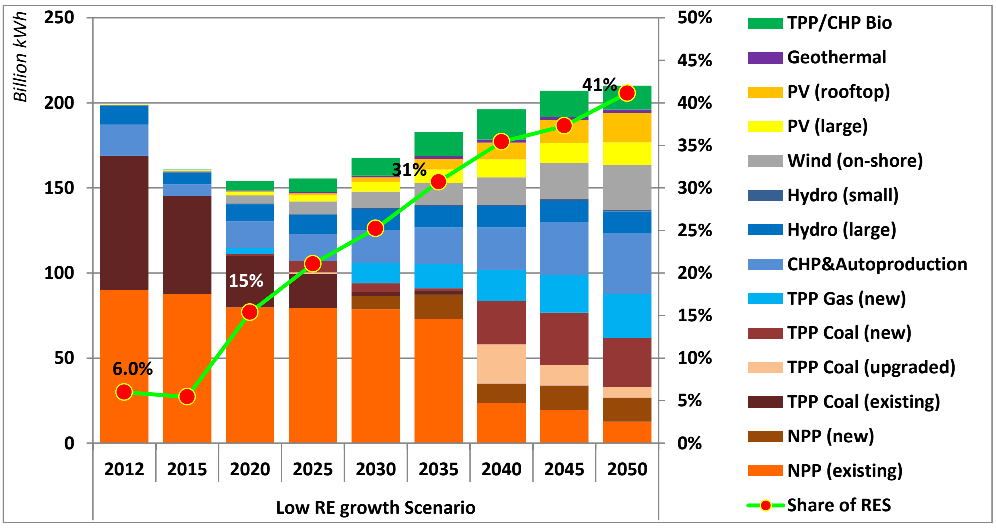

Figure 19. Electricity Generation in Low RE Growth scenario

- Demand for electricity may decrease in the Low Renewable Growth Scenario after 2035 compared to the Reference Scenario, due to increasing electricity prices.
- Renewable electricity generated will primarily be substituted by coal and gas generation and, possibly, generation of electricity from biomass combustion.
- The impact of such restrictions in an increase in the total cost by 1.7 % or around 12 billion euros of the energy system.

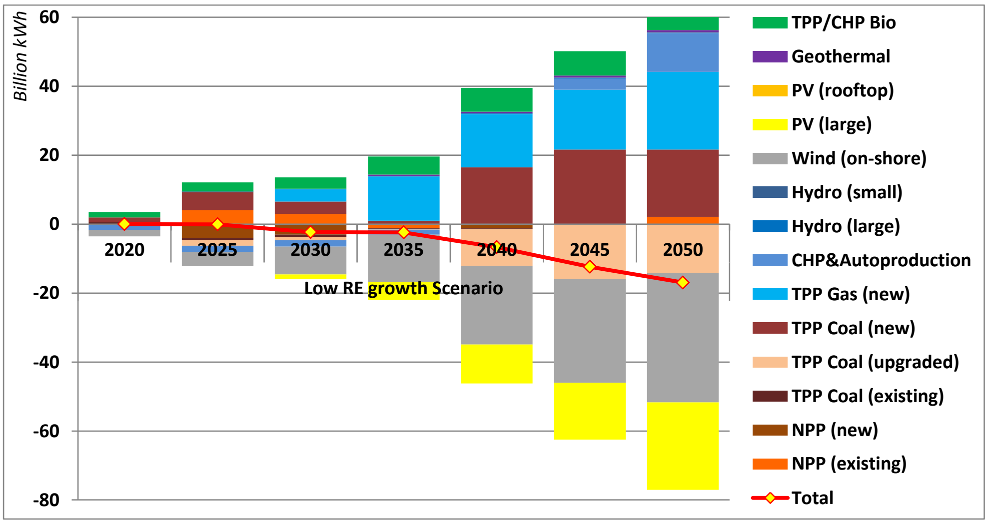

Figure 20. Differences in Electricity Generation between "Low RE growth" and Reference scenarios

Sensitivity Scenario: No New Nuclear in 2025

- The modelling results show that under the objectives of ESU2035, due to a significant reduction in energy intensity and a significant increase in renewables, the existing NPP units will not be fully utilised, and thus the construction of a new unit (#3) at the Khmelnitsky NPP in 2025 seems unnecessary in order to fulfilment the energy demand.
- The construction of KhNPP #3 may become economically feasible by 2030-2035, according to the modelling results. This will reduce the required investment by roughly 270 million euros, due to the optimisation of the commissioning of power generating facilities.
- In this scenario, electricity generation will not differ from the Reference Scenario in other aspects than nuclear plants.

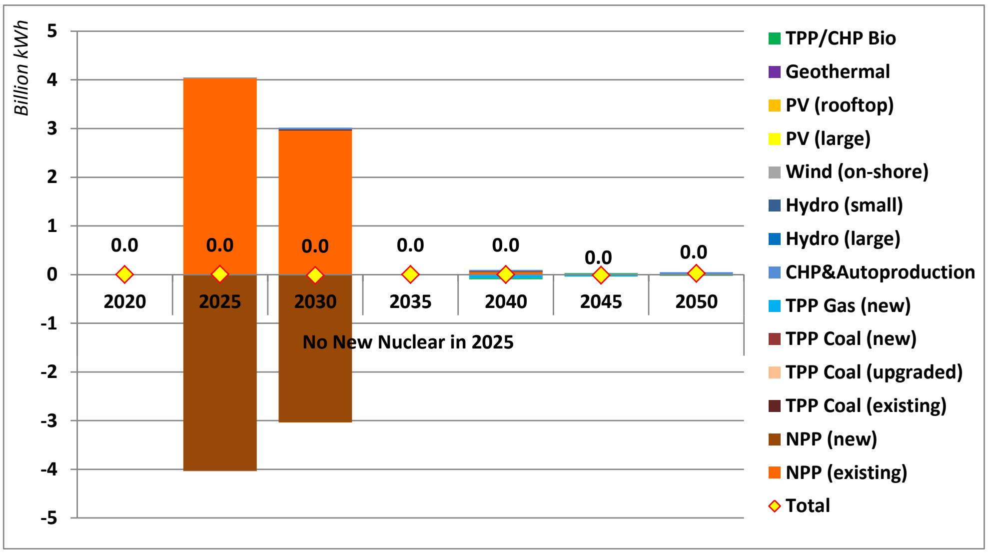

Figure 21. Differences in Electricity Generation between "No New Nuclear in 2025" and Reference scenarios

Sensitivity Scenario: New Balancing Technologies vs. Green-Coal Paradox

- Currently, balancing of the intermittent renewable energy is mainly achieved through operating the coal-fired power plants.
- The introduction of new balancing and manoeuvring technologies will make it possible to decrease the costs of electricity generation, while achieving the required goals with regard to renewables, and reducing the investment costs by 13 billion euros for the period 2020-2050.

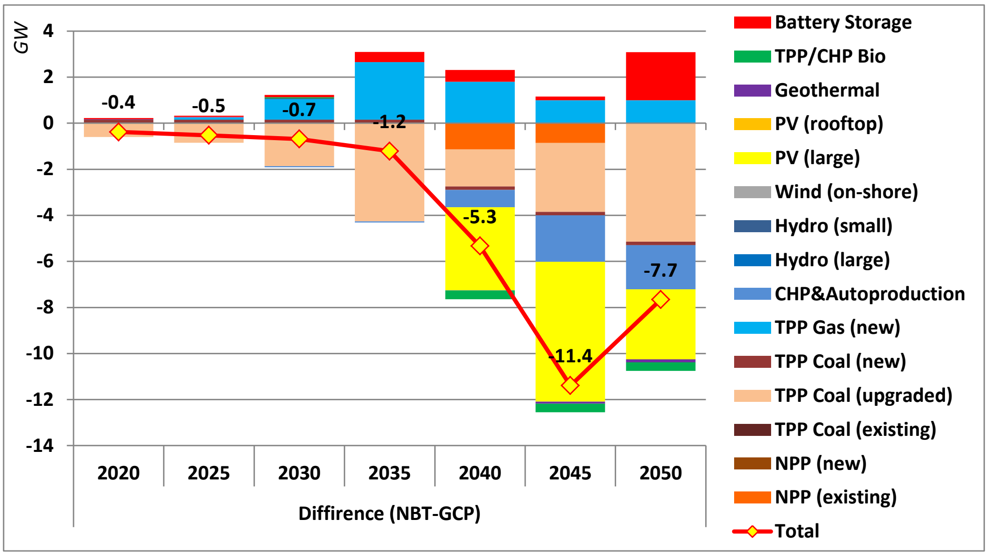

Figure 22. Differences in Electricity Capacity between "New balancing technologies" and "Green-coal paradox" scenarios

Sensitivity Scenario: Optimise Balancing

Compared to the Green-Coal Paradox Scenario, the use of modern forecasting systems and balancing technologies will allow to:

- Increase the production of electricity from renewables;

- Reduce investment costs by 11.5 billion euros (over the period 2020-2050) by reducing the generation capacity needs;
- Reduce the total system cost by 0.5%.

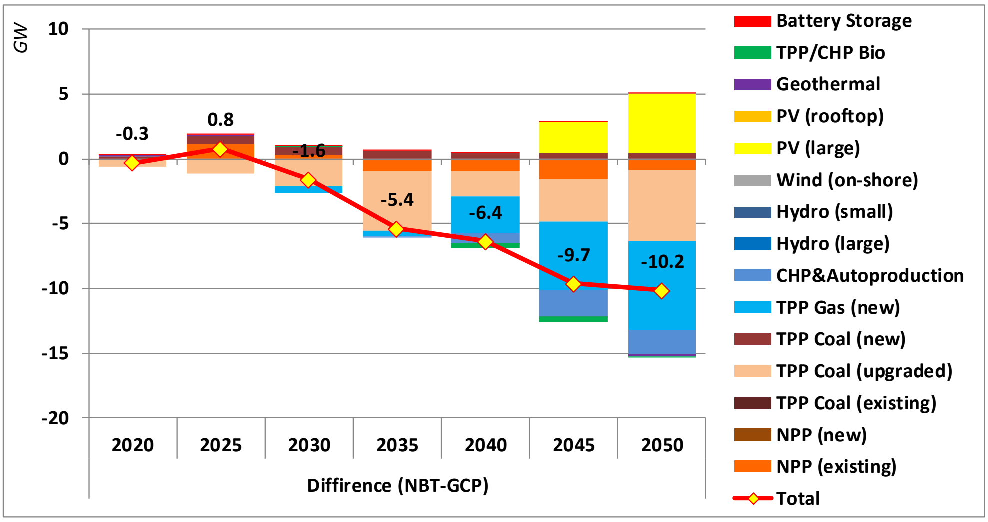

Figure 23. Differences in Electricity Capacity between "Optimise Balancing" and "Green-coal paradox" scenarios

National Strategies

National Strategies adds other national targets and measures from strategic documents (National transport strategy of Ukraine till 2030; National Strategy for Waste Management in Ukraine till 2030; Concept of realization of the state policy of heat supply; and Ukraine 2050 Low Emission Development Strategy) in addition to those of ESU2035.

According to the modelling results:

- Ukraine 2050 Low Emission Development Strategy does not have a significant influence on the results of the Reference scenario, since it was prepared taking into account ESU2035.

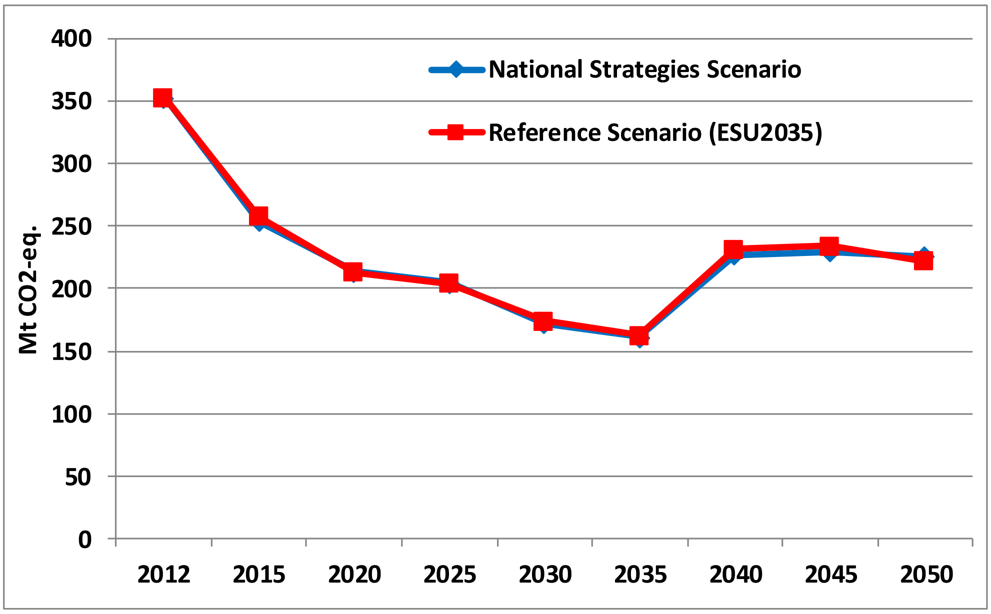

Figure 24. Greenhouse Gas Emission in National Strategies and Reference scenarios

- The national transport strategy will have a significant impact on fuel and energy supply, in particular of road transport. According to the modelling results, demand for biofuels may increase significantly by 2035; the electricity demand increase will follow due to the widespread use of electric vehicles.
- The electric vehicles will reduce energy consumption of the transport sector, due to the high efficiencies in the electric engines compared to internal combustion.

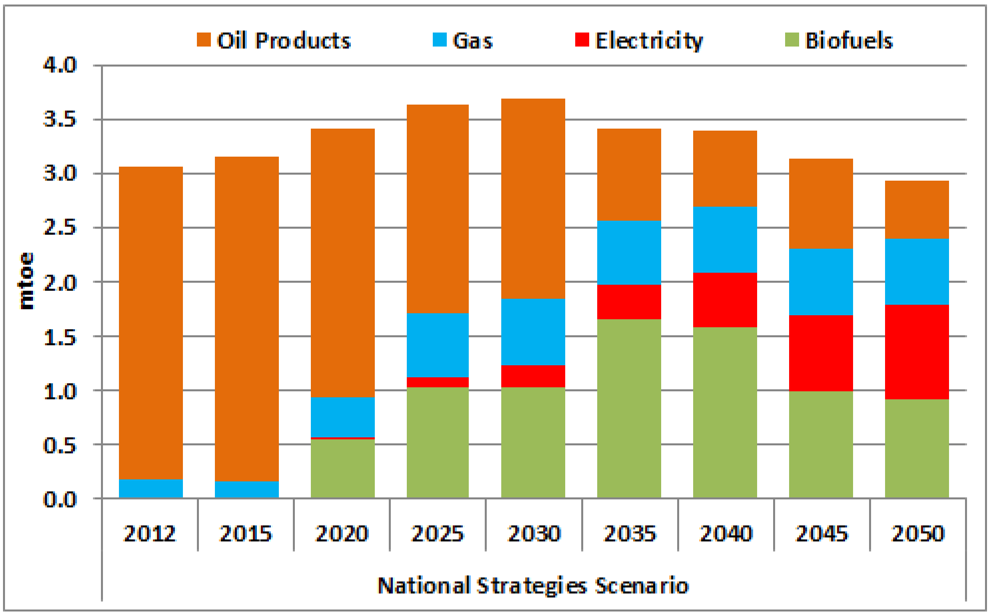

Figure 25. Energy Consumption by Cars in National Strategies scenario

- The share of biofuels in cars may increase up to 50% by 2035, as the potential for biofuel production in Ukraine is relatively high. The share of electric vehicles could increase to 20% in 2035 and 50% in 2050. However, due to the high energy efficiency in EVs, electricity consumed by these corresponds to 10% and 30%, in 2035 and 2050, respectively.

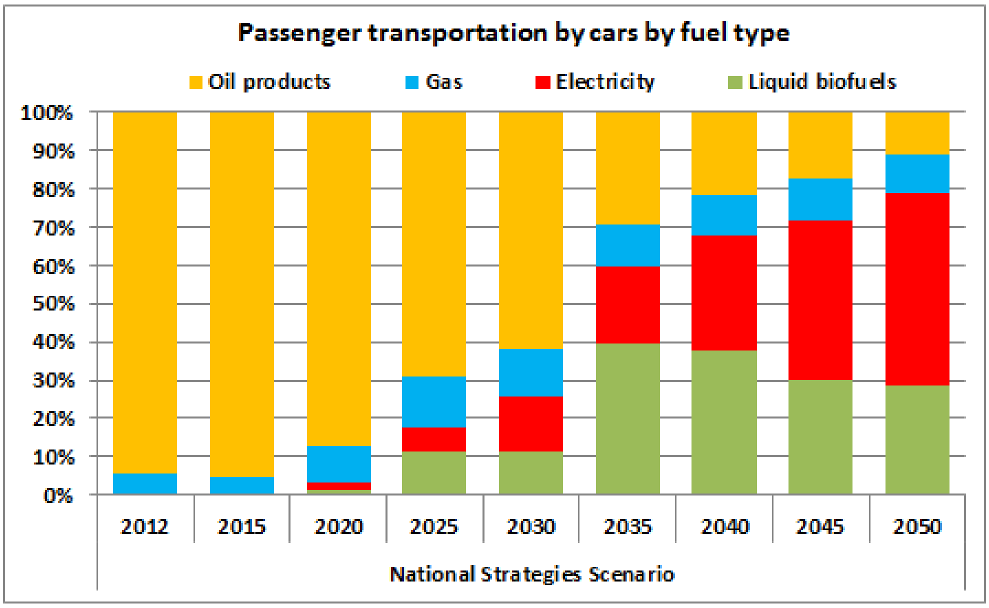

Figure 26. Passenger transportation by cars by fuel type

- The implementation of the government's policies within heat supply implies a substantial increase of the renewable share in centralised heat supply.
- Its implementation will increase production from biomass and other renewables to 40% by 2035, within a decreasing district heating sector.
- Due to the lack of planned environmental policy for small and medium-sized heat production facilities and its enforcement for large facilities, redistribution of coal consumption between these types of heat generation facilities may occur.

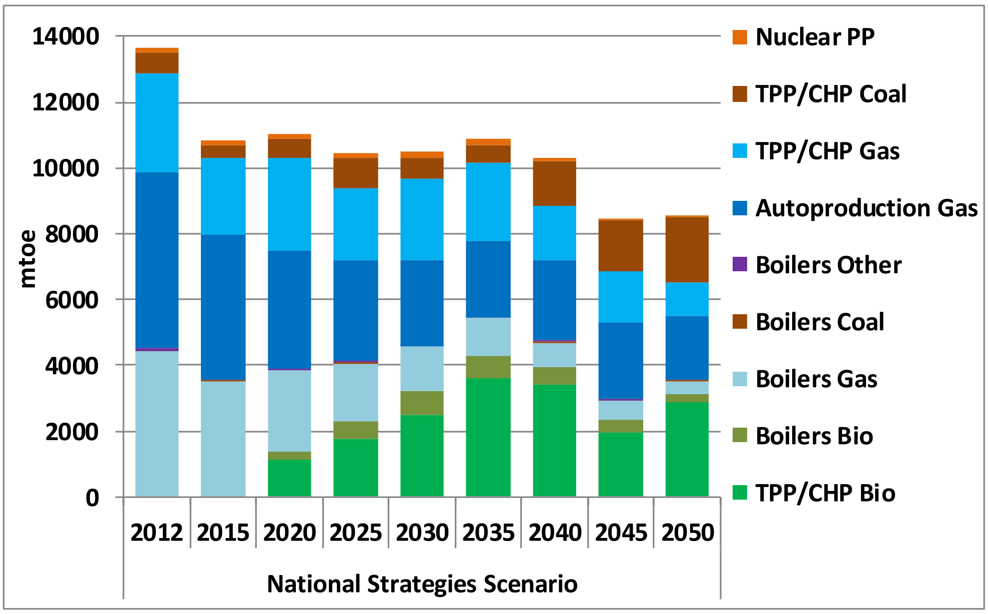

Figure 27. Heat Generation in National Strategies scenario

- Compared to the Reference scenario, TPES in the National Strategies Scenario differs only by a small margin. However, significant structural changes occur: replacement of the most carbon-intensive energy resources, i.e. coal with less carbon-based (gas) and carbon-free (nuclear energy and renewables) sources.
- However, it is clear that without prolonging effective policies, such as those planned in existing national strategies until 2035, the volumes of TPES in Ukraine in 2050 may increase.

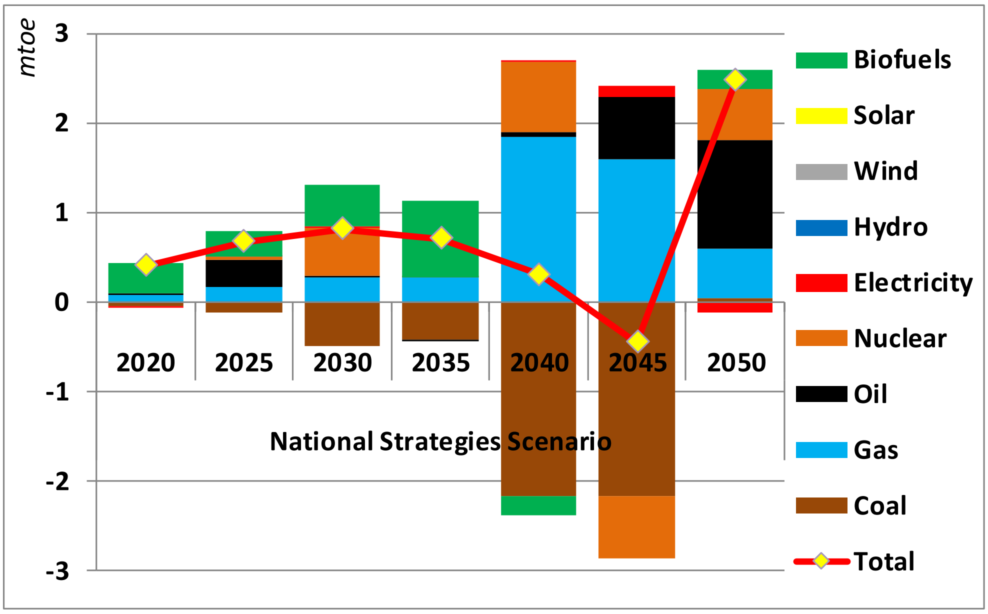

Figure 28. Differences in Total Primary Energy Supply between "National Strategies" and Reference scenarios

- Within the National Strategies Scenario, a higher share of electricity is generated from biomass compared to the Reference scenario.
- Gas consumption decreases throughout the entire period, and by 2030 coal is also reduced due to the need to achieve the goals of the Concept of the implementation of the state policy in the field of heat supply.

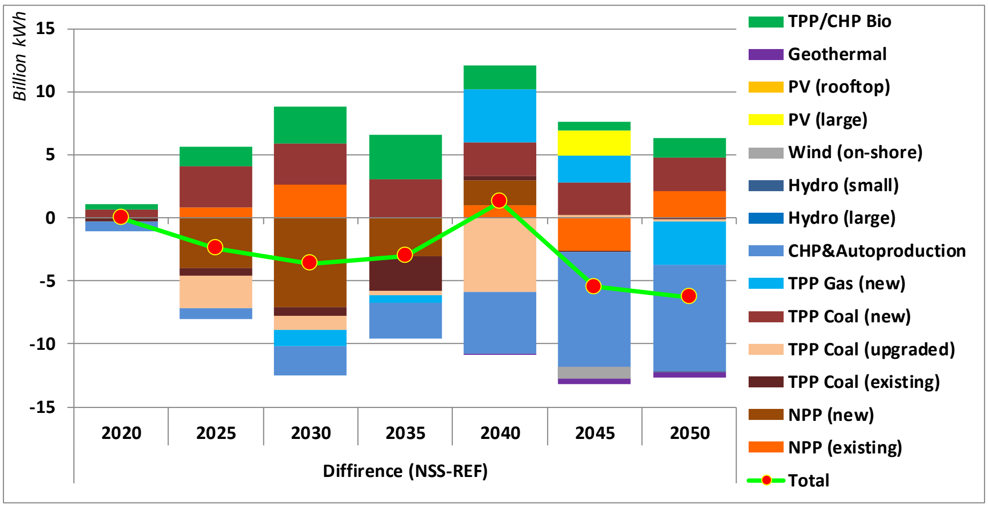

Figure 29. Differences in Electricity Generation between "National Strategies" and Reference scenarios

▪ The National Strategies Scenario, which includes goals that have not been taken into account in the ESU2035, obviously requires additional investment. However, a synchronous implementation of the ESU2035 and other strategies, plans, concepts, etc. may lead to a synergistic effect in the form of higher efficiency of attainment of the targets and the lower corresponding costs.

▪ According to the results, taking into account national strategies requires additional 1-2 billion euros investment primarily from the end-use sectors, in particular due to a higher penetration of electric vehicles.

▪ At the same time, fewer investments in electricity and heat generation may be required.

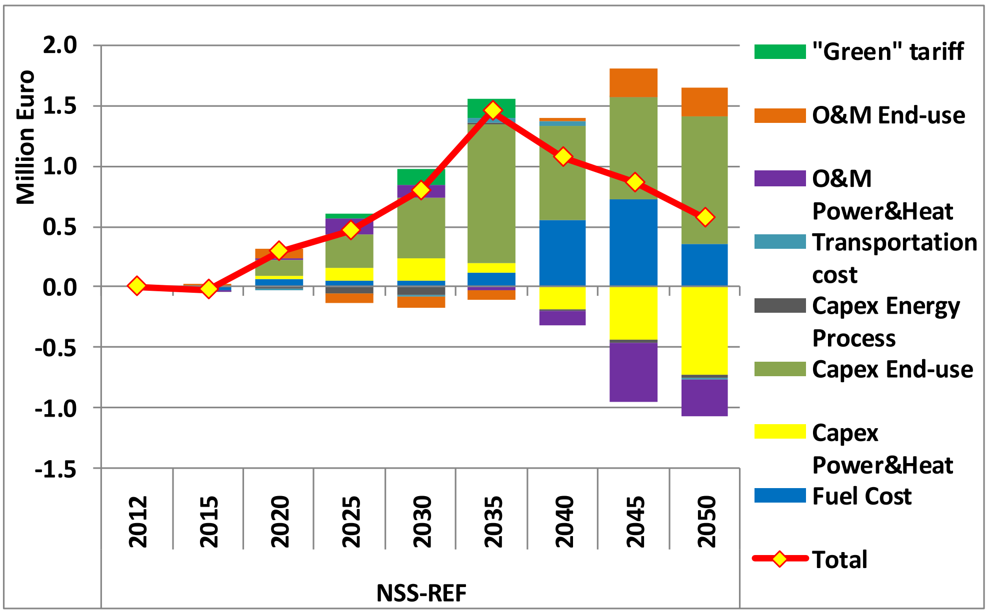

Figure 30. Differences in Total Operation System Cost between "National Strategies" and Reference scenarios

▪ With specific policies and goals related to reducing greenhouse gas emissions, significant reductions can be achieved in order to combat climate change.

▪ As the results show, the realisation of the goals of the ESU2035 and other strategic documents by 2035 could reduce GHG emissions by 55% compared to 2012. In absence of polices beyond 2035, in particular strategies towards the retirement of nuclear power units in the period 2040-2050, GHG emissions will increase.

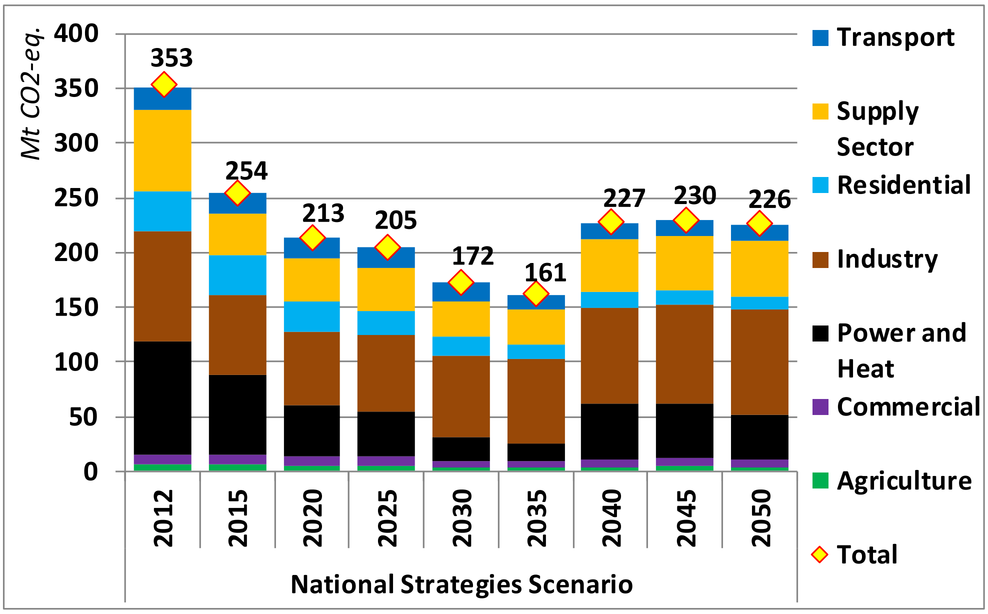

Figure 31. Greenhouse Gas Emission in National Strategies scenario

Low Carbon Society Scenario (GHG emission reduction by 80% in 2050)

- Targeted GHG emission reduction policy will allow continuous progress towards the decarbonisation of the economy of Ukraine.
- Decarbonisation of the economy should be based on the principle of decoupling GDP growth and carbon-intensive energy consumption, i.e. GHG emissions are continuously reduced, and the economy is continuously increasing.
- As the graph below shows, there are essentially three GHG emissions scenarios.

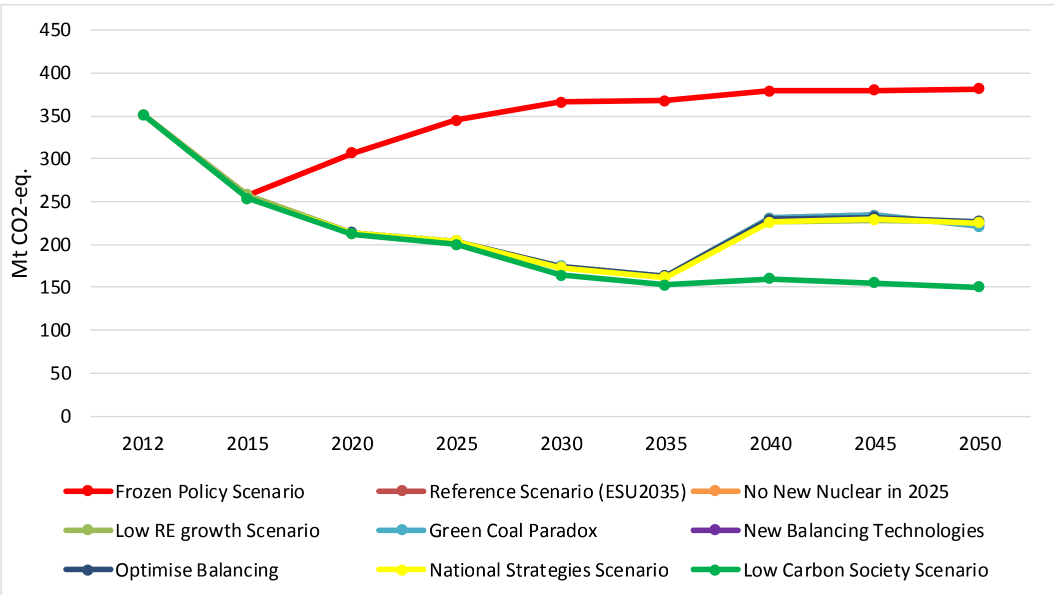

Figure 32. Greenhouse Gas Emission in all Scenarios

- Reduction of greenhouse gas emissions and growth of gross domestic product (GDP), will lead to a reduced carbon intensity of the economy.

- The figure below shows the carbon intensity of Ukraine's GDP, where only energy-related CO_2 emissions are presented, as the rest of the emitting sectors were not modelled. The same practice is used by the IEA.

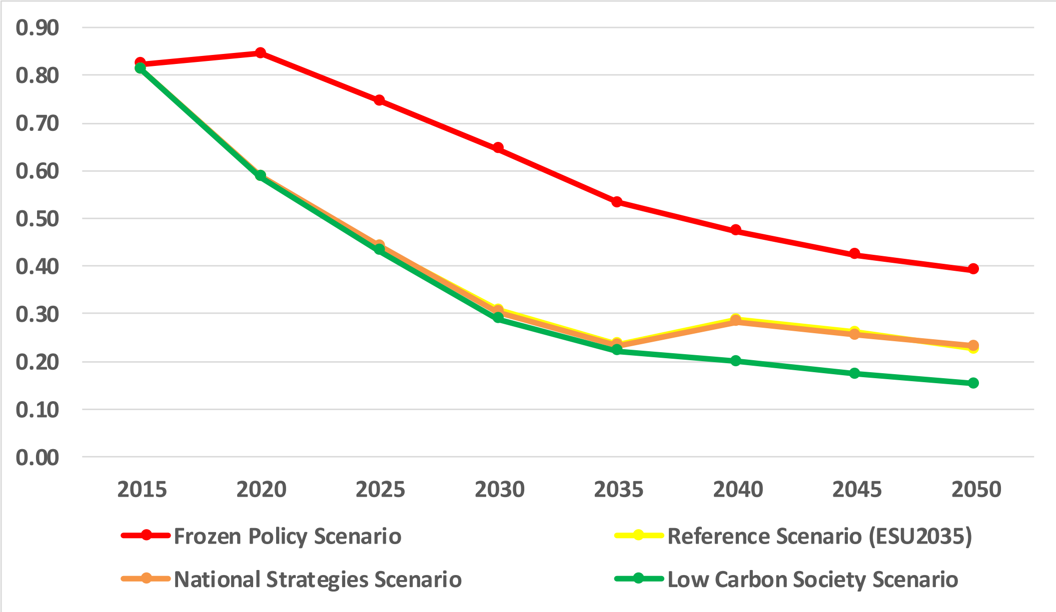

Figure 33. Carbon Intensity of GDP, tCO2e/$1000 GDP (PPP)

- The need for a significant reduction of GHG emissions will increase the role of nuclear power.
- According to model results, there is practically no difference between the total primary energy supply in the Reference Scenario and the GHG emission reduction scenario. However, up to 15 mtoe of coal products in 2040-2050 will be replaced by nuclear power.
- The EU also relies on low-carbon nuclear energy, but aims to reduce its share from 25% to 15% by switching to renewable energy [39].

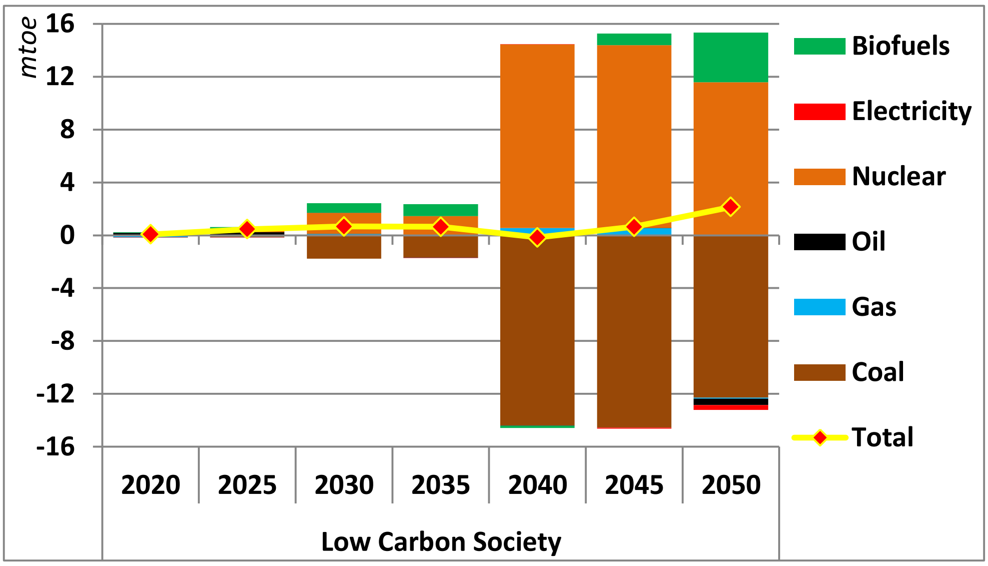

Figure 34. Differences in Total Primary Energy Supply between "Low Carbon Society" and Reference scenarios

- The results show that transforming the energy system to the Low Carbon Society scenario, which in 2050 allows no more than 20% increase of GHG emissions compared to the 1990 level (within the range of the current EU targets), electricity production has to be nearly 100 % fossil free.
- The share of renewables and nuclear account for almost 90%, with 28% - Nuclear, 26% - Wind, 23% - Solar, 7% - Bio-CHP and TPPs, and 5% - Hydro.

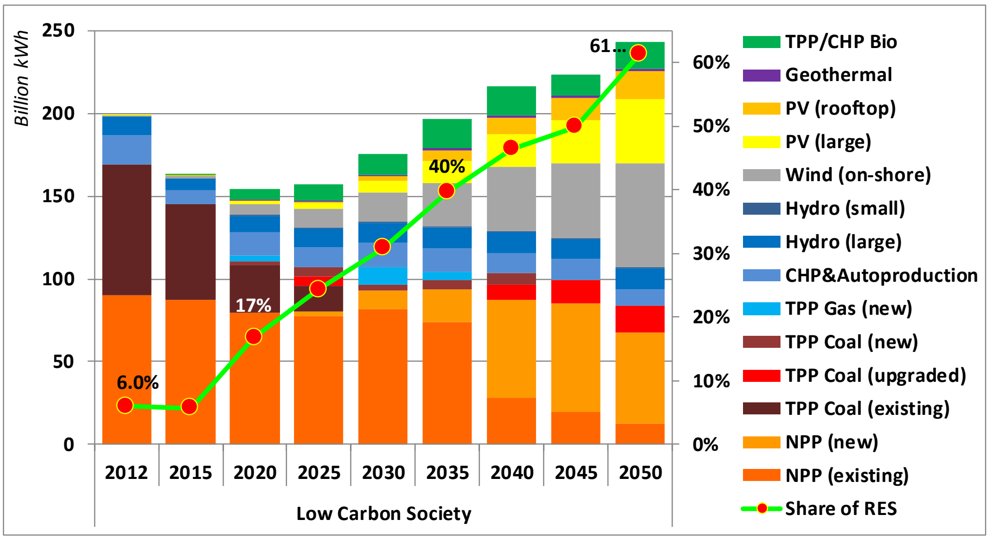

Figure 35. Electricity Generation in Low Carbon Society scenario

- The Low Carbon Society scenario, implying a significant reduction of GHG emissions, requires a significant increase in investments.
- The results show that by 2035 it will be necessary to attract 1-4 billion euros more each year than in the Reference scenario, and 4-6 billion euros more in the period 2040-2050.
- Operation costs can also increase substantially, which is primarily due to nuclear energy.

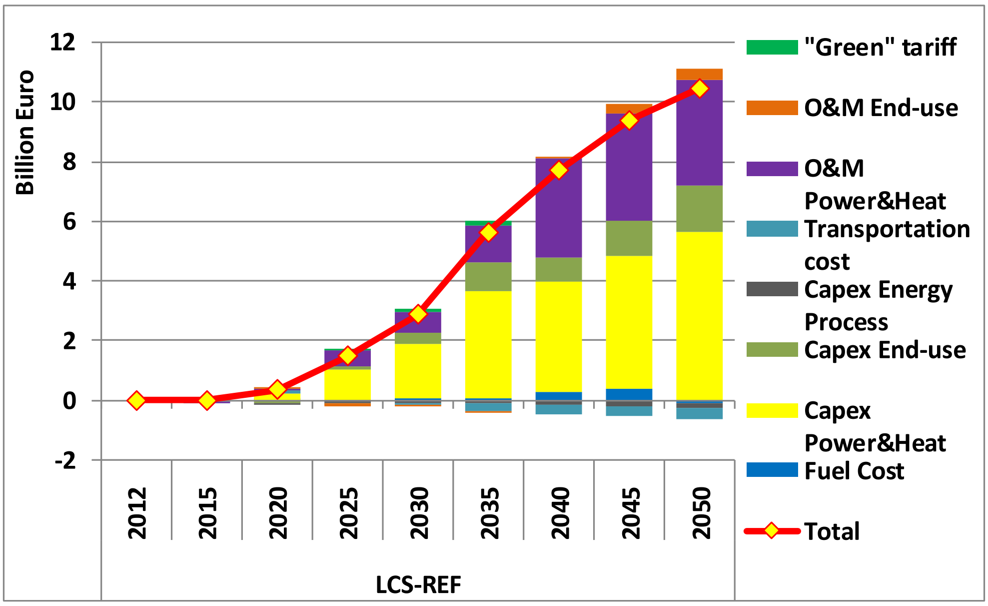

Figure 36. Differences in Total Operation System Cost between "Low Carbon Society" and Reference scenarios

Web-platform

In order to ensure the dissemination and a broad discussion around the results from TIMES-Ukraine for the range of analysed energy scenarios a web-platform (Figure 37) was created that contains the main results of the modelling. Platform access is available at https://www.timesukraine.tokni.com/.

Figure 37. Front page of the web-platform

Conclusions

The application of economics and mathematical methods and models in the fields of strategic energy planning allows making not only qualitative but also quantitative assessment of the introduced or planned policies.

The achievement of the targets set in ESU2035 depends in many ways on the socio-economic development of Ukraine.

There is some uncertainty in the ESU2035 about the development of the energy system for the long-term future up to 2050, in particular with regard to the development of nuclear energy. In the case of the permanent attainment of goals of the ESU2035, the construction of a new block (#3) at the Khmelnitsky NPP for domestic needs of Ukraine is redundant in 2025, while it can be feasible by 2030-2035 from a socio-economic perspective

Even under the moderate growth scenario of wind and solar (according to Ukrenergo, 2018), the total share of renewables in 2035 may reach 31%, which is more than currently foreseen by the ESU2035. The underutilisation of feasible potential of renewables after 2035 will force the use of more expensive thermal generation, which will significantly increase the total cost of the system.

Today's "green-coal paradox" can be addressed using modern balancing technologies and demand management, allowing for more rapid and reliable growth of renewable energy.

Simultaneous compliance with the goals of the ESU2035 and other national strategies will require additional investment. However, this will have a synergistic effect in terms of higher efficiencies in achieving targets and an overall lower system cost. The modelling results indicate that there is a potential for improving the procedures for harmonization of sectoral policies and the need to update the indicators of the ESU2035.

In order to achieve significantly more ambitious targets for the decarbonisation of the economy (Low Carbon Scenario), it is necessary to extend the relevant ESU2035 policies beyond 2035. Otherwise, the relaxation or complete abandoning of the decarbonisation of the energy system can quickly offset the achievements, i.e. the reduction of the energy intensity of the economy, as well GHG and other emissions.

References

[1] Cabinet of Ministers of Ukraine. Energy Strategy of Ukraine until 2035: Security, Energy Efficiency, Competitiveness 2017.

[2] UkrEnergo. Transmission System Development Plan for 2019-2028 [in Ukrainian] n.d.

[3] UkrEnergo. Report on the conformity assessment (adequacy) of the generating capacity [in Ukrainian]. 2018.

[4] Cabinet of Ministers of Ukraine. Resolution of the Cabinet of Ministers of 18 August 2017 No. 605-p On the Approval of the Energy Strategy of Ukraine until 2035: "Safety, Energy Efficiency, Competitiveness 2017.

[5] European Parliament, Council of the European Union. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). 2010.

[6] Podolets RZ, Diachuk OA. Strategic Planning in Fuel and Energy Complex Based on TIMES-Ukraine Model: Scientific Report. Kyiv: 2011.

[7] Ministry of Finance of Ukraine. Macroeconomic overview n.d.

[8] Loulou R, Goldstein G, Kanudia A, Lettila A, Remme U. Documentation for the TIMES Model Part I: TIMES Concepts and Theory 2016:1–151.

[9] Loulou R, Lehtila A, Kanudia A, Remme U, Goldstein G. Documentation for the TIMES Model Part II: Reference Manual 2016:1–384.

[10] State Statistics Service of Ukraine. Methodological recommendations for drawing up the energy balance n.d. http://www.ukrstat.gov.ua/metod_polog/metod_doc/2011/374/mp_eb.zip.

[11] United Nations Framework Convention on Climate Change. UNFCCC Resource Guide for Preparing the National Communications of Non-Annex I Parties. Module 4 Measures to Mitigate Climate Change. Bonn: 2008.

[12] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Long-term scenarios for development of nuclear energy sector of Ukraine through 2050. Kyiv: 2011.

[13] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Modeling and Economic Assessment of Long-Term Innovative Development of Nuclear Energy in Ukraine in the Context of Low Carbon Economy Development. Kyiv: 2018.

[14] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Forecast estimates of electricity consumption in Ukraine for the period up to 2035 and 2050 2015:7.

[15] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Demand for energy resources in short-term and medium-term perspective 2010:26.

[16] Diachuk O, Podolets R. Assessment of the achievement of some key indicators of the effectiveness of the Energy Strategy of Ukraine till 2035. Kyiv: 2017.

[17] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. The key goals of energy policy and scenario projections of energy supply for the new Energy Strategy of Ukraine 2016:37.

[18] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Future demand of coal in Ukraine. Gen. Plan Coal Sect. Dev. Ukr. through 2020, Kyiv: 2011, p. 108–73.

[19] Podolets R, Diachuk O. Calculation of the national energy efficiency target until 2020 and 2030 for Ukraine according to the Directive 2012/27/EU. Kyiv: 2017.

[20] Diachuk O, Chepeliev M, Podolets R, Trypolska G, Venger V, Saprykina T, et al. Transition of Ukraine to the renewable energy by 2050. Kyiv: Publishing house "Art Book" Ltd; 2017.

[21] Podolets R, Diachuk O. National Action Plan on Energy Efficiency through 2020 2015:57.

[22] Podolets R, Diachuk O. National Action Plan on Renewable Energy through 2020 2014.

[23] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Justifying the ratification of the Paris Agreement for the Ukrainian Parliament 2016:8.

[24] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Decarbonisation of energy sector of Ukraine. Ukr. 2050 Low Emiss. Dev. Strateg., Kyiv: 2017, p. 22–38.

[25] Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine. Forecasting GHG Emissions in Ukraine until 2030 and Beyond. Kyiv: 2015.

[26] Diachuk O. The new Energy Strategy of Ukraine till 2020: safety, energy performance, competition. Natl Secur Def 2015;1:17–8.

[27] Podolets R, Diachuk O. Integrated modelling of impacts of global chellenges on sustainable development of the energy sector of Ukraine. Kyiv: 2018.

[28] Podolets R, Borodina O, Diachuk O, Kyryziuk S, Trypol'ska G, Chepeliev M, et al. Development of Modelling Approaches for Analysis and Optimisation of Food, Water and Energy Nexus. Kyiv: 2018.

[29] Podolets R, Heets V, Ostashko T, Skrypnychenko M, Nykyforuk O, Blyzniuk V, et al. Economic, technical, technological and environmental imperatives of targeted energy development in Ukraine. Kyiv: 2018.

[30] Podolets R, Diachuk O, Kniazev S, Pys’menna U, Serebrenikov B, Trypol’ska G, et al. Integration factors in the transformation of the institutional environment and the structure of the energy markets of Ukraine. Kyiv: 2016.

[31] State Statistics Service of Ukraine. Statistical classification in Ukraine n.d. http://www.ukrstat.gov.ua/klasf/zm_kls.htm (accessed March 8, 2019).

[32] Community E. NACE Rev. 2. 2008.

[33] Eurostat. CPA Ver. 2.1 - Statistical classification of products by activity n.d. https://ec.europa.eu/eurostat/web/cpa-version-2.1 (accessed March 8, 2019).

[34] Eurostat. Combined Nomenclature (for international trade of goods an services) n.d. https://ec.europa.eu/eurostat/web/international-trade-in-goods/methodology/classifications (accessed March 8, 2019).

[35] Commission E. ENERGY STATISTICS OF THE EUROPEAN UNION : CONCEPTS AND DEFINITIONS ON ALL FLOWS (" AGGREGATES ") AND PRODUCTS 2015:1–242.

[36] State Statistics Service of Ukraine. Album of Forms of State Statistical Observations n.d. http://www.ukrstat.gov.ua/albom/albom_2019/2_2.htm#Енергетика (accessed March 8, 2019).

[37] World Bank. Commodity Markets Outlook n.d. http://www.worldbank.org/en/research/commodity-markets (accessed October 15, 2018).

[38] Ukraine Ecology and Natural Resources Ministry. Ukraine 2050 Low Emission Development Strategy. Kyiv: 2018.

[39] The European Commission. A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy 2018.