Transition towards High Share of Renewables in Ukraine: Linked Energy System and CGE Model Approach

Maksym Chepeliev, Oleksandr Diachuk and Roman Podolets[1]

Abstract. The adoption of the Paris Climate Agreement has become a symbolic decision for the world community. It will have a significant impact on the development of world economy and energy as well as particular countries since it aims to keep the average temperature rise on the planet well below 2°C (compared to the pre-industrial levels). To make it happen it is necessary for the energy sector to become carbon neutral. Therefore, a so-called "energy transition" from the fossil to renewable types of energy resources based on the principles of sustainable development is needed. In the case of developing countries, this task can be even more complicated than in the advanced economies, as governments need to provide an additional catching-up economic growth and social equity improvements. In this context, an economic impact is the key criteria to prioritize environmental policies, as their implementation should primarily be aimed at the increase of energy efficiency and greenhouse gas (GHG) emissions reduction, but in an economically and socially acceptable way.

In this paper, we explore the pathways for transition towards high share of renewables in Ukraine, which faces significant economic and environmental challenges. We use the soft-linkage of the energy system TIMES-Ukraine and Ukrainian computable general equilibrium models, which allows us to estimate an economy wide and environmental implications of Ukraine's long-term transition towards 91% share of renewables in final energy consumption by 2050.

As results show, further maintenance of the existing highly inefficient Ukrainian energy system is even more expensive than implementation of the renewable energy development policies. With initially low energy efficiency rates, long-term transition towards high share of renewables in Ukraine provides a good opportunity to explore "double dividends", benefiting both the economy and the environment. According to our estimates, while GHG emissions reduce by 76% in 2050 relative to the 2012 level, GDP may increase up to 14-16% by 2050 in case of efficient policies implementation.

Key words: Ukraine, renewable energy sources, energy transition, computable general equilibrium modelling, energy system modelling, double dividends.

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1 Introduction

Humanity's pressure on the Planet Earth has crossed safe operating boundaries on several directions (Steffen et al. 2015). One of such dimensions includes climate change, with both advanced and transition economies facing challenges of the low carbon development. In this context, the adoption of the Paris Climate Agreement has become a symbolic decision for the world community (UNFCC, 2017). It will have a significant impact on the development of world economy and energy as well as particular countries since it aims to keep the average temperature rise on the planet well below 2°C (compared to the pre-industrial levels). To make it happen it is necessary for the energy sector to become carbon neutral. Therefore, a so-called "energy transition" from the fossil to renewable energy sources (RES) based on the principles of sustainable development is needed.

In the case of developing countries, this task can be even more complicated than for the advanced economies, as governments need to provide an additional catching-up economic growth and social equity improvements. In this context, an economic impact is the key criteria to prioritize environmental policies, as their implementation should primarily be aimed at the increase of energy efficiency and greenhouse gas (GHG) emissions reduction, but in an economically and socially acceptable way. While transition economies often face much more significant environmental challenges than the developed countries, their initial position often provides much better opportunities for environmental, social and economic development. In some country cases there are even prerequisites for reaching the "double dividends" effect (Parry and Bento, 2000), by improving both environmental and economic parts. Based on the current situation and developments, Ukraine seems to be the perfect candidate for such case. According to the World Bank (WB, 2017b), it has 5th highest GDP carbon intensity in the world, while Ukraine's share of renewables in the total final energy consumption was only 4.2% in 2014, almost five times lower than world average share of 20% (IEA, 2018). Number of policy initiatives, implemented by Ukrainian government in recent years (Chepeliev et al., 2018), serve a good starting point, but are not sufficient for the effective long-term "energy transition".

In this paper, we explore the pathways for transition towards high share of renewables in Ukraine, which faces significant economic and environmental challenges. We use the soft-linkage of the energy system TIMES-Ukraine and Ukrainian computable general equilibrium models, which allows us to estimate an economy wide and environmental implications of Ukraine's long-term transition towards 91% share of renewables in final energy consumption by 2050.

The rest of the paper is organized as follows. Section 2 provides an overview of the Ukrainian energy sector and some international comparisons. Section 3 discusses the methodological approach. In particular, it provides an overview of the Ukrainian general equilibrium model (UGEM) and energy system TIMES-Ukraine model, as well as discusses their soft linkage. Section 4 provides an overview of the baseline and renewable energy scenarios. Section 5 discusses energy and environmental impacts of the renewable energy scenario. In Section 6, we provide an overview of the economic impacts of the transition to high share of renewables in Ukraine. Finally, Section 7 concludes.

2 Current state of the Ukrainian energy sector

While aggregate share of fossil fuels in the Ukraine's total primary energy supply is higher than in the EU, but lower than in OECD, energy balance composition significantly differs both from EU and OECD indicators (Table 1). In particular, the use of coal in Ukraine is significantly higher than in the OECD and EU, although close to the World average. At the same time, the share of crude oil and oil products use in Ukraine is over three times lower than the EU and OECD. This follows from the fact that in Ukraine oil products are almost exclusively used in the transportation sector, while are not exploited in the electricity and heat generation activities (contrary to the EU and OECD). Another distinctive feature of the Ukrainian energy balance is relatively high share of nuclear energy, which is over five times higher than world average and 50% higher than EU average (Table 1). Currently there are policy debates on whether such high share of renewables should be preserved in the long run.

Table 1. Key energy balance indicators for Ukraine, OECD, EU and the World average in 2014

Total primary energy supply	World		OECD		EU		Ukraine	
	thousand toe	%	thousand toe	%	thousand toe	%	thousand toe	%
Coal	3,918,491	28.6%	1,012,463	19.2%	268,433	17.2%	35,576	33.7%
Crude oil	4,349,857	31.8%	2,061,714	39.1%	591,918	37.8%	3,043	2.9%
Oil products*	-64,557	-0.5%	-180,603	-3.4%	-82,930	-5.3%	7,645	7.2%
Gas	2,900,579	21.2%	1,343,845	25.5%	342,846	21.9%	33,412	31.6%
Nuclear energy	661,353	4.8%	516,273	9.8%	228,456	14.6%	23,191	21.9%
Hydro energy	334,945	2.4%	120,471	2.3%	32,248	2.1%	729	0.7%
Geothermal, solar, etc.	181,072	1.3%	98,024	1.9%	40,069	2.6%	134	0.1%
Biofuel and waste	1,412,908	10.3%	299,787	5.7%	141,641	9.1%	1,934	1.8%
Electricity*	2,383	0.0%	395	0.0%	1,333	0.1%	-725	-0.7%
Heat energy	2,096	0.0%	899	0.0%	962	0.1%	745	0.7%
TOTAL	*13,699,127*	*100%*	*5,273,268*	*100%*	*1,564,975*	*100%*	*105,684*	*100%*

* Negative values indicate that exports exceed the amount of imports and domestic production.
Source: authors estimates based on the IEA (2018).

Since 2005, Ukraine has reduced its total primary energy supply (TPES) by over 25% (in 2014), with major reduction associated with natural gas consumption (Figure 1). Key drivers of such a sharp TPES reduction include economic recession, as well as military and political conditions. At the same time, market transformations accompanied by energy efficiency improvements and GDP structural shifts towards higher services share have also contributed to these trends. Since 2007, due to the decline in domestic oil refinery, crude oil supply was substituted by the import of oil products.

The final energy consumption (FEC) in Ukraine experienced a sharp drop of the industries share (from 45% in 2005 to 35% in 2014). At the same time, the share of residential consumption remained almost unchanged between 2005 and 2014 and equaled 35% (except for 2007-2008, when households' shared reduced to 29-30%). Over the analyzed period, the steady growth was observed for the services sector, as its share in FEC has increased from 3% in 2005 up to 8-9% in 2012-2014.

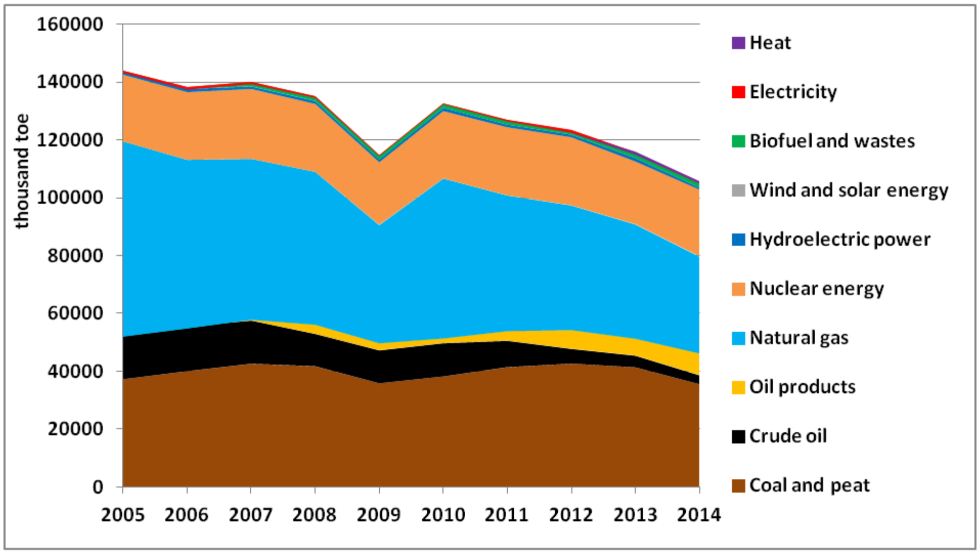

Figure 1. Dynamics of total primary energy supply in Ukraine

Source: authors estimates based on the IEA (2018).

While there has been a notable increase in the share of RES in FEC since 2005, Ukraine is still far behind world average indicators, as well as most Eastern European countries (Figure 2). In particular, Ukraine's RES share in GFEC is five times lower than world average with especially large gap in case of biofuels and waste-based energy generation. Despite decrease of Ukraine's GDP energy intensity (by almost 50% since 2005) and carbon intensity (by over 20% since 2005), Ukraine's economy still far behind World average, OECD and EU indicators, as well as Eastern European countries (Appendix A). While on the one hand such picture represents some lost opportunities in the preceding years, on the other hand it also indicates significant potential for the forthcoming developments, which can and should be explored in the nearest future.

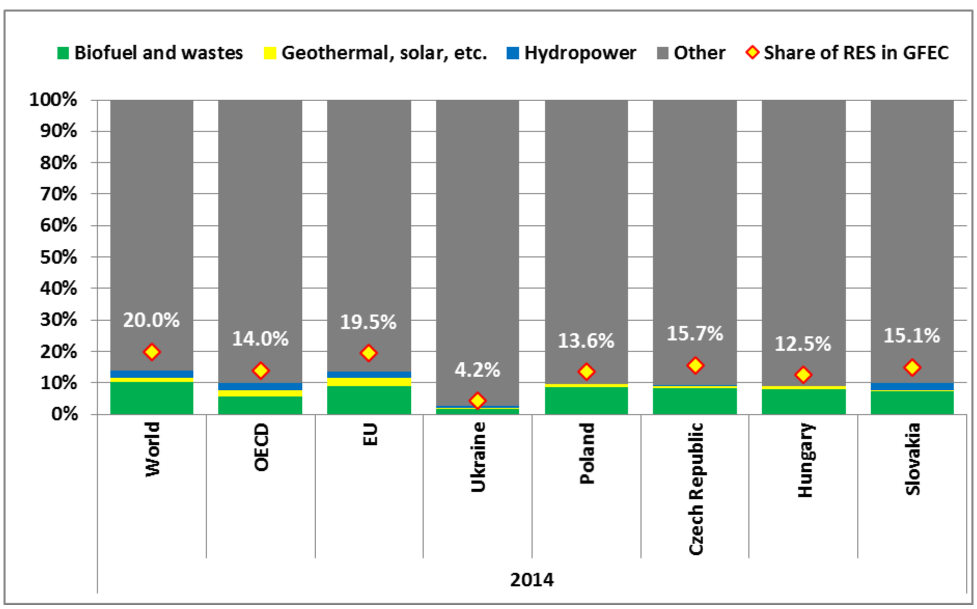

Figure 2. RES share in the gross final energy consumption (GFEC) in 2014

Source: authors estimates based on the IEA (2018).

3 Methodological approach

This section describes the general methodological approach, which we use for the assessment of Ukraine's transition towards high share of RES by 2050. We start with an overview of the energy system TIMES-Ukraine model, which we use for the assessment of policy impacts on the energy sector and environment. We further describe the Ukrainian general equilibrium model (UGEM), which is used to estimate macroeconomic and sectoral impacts of the RES policies. We also discuss the soft-linkage of TIMES-Ukraine and UGEM models, outlining some limitations of the applied methodology and possibility for further improvements.

3.1 TIMES-Ukraine model

TIMES-Ukraine is a typical linear quasi-dynamic optimization perfect foreseen energy system model of MATKAL/TIMES family (Loulou et al., 2004). It provides a technology-rich basis for estimating energy dynamics over a long-term horizon (Podolets and Diachuk, 2011). Ukrainian energy system is divided in the model into seven sectors: energy supply; generation of electricity and heat; industry; households; services; transport and agriculture. The industrial sector is represented by manufacturing only, since mining of energy resources and power sector are the sources of energy supply, and fuel consumption for own needs and transportation losses are not accounted in final energy consumption. Industrial sectors are divided into two categories by the level of energy intensity. Energy-intensive sub-sectors are presented in terms of technologies for manufacture of the main types of their products, i.e. final energy demand is introduced as a unit of commodity production. Energy intensive technological processes include production of iron and steel, chemical production, manufacture of other non-metal mineral products, production of pulp and paper. For other industrial sub-sectors the structure of energy flows is standard according to the four types of general processes: electric engines, electrochemical processes, thermal processes and other processes. Corresponding technologies cover energy demand for technological heat, machine drives and other processes.

The transport sector in TIMES-Ukraine is represented by the types of transportation: road, railway, pipelines, aviation and navigation. Respectively, energy services, which are provided by technologies of road and rail transport include transportation of passengers and freights. Pipeline transportation demand is quite specific as it relies on oil and gas internal demand and projection of transit. Representation of other transport technologies is simplified. 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. Figure 3 provides a simplified overview of the energy system representation in TIMES-Ukraine model.

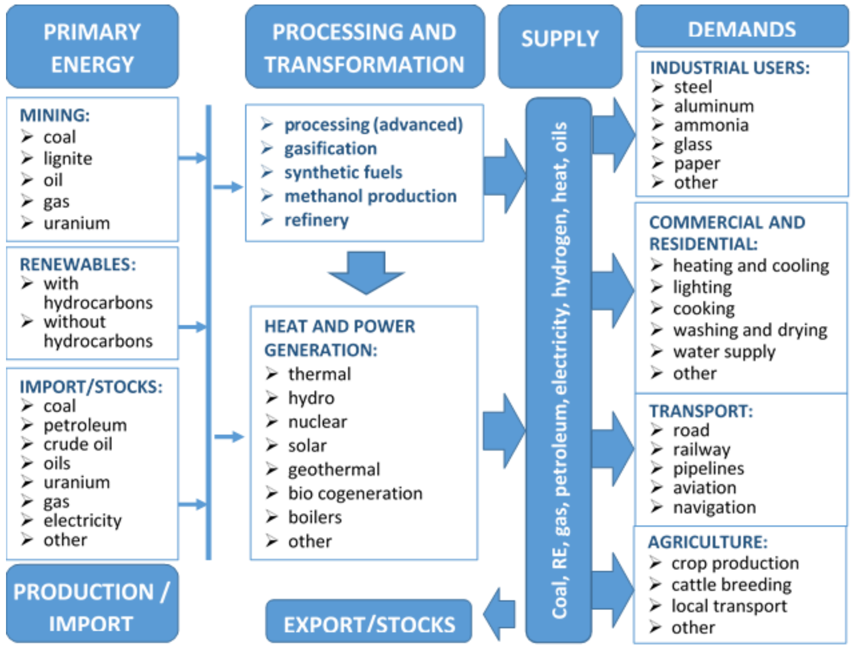

Figure 3. Representation of the energy system in TIMES-Ukraine model
Source: Authors.

Energy system models, like TIMES-Ukraine, are usually used for long-term analysis of energy system development scenarios. By changing the assumptions on useful energy demands, technologies, prices or other exogenous variables baseline path is developed. On the next step, policy scenarios are designed by imposing additional constraints or targets for the energy system. In this study, we first develop a baseline scenario (BAU) and then impose renewable energy development targets (energy system constraints/targets) to simulate the implementation of RES scenario. For each scenario (baseline and energy policy) the model estimates the least cost (or maximum surplus) trajectory of the system, i.e. energy supply and demand by sector and fuel type, energy prices, the optimal technology mix etc. Following such data, we can further explore the cost of the selected policy pathways, identify the most efficient technologies and investigate energy system transformations.

While such approach provides relatively deep view into the energy system, energy policy costs and implications for energy and environment, it does not link them to the macroeconomic and social context. At the same time, in many cases assessment of the social and economic impacts of energy policies can be even more desired than implications for the energy sector per se. Therefore, to complement the methodological framework this study also uses dynamic computable general equilibrium model for Ukraine (UGEM), which is discussed in a more detail in the next Section.

3.2 Dynamic UGEM model

As energy policy impacts go far beyond energy sector, we also need a modelling tool that would provide us a top-down view of the national economy. For this reason, in addition to the TIMES-Ukraine, we use dynamic UGEM model. Current version of the model is based on the static model described in Chepeliev (2014) and dynamic mechanisms introduced in TRPC (2014). It is a typical single-country recursive dynamic computable general equilibrium model with producers divided into 40 sectors and households disaggregated into 10 groups according to their income level. Fig. 4 represents key circular flows in the UGEM.

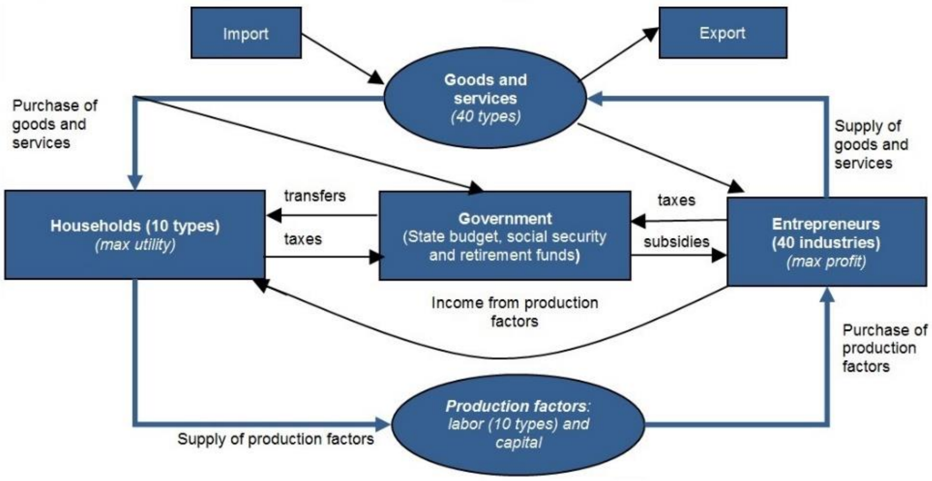

Fig. 4. Circular flows in the UGEM model
Source: Authors.

It is assumed that producers are maximizing their profits and households are maximizing utility. Enterprises are producing goods and providing services, using capital, labor and intermediate products. Domestic producers sell their products at the national or international markets. In the domestic market, final goods and services are purchased by households, government or contribute to the gross capital formation. Households receive labor and capital payments, as well as money transfers. Government earns revenue and receives tax payments, providing transfers and subsidies to households and producers. To represent production and consumption processes in the UGEM, constant elasticity of substitution[2] (CES) production functions are used. In the case of main production block, a multi-nested CES function is used (Figure 5), which distinguishes energy and non-energy commodities, as well as value added component.

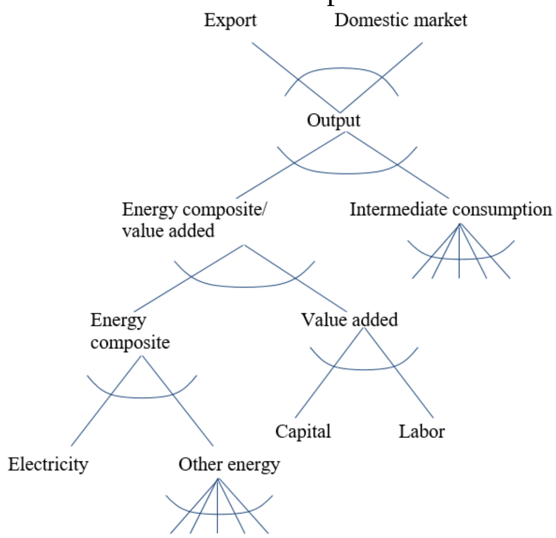

Fig. 5. Production block nesting structure in the UGEM model
Source: Authors.

[2] Elasticity of substitution indicates relative consumption quantities changes resulting from the corresponding relative price changes.

UGEM is formulated as a static model and solved sequentially over time. Capital stock is updated in every period with a capital accumulation equation (1).

$$CS_{i,t+1} = (1-\delta)CS_{i,t} + Inv_{i,t}, \tag{1}$$

$CS_{i,t+1}$ is the value of capital stock at the beginning of the period $t+1$ in the i-th sector; δ equals depreciation rate; and $Inv_{i,t}$ is volume of investments in the i-th sector during the period t.

Labor supply is changing at the same rate as a total population according to the equation (2).

$$LS_{t+1} = (1+ng_t)LS_t, \tag{2}$$

LS_t is the number of people employed during the period t and ng_t is the population change rate during t.

Energy sector in the UGEM is represented by 7 subsectors: coal mining, extraction of the natural gas and oil, coke and oven products, petroleum products, electricity production and distribution, distribution of natural gas, heat and hot water supply. Key input data for the model is sourced from Input-Output tables, households' surveys and National accounts. It is organized in the form of Social Accounting Matrix[3] based on the 2013 data and further updated to the 2015 using RAS method[4].

Computable general equilibrium models, like UGEM, are usually used for "What-If" type of analysis. After the input data is collected and model is calibrated to replicate the base year equilibrium, policy scenarios are designed in a way that changes values of the exogenous variables of the model. As a result, an initial equilibrium is altered and a new equilibrium (or set of equilibriums in the case of dynamic model) is estimated. While UGEM model is able to assess the economy wide impacts of energy and environmental policies (e.g emission taxation), it does not represent energy sector in such a detailed was as TIMES-Ukraine model does. To this extent an environmental policy analysis can benefit from the linkage of these two models, which we further discuss in the next Section.

3.3 Model linkage

To provide an environmental and economic assessment of Ukraine's transition towards high share of renewables, we use a soft-linkage of TIMES-Ukraine and UGEM models (Fig. 6). *First*, we calibrate both models to the single set of macroeconomic, demographic and other assumptions included into the baseline path. In this way, we ensure a harmonized starting point for the model linkage. *Second*, we provide an assessment of the renewable energy transition pathway using TIMES-Ukraine model. In particular, we set the target share of renewables in 2050 (91% in final energy consumption) and let the model estimate the most cost-efficient way to achieve this target. Apart from energy and environmental effects of such simulation, we are particularly interested in the amount of additional investments required to achieve the RES share target, as well as efficiency improvements that occur due to the implementation of new/better technologies. At this stage, TIMES-Ukraine model is only able to estimate the costs of corresponding measures/technologies, but does not give any information on the sourcing of these costs or their viability for the national economy. Therefore, on the *third* step, we feed in estimated investment costs and sector-specific energy efficiency changes to the UGEM. We assume that additional investments are provided by producers themselves, thus changing (increasing) the price of corresponding commodity. We do

[3] Social accounting matrix definition and examples can be found in Breisinger et al (2009).

[4] For the discussion of RAS method, see Trinh and Phong (2013).

not assume any external funding sources, such as foreign borrowings. We further use this investment and technological changes as exogenous shocks for the UGEM to provide an economic impact assessment of the RES transition path in Ukraine.

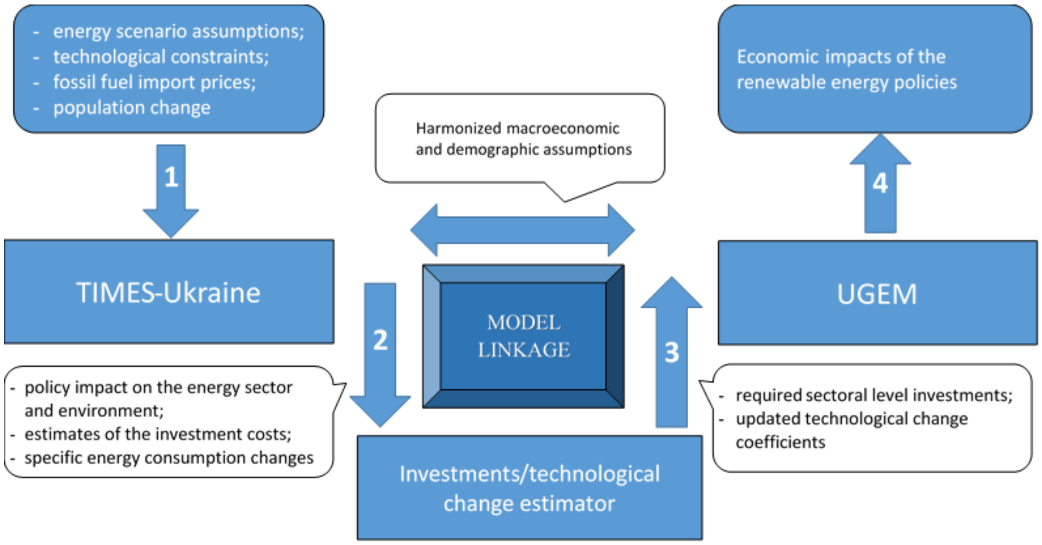

Figure. 6. TIMES-Ukraine and UGEM models linkage
Source: Authors.

Such approach is of course not without limitations and need for further improvements. First, under the current set up we use only a one way link – from TIMES-Ukraine to UGEM. In other words, TIMES-Ukraine simulation serves as a source of policy shocks for UGEM model. A more consistent way of model linkage should include iterative data exchange between models until outputs of the one model would not match inputs of the other within the defined level of tolerance. Second, in the current UGEM sectoral structure we do not have explicit representation of the renewable technologies, which are fully covered by TIMES-Ukraine technological disaggregation. Although, this should not be viewed as a major drawback, such representation would allow for a more consistent sectoral/technological mapping between two models. In terms of policy framework set up, more attention can be given to the sourcing of additional investments. As noted before, we assume that all additional costs associated with RES transition are covered by energy users (both households and industrial users), therefore no external funding is introduced. In this context some alternative assumptions on investment sourcing may be worth to explore. Nevertheless, we consider an approach used in this paper to be more inclusive than a stand alone use of both models.

As has been shown by numerous studies, results of the CGE model simulations can significantly depend on the values of exogenous parameters, in particular, elasticities of substitution and transformation. Sometimes, variation of these parameters can even change the results qualitatively, for instance, by turning net welfare gain into loss under the trade policy experiment (Taylor and von Arnim, 2006). Therefore, in this study we accompany all UGEM-based estimates with error bars. We follow a Systematic Sensitivity Analysis (SSA) approach developed by Arndt and Pearson (1998) and apply a 50% variation to all 12 groups of substitution and transformation elasticities in the UGEM model (Chepeliev, 2014). We further derive 95% confidence intervals and indicated them using error bars. We use a triangular distribution for parameters variation and Strouds quadrature for approximation. To derive confidence intervals we assume normal distribution of the elasticities.

4 Baseline and renewable energy scenarios

In this Section, we provide an overview of the baseline (BaU) and renewable energy (RES) scenario, which includes 76% GHG emissions reduction relative to the 2012 level by 2050 and is consistent with limiting global warming to well below 2^{o}C. We focus on the macroeconomic and demographic assumptions that underline both scenarios, as well as discuss some energy mix and emission profiles of the BaU path. BaU scenario is based on the current energy policy efforts and serves as a reference for model calibration, while RES policy is imposed on the BaU path. For more details on the potential and cost of renewable energy sources used in the current paper, an interested reader is referred to Diachuk et al (2017).

4.1 Business as usual scenario

In terms of macroeconomic drivers, we assume an average 4% GDP growth rate over 2016-2050, with higher growth rates associated with agriculture and construction, but without any significant sectoral shifts by 2050 (Appendix B; Diachuk et al., 2017). For the demographic forecast, we assume -0.4% annual average population change over the same period, which corresponds to the central scenario provided by the Ukrainian Institute of Demography and Social Studies (PIDSS, 2014). It is assumed that domestic and world energy prices change in line with World Bank forecasts during 2015-2035 (WB, 2017a) and 2030-2035 growth rate continues until 2050.

BaU scenario is developed under the assumption of no fundamental changes in the energy system, i.e. current trends will continue and no new policies will be implemented (IPCC, 2017). Thus resulted fuel mix and energy demand are fully defined by the demand drivers. Meanwhile gradual replacement of technologies still takes place, as the life time of existing equipment terminates. The cost of new technologies that replace the old ones decreases in time, while their efficiency increases.

Nevertheless, with a highly carbon-intensive economy like Ukraine, BaU path brings significant increase in the GHG emissions, as they grow by almost 68% in 2050 relative to 2012 levels (Figure 7). It should be noted that in this study we consider only industrial processes and energy sector related GHG emissions in terms of IPCC definitions. In 2012, they amounted to 88% of total GHG emissions in Ukraine (Diachuk et al. 2017).

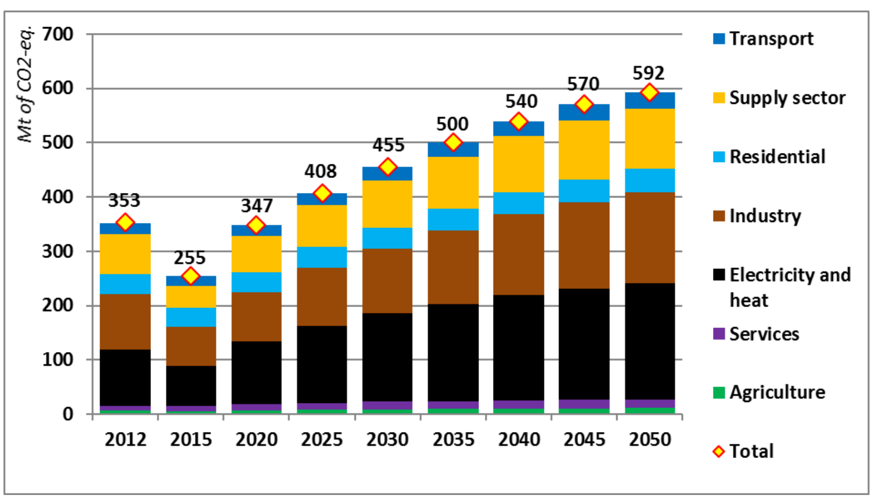

Fig. 7. Forecast of the GHG emissions in Ukraine according to the BaU scenario
Source: Developed by authors using TIMES-Ukraine model.

Sharp reduction in the GHG emissions during 2013-2015 is associated with severe economic recession and violation of Ukraine's territorial integrity. Within the BaU path we assume that state sovereignty would be restored by 2020, therefore GHG emissions grow faster during this transition phase, relative to post-2020 period. At the same time, maintenance of the highly energy intensive economy like Ukraine would require significant expenses in the long-run (Figure 8). Due to the high level of depreciation, significant investments are required just to replace the existing technologies without any significant upgrade.

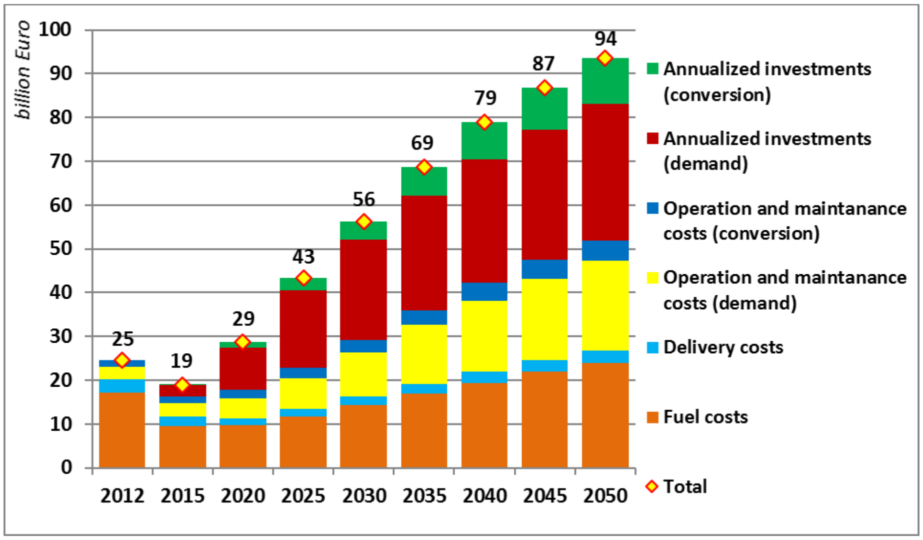

Figure 8. Energy system costs under the BaU scenario (constant 2012 EUR)
Source: Developed by authors using TIMES-Ukraine model.

Following the BaU scenario, Ukraine's share in global GHG emissions would almost double relative to 2015 level and reach 1.4% by 2050 under the assumption of world Reference CO_2 emissions (US EIA, 2016). This would impose significant costs for natural environment, domestic health system, local ecosystems, energy system itself and consumers in general. Such scenario may also increase a probability of technological and environmental disasters/accidents (both on national and local levels). With almost five-fold increase in the energy system costs and 2.3 times rise in GHG emissions, BaU scenario suggests that implementation of RES transition pathway in Ukraine would primarily serve its national economic, social and environmental interests.

4.2 RES scenario

The main goal of the RES scenario is to analyze benefits and challenges of moving towards high share of renewables in Ukraine – 91% in final energy consumption. The main hypothesis is that in order to limit the global warming much below 2°C compared to pre-industrial level, it is extremely important to ensure the "energy transition" on the principles of sustainable development from fossil to renewable energy sources, with further increase of energy efficiency.

In RES scenario the largest possible share of renewables is key driving force for energy system transformation. RE scenario also assumes implementation of the Energy Community acquis (EC, 2017). With such a stringent constraints, this scenario should be considered more as an exploratory assessment of RE potential and energy system flexibility, rather than guideline for specific policy measures. At the same time as our results show, RES scenarios can be considered as a feasible policy perspective for Ukraine in the long-run.

It should be noted that while most similar studies focus on a complete phase out of fossil fuels, in case of Ukraine, we take a 91% RE share as an economically feasible target. The main reason behind this decision is that according to our analysis further increase of the RE share in GFEC results in the exponential growth of additional investments and total system costs. Numerous assumptions regarding potential of renewables in Ukraine underlie the RES scenario exploited in this paper. For their detailed discussion, an interested reader is referred to Diachuk et al (2017).

In terms of GHG emissions, RES scenarios is much more stringent than current Ukrainian NDC contribution (Figure 9). To estimate the correspondence between RES scenario emissions and temperature paths, we have applied an approach used by Climate Interactive (CI, 2017). We take Ukrainian NDC level as a peak of GHG emissions in 2030 and apply required emission reduction rates for developing country. Under such approach, RES scenario corresponds to the 1.5°C target (Figure 9). While Ukrainian NDC level may seem high compared to the actual 2012 (pre-war) emissions, relative to the 1990 GHG emissions it is almost 40% lower. In addition, a significant emissions drop during 1990-2000 was achieved almost solely by sharp economic recession, therefore in case of rapid economic recovery without significant structural shifts NDC may serve as a reasonable upper bound for possible emission peak. At the same time, it should be noted that while Ukraine's NDC contribution indicates that this target will be revised after the restoration of country's territorial integrity and approval of post-2020 economic strategies, under current formulation Ukrainian NDC is not even closely compatible with 2°C target.

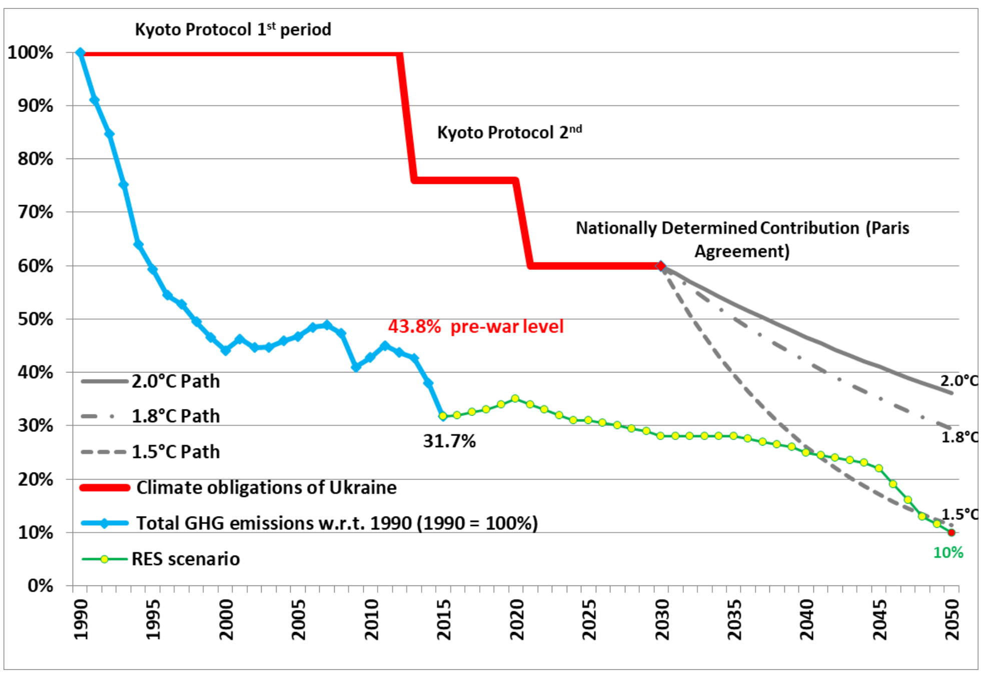

Figure 9. Emission under RES scenario and climate obligations of Ukraine

Source: TIMES-Ukraine model estimates; GOU (2015); CI (2017).

Note: Estimates of the temperature paths for Ukraine are based on the CI (2017) methodology. Ukrainian NDC level is taken as a peak emission in 2030, afterwards annual reduction rates of 3.5% (in case of 1.8°C path) and 8% (for 1.5°C path) are applied to derive corresponding emission levels by 2050.

5 Energy system and environmental effects

Achievement of the 91% RES share in the FEC requires significant transformations in the Ukrainian energy system. They include not only changes in generation mix, but also reduction in demand. In particular, implementation of the energy efficiency measures proofs to be the most cost efficient set of policies towards low emission development in Ukraine (Figure 10). Implementation of such set of measures within the RES scenario allows to decrease the final energy consumption by 42% in 2050 relative to the BaU path.

While industrial sector would remain the larges final energy consumer, its level of consumption in 2050 would be even lower than in 2012. Industrial sector FEC would peak in 2040 and decrease afterwards under RES scenario (Figure 10). Share of the fossil fuels would be reducing starting from 2025, while total share of renewables can reach 88% by 2050. At the same time, electrification of the industrial sector can be major challenge, as it requires the replacement of almost all existing energy intensive industrial equipment with a new one that uses only electricity and heat.

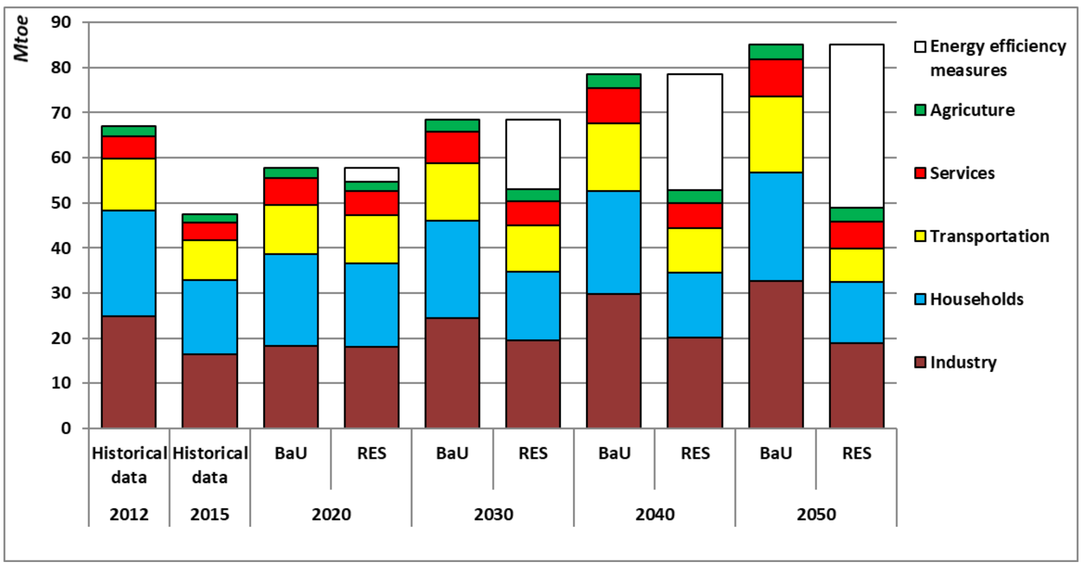

Figure 10. Final energy consumption by users under BaU and RES scenarios
Source: TIMES-Ukraine model estimates.
Note: "Mtoe" stands for million tons of oil equivalent.

Energy transition under the RES scenario would also require rapid electrification of the residential sector and the whole economy. In particular, electricity share in FEC would increase from 17% in 2012 to 56% in 2050 with 52% of the electricity being generated from renewables. Biofuels and waste, RES-based central heating and solar energy would contribute another 39% of the final energy consumption on the national level (Figure 11). Under the RES scenario, households could completely abandon direct use of fossil fuels by 2050. Following electrification in the transportation sector, its energy efficiency can improve by 56% in 2050 relative to the BaU path, while energy sources would be distributed almost proportionally between electricity from renewables and biofuels (including waste). The latter one would be primary energy source for air and water transportation activities. According to RES scenario, final energy consumption by services would show a slight increase in 2050 relative to 2015 levels (less than 20%), although it would be 29% lower than in the baseline scenario with most contribution coming from the energy efficiency measures (thermal insulation of buildings, use of high-efficient electric equipment). According to our estimates, in case of agriculture, energy efficiency potential is not very high (around 5% in 2050 w.r.t. BaU). In case of agriculture, RES scenario shows a possibility of reaching 96% share renewables in FEC by 2050 with biofuels and waste contributing up to 70%. Our estimates do not show any major energy-related technological improvements in this sector, but mostly switch from petroleum products to biofuels (biodiesel, bioethanol) for motor vehicles and agricultural machines, as well as increasing share of "green" electricity and heat. While our results do not support high economically feasible potential for energy efficiency measures in agriculture in Ukraine, this question requires a deeper investigation.

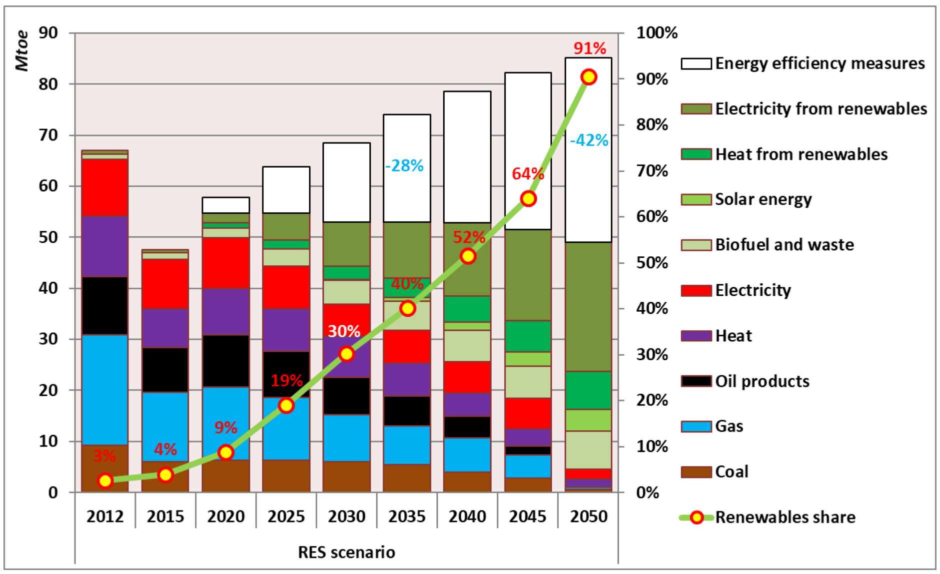

Figure 11. Final energy consumption by sources and renewables share under the RES scenario
Source: TIMES-Ukraine model estimates.
Note: "Mtoe" stands for million tons of oil equivalent.

As depicted at Figure 12, RES scenario is associated with significant change in the electricity generation mix. Existing nuclear plants would be gradually decommissioned, while new nuclear units (under current forecasts) would not be able to compete with other generation technologies. As a result, new coal power plants become a basis of the load curve, while 2/3 of the demand would be covered by renewables. As RES scenario shows (Figure 12), apart from hydro energy, other renewables (solar, wind, biomass) have even higher technically feasible potential. Wind and solar power plants would contribute the largest share of electricity generation, accounting together for over 80% in 2050 (Figure 12).

Implementation of their potential would require additional expansionary measures and technical solutions. In particular, they should include development of the grid and long-term electricity storage technologies, implementation of the demand control system for the load curve smoothing, further development of the transmission capacities and elimination of operational constraints that renewable generation faces for the integration to the national energy system. Additional expansionary measures should include introduction of tariff incentives for the renewable energy co-generation and development of the attractive funding opportunities. The latter one is especially important for Ukraine, as under the current conditions, high level of the green tariffs is almost fully offset by unaffordable funding options.

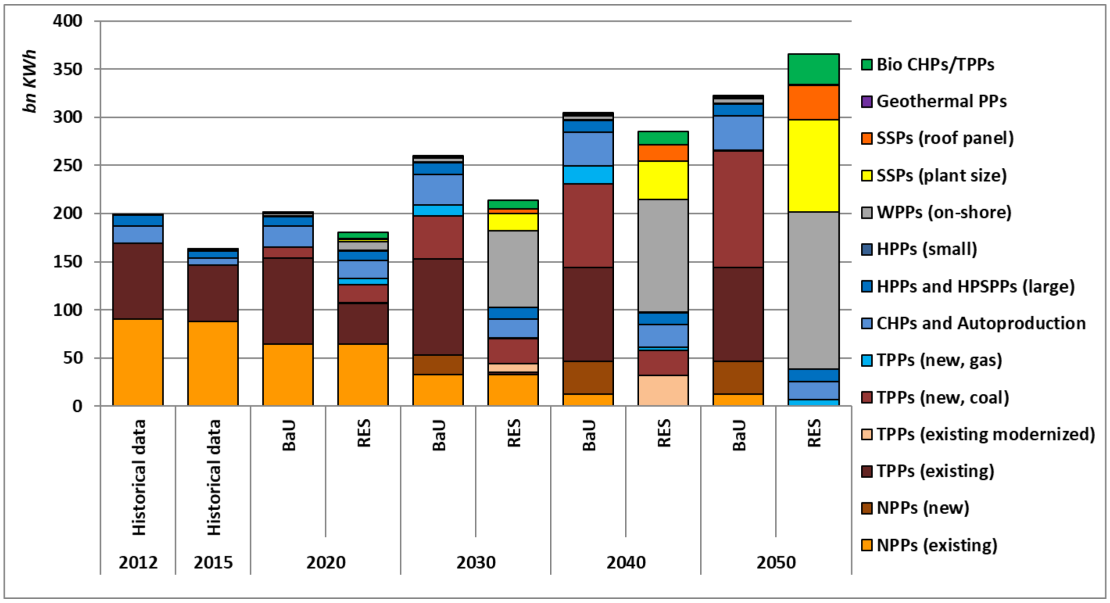

Fig. 12. Electricity generation mix under BaU and RES scenarios

Source: Developed by authors using TIMES-Ukraine model.

Note: CHPs – combined heat and power plants; TPPs – thermal power plants; SPPs – solar power plants; WPPs – wind power plants; HPPs – hydro power plants; HPSPPs – hydro pumped storage power plants; NPPs – nuclear power plants.

One of the key features of the RES scenario is that this policy achieves absolute decoupling of GDP from GHG emissions and energy use. This feature is especially important for the developing country like Ukraine as with relatively high GDP growth rates transition economies are expected to be the main contributors towards growing pressure on the Earth system in the nearest future (Steffen et al. 2015). In case of RES scenario, GHG emissions are estimated to be six times lower than under the BaU path in 2050 (Figure 13).

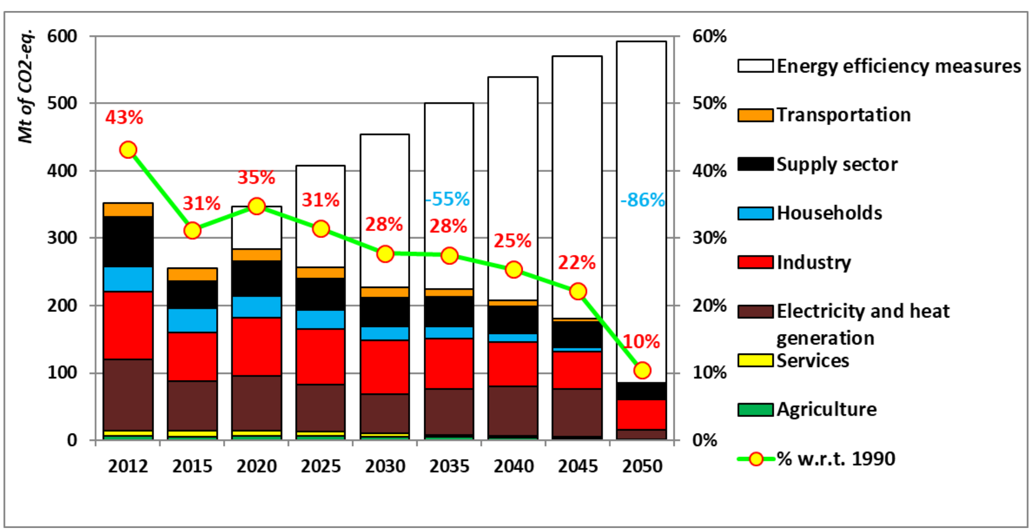

Fig. 13. GHG emission under the RES scenario

Source: Developed by authors using TIMES-Ukraine model.

According to our estimates, total energy system costs, which include capital investments, maintenance costs, subsidies (feed-in tariffs) and costs of fuel, would grow rapidly after 2020 within the BaU path (Figure 14). Substantial relative increase would be observed in case of maintenance costs, as well as final energy consumption technologies. The latter one have a significantly lower lifetime relative to electricity and heat generation technologies and therefore should be replaced with a higher frequency. At the same time, cumulative energy system costs under the RES scenario are even lower than in the BaU case, as transition towards high share of renewables significantly lowers the cost of fuels (Figure 14), which proofs to be the key driver behind such differentiation. Nevertheless, capital investments, aggregated over all three categories (Figure 14), are 10% higher in the RES scenario in 2050 relative to the BaU path.

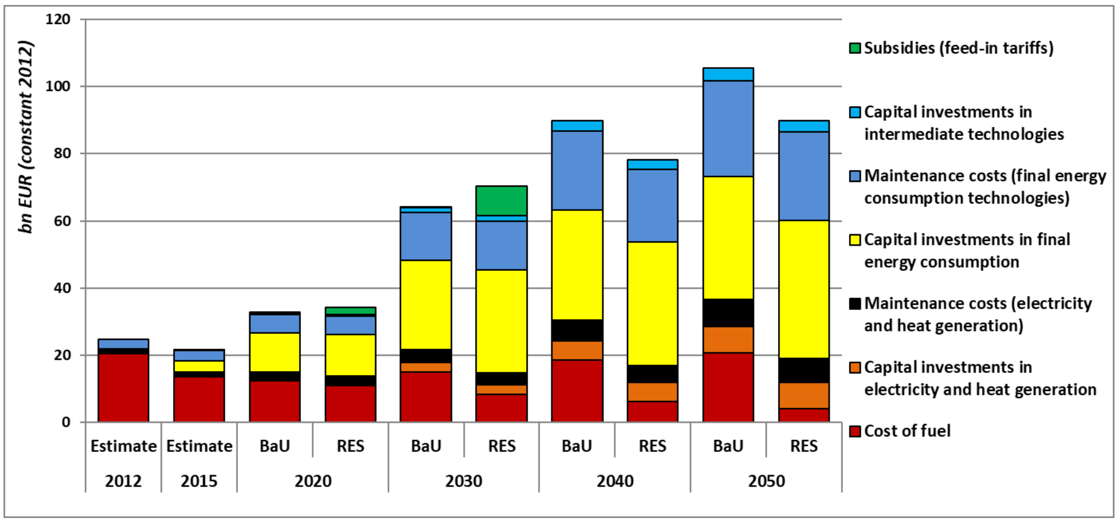

Fig. 14. Annual energy system costs under BaU and RES scenarios
Source: Developed by authors using TIMES-Ukraine model.

6 Economic assessment of RES scenario

In this section, we use a dynamic UGEM model to provide an assessment of the economic effects of renewable energy transition scenario in Ukraine. We start with the discussion of macroeconomic effects and further proceed with the sectoral impacts. All results are estimated relative to the BaU scenario discussed in Section 3 and show additional changes associated with the implementation of RES policies.

As discussed above, to provide an assessment of economic effects of the RES transition path we use an estimate of the additionally required capital investments estimated by the TIMES-Ukraine model and impose them as an additional production costs faced by energy users (industrial sector, households, transportation, etc). We also use TIMES-based estimates of the energy efficiency changes by corresponding energy user and introduce them as efficiency improvements in the UGEM. It should be noted that considering the relative nature of impacts under RES scenario, negative values of reported indicators do not necessarily imply a decrease in their absolute values under the analyzed energy policies, and in most cases reflect the slowdown in the corresponding growth rates.

According to our estimates, implementation of the RES scenario in general is associated with positive macroeconomic impacts. This is especially the case in the medium and long term (Figure 15). Such effects could be explained by dynamics of investment processes. In particular, GFCF increases substantially during the first years, but the level of energy efficiency is growing at a much slower pace, especially in case of energy intensive sectors. At the same time, in the medium term positive contribution of energy efficiency improvements and substitution exceeds investment costs of the energy policy scenarios. Considering the dynamics of investments and technological changes, macroeconomic impacts have a cumulative nature, i.e. additional growth relative to the reference scenario increases over time. While in 2025 additional GDP increases by 6-7%, in 2050 it can contribute over 16% relative to BaU scenario (Figure 16).

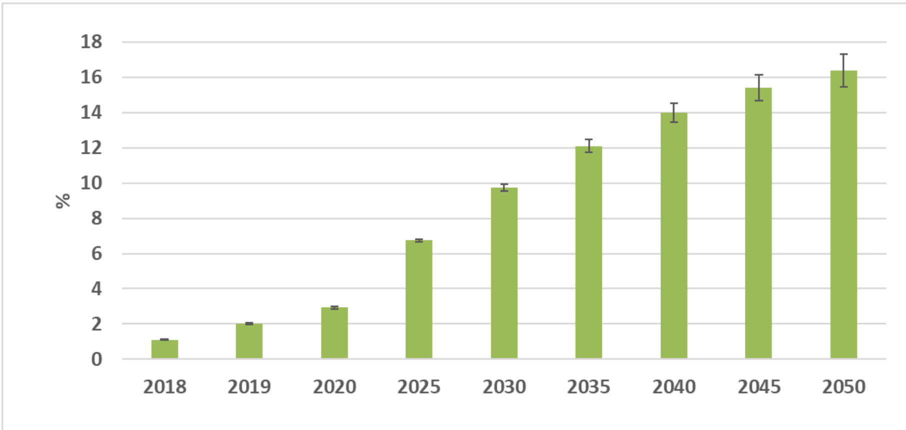

Figure 15. GDP impacts of the RES scenario implementation (w.r.t. BaU, %)

Source: Developed by authors using UGEM model.

Note: Error bars indicate 95% confidence intervals for substitution and transformation elasticity changes under the SSA approach. See section 3.3 for more details.

Under current policy assessment, we assume that no external funding is used to generate investments. Thus, producers increase prices to account for additional investment costs, while households purchase more investment goods by lowering consumption of other commodities. On the one hand, such assumption reduces direct aggregate costs of the RES policies, as it does not include any borrowings and associated interest payments. On the other hand, it implies a more rapid price increase and changes in the structure of final consumption. To stipulate additional investments, we introduce a sector-specific “investment” tax with corresponding revenues used for capital goods accumulation.

The need to accumulate additional investments serves as a key success factor as well as main challenge towards RES policies implementation. It is the ever-increasing level of gross-fixed capital formation, combined with efficiency improvements of fixed assets, which is a prerequisite for successful implementation of energy policy measures.

In terms of investment sources, a key role is played by industrial users, in particular, electricity sector. While most “low hanging fruits” of the energy efficiency improvements are associated with residential consumers, in order to reach high levels of renewables penetration and significant reduction in GHG emissions, much more efforts are required from industrial users.

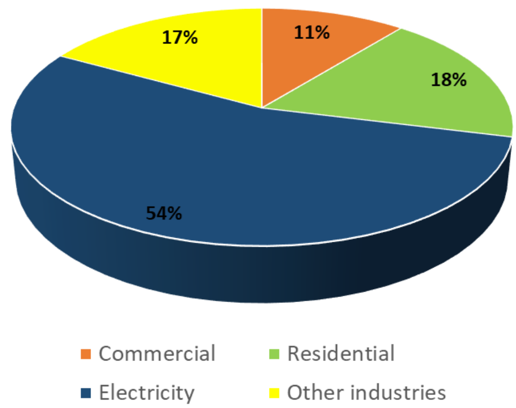

Figure 16. Distribution of the additional investments by sources in RES scenarios, 2017-2050 aggregate (w.r.t. BaU, %)

Source: Developed by authors.

According to the National accounts (SSSU, 2016), Ukrainian households' expenditure on capital goods are around 11% of the total national investments (1,3 bn EUR in 2015), while implementation of the RES scenario additionally requires around 120 bn EUR over the 2017-2050 period. This may seem to require a substantial change in the households' consumption structure and a significant increase of the marginal propensity to accumulate. Although it should be noted that the estimates of the additional residential investments, provided in this paper, include not only an acquisition of capital goods, but also a broad category of the final consumption expenditures (household and electrical appliances, motor vehicles, etc). From this point of view, additional residential investments represent a relatively small share of the total final consumption expenditures – less than 0.5% over the 2017-2050 period.

With growing GDP, households also experience positive impacts under the RES scenario implementation. In the short run, they are relatively insignificant or even slightly negative, but in the mid and long term, additional income growth can reach up to 16% (Figure 17).

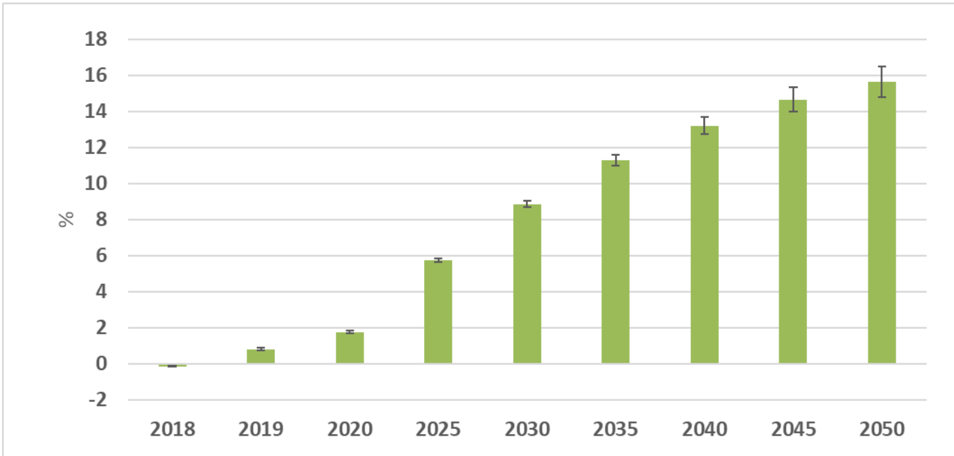

Figure 17. Impacts of the RES scenario implementation on households real income (w.r.t. BaU, %)

Source: Developed by authors using UGEM model.

Note: Error bars indicate 95% confidence intervals for substitution and transformation elasticity changes under the SSA approach. See section 3.3 for more details.

Households of the lower income deciles experience higher income growth rates than the richest one. Higher decile households have bigger share of services in their final consumption, and as domestic prices for services grow quicker than aggregate consumer price index, lower income deciles benefit more.

Implementation of the RES scenarios is accompanied with significant structural changes, which are mostly associated with an energy sector and energy intensive industries. There are several determinants, which contribute to these shifts.

First, efficiency improvements. Following the current model linkage approach, additional investments in the energy sector results not only in the higher capital accumulation rates, but also in the productivity growth (includes both energy efficiency improvements and substitution away from fossil fuels). Gains from a sector-specific efficiency changes depend on the rate of investments return.

Second, relative price effects. As changes in the supply and demand affect relative prices, they can either enhance or slow down output growth as well as impact energy demand. Thus, even under significant efficiency improvements (e.g. changes in the coal consumption efficiency) if price of the corresponding commodity (in our case coal) is growing even more rapid, sectoral output would decrease (under other equal conditions). In such a case, both efficiency changes and price effects would contribute to the reduction of coal use. Under a more usual case, energy efficiency improvements would result in the reduction of the supply prices.

Finally, demand side also plays a crucial role in the sectoral impacts of RES policies, which includes both domestic and international markets. For the representation of international trade in the UGEM model, we use a small open economy approach, thus assuming that international market prices are not affected by domestic policies.

In general, RES scenario leads to the output reduction in fossil fuels mining and processing industries (Figure 18). In particular, coal mining, gas distribution and coke output decline by over 40% relative to BaU in 2050. Energy efficiency improvements and fossil-fuel prices reduction contribute to the output growth in some energy intensive industries, including basic metals, electricity and heating. As the share of biomass increases, agriculture and wood processing sectors raise their output to meet the growing demand. Some resources from mining and fossil fuel production shift towards services, as a result their output share slightly increases. As a result of a significant increase in the share of biomass in the final consumption relative to the BaU scenario, there is an additional output growth in the woodworking industry and agriculture.

On average, estimates of the output changes show higher degree of uncertainty compared to aggregate macroeconomic effects. Nevertheless, in most cases results do not change qualitatively, while high uncertainty around quantitative estimates is justifiable considering the role of substitution elasticities.

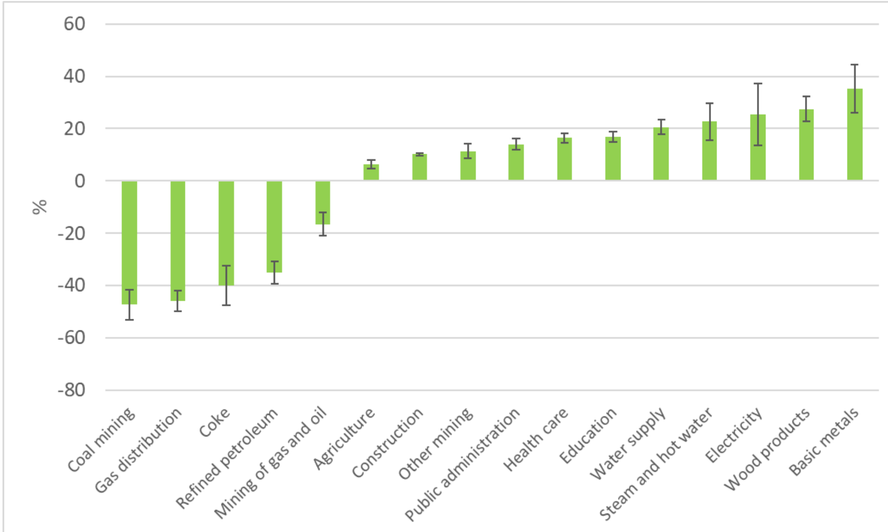

Figure 18. Changes in the sectoral output under RES scenario in 2050 (w.r.t. BaU, %)
Source: Developed by authors.
Note: Error bars indicate 95% confidence intervals for substitution and transformation elasticity changes under the SSA approach. See section 3.3 for more details.

7 Conclusions

With one of the highest levels of energy and emission intensities in the world, Ukraine has a high potential to exploit the "low hanging fruits" of the energy sector transformation by implementing a policy towards development of a high share of renewables, which can benefit both economy and environment. To explore such opportunities we use an integrated modelling approach, which includes energy system TIMES-Ukraine model and Ukrainian general equilibrium model. Using such methodology, we provide an assessment of Ukrainian ambitious scenario, which includes transition towards 91% share of renewables in GFEC by 2050 and corresponds to 1.5^{o}C target in terms of Ukrainian contribution to the combating global warming.

According to our results, further maintenance of the existing highly inefficient energy system in the long-run is even more expensive than transition towards 91% share of renewables. As in case of BaU scenario, fuel expenditures account for almost 86% of total system costs and represent the most attractive "low hanging fruits" in terms of costs reduction.

With initially low level of energy efficiency in Ukraine, implementation of the RES scenario leads to the positive macroeconomic and sectoral effects. According to our estimates, GDP may increase up to 10% by 2030 and 16% by 2050 in case of successful policies implementation. Households may also experience substantial real income growth – up to 16% in 2050. In this context, Ukraine benefits from double dividends, while RES also provides an economically acceptable way of going from relative to absolute decoupling. At the same time, existing institutional environment and inefficient market framework can pose significant risks towards RES policies implementation. As a result, national energy markets transformation towards transparency and competitiveness becomes a necessary condition of energy policies success. In this context, Ukraine's further engagement into European legal framework through the European Energy Community may provide an effective support on the way forward.

In terms of methodological consistency, an approach used in this study is of course not without limitations and need for further improvements. First, under the current set up we use only a one-way link – from TIMES-Ukraine to UGEM. In other words, TIMES-Ukraine simulation serves as a source of policy shocks for UGEM model. A more consistent way of model linkage should include iterative data exchange between models until outputs of the one model would not match inputs of the other within the defined level of tolerance. Second, in the current UGEM sectoral structure we do not have explicit representation of the renewable technologies, which are fully covered by TIMES-Ukraine technological disaggregation. Although, this should not be viewed as a major drawback, such representation would allow for a more consistent sectoral/technological mapping between two models. In terms of policy framework set up, more attention can be given to the sourcing of additional investments. As noted before, we assume that all additional costs associated with RES scenario implementation are covered by energy users (both households and industrial users), therefore no external funding is introduced. In this context, some alternative assumptions on investment sourcing would be worth to explore. Nevertheless, we consider an approach used in this paper to be more inclusive than a stand alone application of both energy system and computable general equilibrium models.

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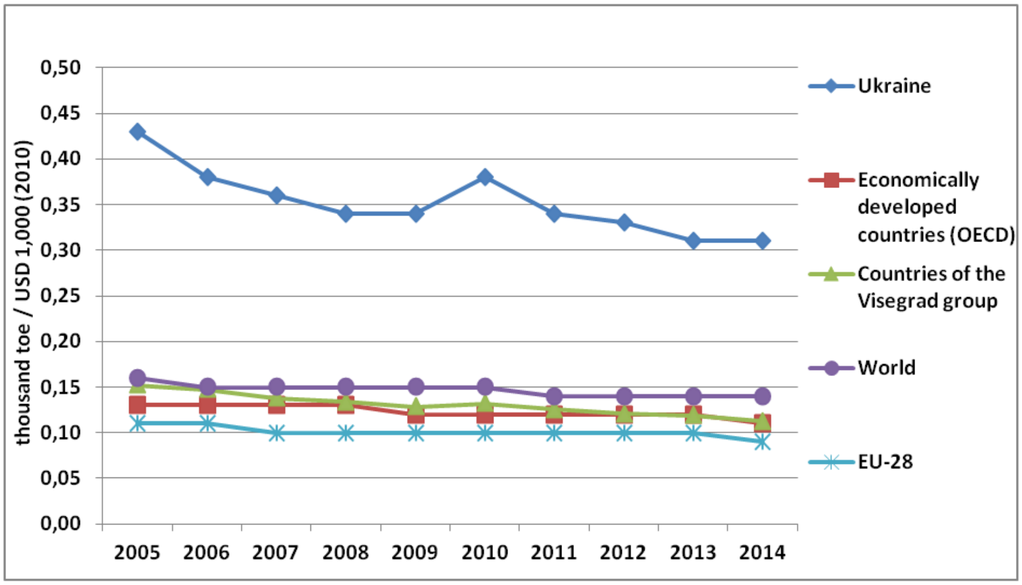
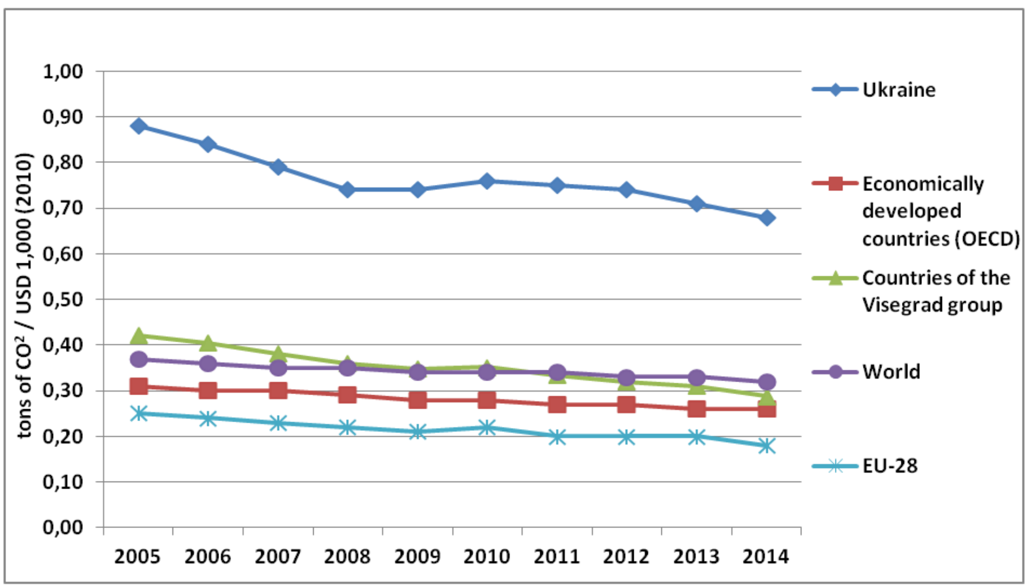
Appendix A. Energy and carbon intensity of Ukrainian GDP



A.1 Ukraine's GDP energy intensity (PPP)

Source: authors' estimates based on IEA data (http://energyatlas.iea.org/?subject=1378539487).



A.2 Ukraine's GDP carbon intensity (PPP)

Source: authors' estimates based on IEA data (http://energyatlas.iea.org/?subject=1378539487).

Appendix B. Annual average Ukraine’s GDP growth rates during 2016-2050, %

Sectors/Years	2016-2020	2021-2025	2026-2030	2031-2035	2036-2040	2041-2045	2046-2050
Agriculture, forestry and fishing	1.4	5.7	4.9	5.1	5.1	5.1	5.1
Mining and quarrying	3.0	3.4	2.3	2.0	2.0	2.0	2.0
Processing industry	6.5	5.6	4.1	3.3	3.3	3.3	3.3
Supply of electricity, gas, steam and conditioned air	4.4	4.9	4.8	4.5	4.5	4.5	4.5
Construction	8.0	6.4	5.1	5.1	5.1	5.1	5.1
Manufacturing – total	4.2	5.3	4.3	4.0	4.0	4.0	4.0
Services– total	2.5	5.0	4.2	4.0	4.0	4.0	4.0
Aggregate GDP	2.8	5.0	4.2	4.0	4.0	4.0	4.0

Source: based on Diachuk et al (2017).