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The role of bioenergy in Ukraine's climate mitigation policy by 2050

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ABSTRACT

The development of renewable energy sources (RES) is considered to be a key instrument in addressing climate change. However, different RES have different potential and economic feasibility depending on country-specific conditions and mitigation ambitions. Understanding the relative importance of each RES could help policy-makers focus their efforts on the most promising options. In this paper, we focus on Ukraine and explore the potential of biomass use under two mitigation scenarios – with 68% and 83% of greenhouse gas emissions reduction in 2050 relative to the 2010 level.

First, using the TIMES-Ukraine energy system model, we show that biomass would play a major role in the future climate mitigation. If constrained at the baseline scenario level (due to political or other reasons), mitigation costs would be substantially higher – by 14.0–19.6 B € or 10.8–14.3 €/tCO_2-eq., over the 2020–2050 time frame. Second, we quantify the importance of each biomass source. We show that woody biomass and bioliquids are the most important biofuels under the high-ambition climate scenario, while biowaste and bioliquids play a key role in the lower ambition pathway. Finally, we analyse the current policy environment in the context of future biomass development and conclude with a set of policy recommendations toward the realization of the biomass potential in Ukraine. We believe that findings presented in the paper would be relevant not only for supporting the decision-making process in Ukraine, but could also provide useful insights for other countries with similar conditions.

1. Introduction

Playing a crucial role in the national economy, the Ukrainian energy sector faces severe challenges regarding future development. Energy intensity of Ukraine's gross domestic product (GDP) is over three times higher than the European Union's (EU) average [1]. The country's GDP has one of the highest carbon intensities in the world – Ukraine holds 22nd place among over 200 reported countries [1]. Ukraine depends highly on energy imports – 39% share of imports in the total primary energy supply (TPES) [2]. The country faces declining domestic fossil fuel production – 40% reduction over 2010–2017 – while the share of renewable energy sources (RES) has modestly increased by 2.6% points since 2010 to reach 5.5% in 2017 [2]. The share of RES in the final energy consumption in Ukraine was 6.5% as of 2017, substantially lower than in its neighbouring Eastern EU countries like Romania (23.4%), Hungary (14.3%), Slovak Republic (12.4%) and Poland (11.1%) [3]. The role that biofuels and waste play in the Ukrainian energy mix is also much less significant compared to other countries. While in 2017 the share of biofuels and waste supply in TPES was 9.8% in the EU and 9.5% for the world on average, in Ukraine this share was only 3.3% [2]. To solve these issues, a wide range of robust energy, social and economic policies should be designed and implemented. Development of RES is considered to be one of the key steps towards Ukraine's energy sector transformation [4].

In recent years, several legislations have been implemented to support the development of renewables. In particular, the energy strategy of Ukraine until 2035 targets the share of RES in TPES to be 17% in 2030 and 25% in 2035, up from 4% in 2015 [5]. Some sector-specific renewable targets have been defined by other legislative documents. For instance, the concept of the implementation of the state policy of heat supply up to 2035 defines the share of renewable sources in heat production to be 30% in 2025 and 40% in 2035 [6]. The achievement of such targets may require significant investment expenditures. For instance Ref. [7], reports that to reach the 16.1% share of RES in TPES by 2030 an additional 117 B € of investments (relative to the baseline scenario) might be required. To reduce the pressure on the economy and energy users, the most cost-efficient ways of reaching the greenhouse

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Abbreviations

€	Euro (currency)
AFOLU	agriculture, forestry and land-use
B	billion
BaU	business as usual
Bcm	billion (1,000,000,000) cubic metres
BECCS	bioenergy with carbon capture and storage
BioCHP	biomass-based combined heat and power plant
CAT	climate action tracker
CHPP	combined heat and power plant
CH_4	methane
CO_2	carbon dioxide
EU	European Union
GDP	gross domestic product
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
kW_{electr}	kilowatt of electricity
m^3	cubic metres
Mtoe	million (1,000,000) tonnes of oil equivalent
M	million
NDC	nationally determined contribution
PES	primary energy supply
RES	renewable energy sources
t	tonnes
tCO_2-eq.	tonnes of carbon dioxide equivalent
TIMES	The Integrated MARKAL-EFOM System
TPES	total primary energy supply
TPP	thermal power plant
TSC	total system costs
UABio	Bioenergy Association of Ukraine

gas (GHG) emissions reduction targets should be considered and implemented.

In this paper, we explore the role and potential of biomass use in Ukraine. There are several advantages of biomass-based energy generation over other RES. *First*, unlike most other RES, energy produced from biomass does not require backup generation or storage capacities, in fact, it can itself be stored and used to produce energy on demand. *Second*, biomass can be converted to the variety of energy carriers, including not only electricity, but also heat and liquid biofuels. *Third,* it serves as a high-priority option for distributed generation [8]. *Finally,* biomass use can significantly contribute to the improvement of waste management practices as its production is often based on agricultural and food waste [9]. Altogether, this makes biomass highly attractive, but still a significantly underexplored input in the Ukrainian energy mix.

A number of recent studies have provided an assessment of the role of biomass in the long-term climate mitigation efforts. According to the Intergovernmental Panel on Climate Change (IPCC) 1.5 °C Special Report, scenarios that achieve an ambitious 1.5 °C target mostly rely on the large-scale application of bioenergy with carbon capture and storage (BECCS) and agriculture, forestry and land-use (AFOLU) carbon dioxide removals [10]. Ambitious 1.5 °C-consistent mitigation efforts, under the SSP2 baseline,[1] result in a 22% share of biomass in the global primary energy supply (PES) by 2050 and 28% by 2100 [10]. Daioglou et al. [12] report that in scenarios meeting the 1.5 °C target, biomass could exceed 20% of global final energy consumption in 2050. A major role of biomass in the ambitious global climate mitigation efforts is also supported by other studies.

Rogelj et al. [13] show that the share of biomass in electricity generation could be between 20% and 68% by mid-century under the 1.5 °C-consistent scenarios. Moriarty and Honnery [14] argue for a dual use of non-food biomass, when the biomass can be first used for material applications (substituting more carbon-intensive commodities, such as metals), followed by reuse, and then finally combusted for energy. Authors suggest that such an approach can potentially make biomass even more attractive for future climate mitigation efforts. Dhillon and von Wuehlisch [15] indicate the tremendous potential of biomass to mitigate climate change, though note that there should be financial incentives to promote climate-friendly best practices, including wider use of bioenergy.

Several studies have explored the role of biomass in the future energy supply in Ukraine. Schafartzik et al. [16] focus on the risks and limitations of biofuel development, considering environmental, social and economic trade-offs. They conclude that both environmental and economic benefits from increasing biofuel production in Ukraine are highly uncertain. A more promising outlook for long-term biogas development in Ukraine is provided by Ref. [17], though large investment requirements are identified as one of the main obstacles. International Renewable Energy Agency [18] indicates that Ukraine has a potential for a tenfold increase in biomass use for energy purposes, of which 73% could be used for heat, 7% for transport fuel and the rest for electricity generation. Child et al. [19] show that solid biomass could contribute by around 20% to the total electricity generation by 2050 under the 100% renewable energy system scenario for Ukraine.

Given that the forest area in Ukraine is only 17%, significantly lower than the EU average (42%) [20], around 30% of biomass potential in Ukraine by 2035 is expected to be derived from woody biomass, while the remaining 70% will come from agricultural residues [21]. The significant potential of biomass use in Ukraine remains largely unutilized, as heat is produced mostly using natural gas. Targets of the installed capacity of the biogas units, declared in the Renewable Energy Action Plan until 2020, were fulfilled only by 21% as of the beginning of 2020 [22].

Several reports by the Bioenergy Association of Ukraine (UABio) review the current state of the bioenergy sector, estimate biomass potential and discuss possible challenges for a more widespread use of biomass. Obstacles to the use of agriculture-derived biomass in Ukraine are analysed in Ref. [23]. Energy prospects of municipal solid waste in Ukraine, which belongs to biomass according to Ukrainian legislation, are reviewed in Ref. [24]. Finally [25], suggests measures towards the creation of a competitive solid biofuels market in Ukraine. UABio reports conclude that while biomass in Ukraine has a high potential to contribute to the clean energy mix, substituting a large share of fossil fuels, attract foreign and domestic investments and boost employment in the local communities, as well as significantly improve waste management practices, a number of challenges need to be overcome. These include reorganization of the biofuel market, additional initiatives of the government support for biofuels, changes in biofuel-related legislations and access to the affordable financing opportunities for the implementation of biofuel projects.

Despite some controversies on the environmental and economic benefits of the wider use of biomass in Ukraine, there are three key limitations identified in the existing literature. First, available assessments of the future biomass and bioenergy use in Ukraine are provided in isolation from the potential of other energy sources. This neither includes consideration of other RES – their competitive advantages and limitations – nor does it include the impact of possible future biomass use on the energy sector and energy users. Second, an assessment of the interactions between different biofuels, their substitutability and

[1] Under the SSP2 baseline scenario trends broadly follow their historical patterns [11].

relative importance in the total biomass-based energy supply mix in Ukraine has not been explored in the literature. Finally, available biomass use scenarios do not take into account Ukraine's fair climate mitigation efforts consistent with limiting global warming to below 2.0 °C or 1.5 °C compared to the pre-industrial level.

In this paper, we explore two ambitious climate mitigation scenarios achieving 68% and 83% in GHG emissions reduction in 2050 relative to the 2010 level. These targets, as will be further discussed in the paper, are in line with carbon budgets consistent with Ukraine's fair contribution toward limiting global warming to below 2.0 °C [26,27]. Using the TIMES-Ukraine energy system model [7], we explore climate mitigation scenarios considering two options: (a) biomass supply is constrained at the baseline scenario level; (b) biomass supply is defined based on the economic feasibility (energy system costs' minimization). We further assess the impacts of the biomass feedstock availability by types[2] on the cost of climate mitigation policies and average costs of emissions reduction over the 2020–2050 time frame, identifying the role of each biofuel. In addition, we explore interactions between different biofuels, by identifying the substitution possibilities of one biofuel (with limited supply) with another (without limited supply). Overall, our results confirm the assumption that biomass could play a major role in the future of Ukraine's climate mitigation efforts (with a higher share in TPES than wind and solar combined). At the same time, to realize this potential, a number of existing regulatory, market and infrastructure-related obstacles should be addressed, as discussed in the paper. We believe that findings presented in this study can be useful not only for supporting the decision-making process in Ukraine, but can also provide valuable insights for other developing countries with similar conditions.

The rest of the paper is organized as follows. Section 2 provides an overview of the potential of biomass use in Ukraine, as well as cost and technological assumptions of the biomass-based energy technologies. Section 3 outlines the methodological framework, in particular the TIMES-Ukraine energy system model. Section 4 describes climate mitigation policy scenarios and discusses Ukraine's fair contribution to the global climate mitigation efforts. Section 5 provides an economic and environmental assessment of the role of biomass in the climate mitigation policies. Finally, Section 6 provides policy recommendations to enable the realization of the biomass potential in Ukraine s and concludes.

2. Potential of biomass use in Ukraine

In Ukraine, biomass use has significant potential for heat, electricity and liquid biofuel production due to the abundant residues in agriculture, untreated solid waste landfills, favourable climate conditions, agricultural land availability and affordable labour supply. As of 2020, 40% of agricultural waste could potentially substitute up to 10 billion cubic metres (bcm) of natural gas per year [28]. Dedicated energy crops that could be planted on 4 million ha of marginalized lands could substitute up to 20 bcm of natural gas, whereas biogas/biomethane could substitute up to 7.8 bcm of natural gas [28]. The overall potential of natural gas substitution with biomass is almost 38 bcm, whereas total natural gas consumption in Ukraine in 2019 was 30 bcm [28].

According to the State Statistics Service of Ukraine,[3] only 11% of the economically feasible bioenergy potential was used in 2015 (Table 1). Over half of the economically feasible potential is associated with agricultural waste and woody biomass, while the rest includes energy derived from energy crops and biogas (Table 1). By 2050, an economically feasible potential of biomass is projected to reach 42 million tonnes of oil equivalent (Mtoe), mainly due to the increased cultivation and supply of energy crops, as well as the supply of biogas from by-products of the agri-food industry (Table 1).

To provide an assessment of the future use of biomass in Ukraine several assumptions regarding costs and technological performance of different biomass-based technologies were made (Please see Table A.1, Appendix A).

To model the long-term development of the energy sector, it is assumed that the share of hot water supply provided by biomass-based boilers equals the share of population that uses biomass-based boilers for heating in 2050. Use of biomass as a cooking fuel is considered to be a limited option. According to the Bioenergy Association of Ukraine, as of 2016 the production of thermal energy from biomass is cost-competitive compared to natural gas and will remain so in the future [29]. The payback period for biomass power plants is assumed to be eight years subject to the current feed-in-tariff,[4] while the biomass combined heat and power plants (CHPP)[5] are assumed to have a payback period of 4.5 years [29]. Key technological and cost assumptions of biomass thermal power plants (TPPs) and CHPPs are provided in Tables A.2 and A.3 respectively (Appendix A). For the modelling of residential and industrial boilers, key assumptions are outlined in Tables A.4 and A.5 (Appendix A). Cost and technological assumptions for other generation technologies, including solar, wind, hydro, nuclear and fossil fuel-based generation, could be found in Ref. [7]. The latter report also provides an overview of other technological and modelling assumptions used in this paper.

3. Methodological approach

To explore the climate mitigation scenarios and the future role of biomass in Ukraine, we use the TIMES-Ukraine energy system model [7, 29]. This is a linear programming optimization model of energy flows. The energy system of Ukraine is represented in the TIMES-Ukraine model as a single region and consists of seven sectors: the energy supply sector (production, imports, exports, international bunkers, stock changes, and the production of secondary energy resources – petroleum products, briquettes, etc.); electricity and heat production; industry; transport; residential users (household); trade and services; and agriculture (including fishing). The energy system in the model covers energy and industrial process sectors, following the IPCC definitions [31]. Fig. 1 provides an overview of the energy system representation in the TIMES-Ukraine model. A more detailed outline of the energy system structure is provided in Fig. B.1 (Appendix B).

An overall approach to the energy policy assessment within the TIMES-Ukraine modelling framework, which is applied in the current study, includes several steps. *First,* data on the underlying drivers of the future energy supply and demand are collected. These include macroeconomic and sectoral value-added forecasts, demographic forecasts, energy price forecasts, etc. *Second,* a baseline scenario is developed, based on the assumptions of future energy demand, macroeconomic and demographic forecasts, technological assumptions, price forecasts, etc. *Third,* policy scenarios are designed by imposing additional constraints or targets for the energy system development. For each scenario (baseline and policy scenarios) the model estimates the least-cost trajectory of the system,[6] i.e. energy supply and demand by sector and fuel type,

[2] To explore this point, feedstocks are combined into several groups, which is discussed in Section 5.

[3] http://www.ukrstat.gov.ua/.

[4] Based on the current legislations, we assume that the feed-in tariff will be in place till 2030, gradually reducing over time. No feed-in tariffs are assumed post-2030. This assumption is applied to all scenarios.

[5] District heating plays an important role in Ukraine's energy sector. Based on the [30] estimates, centralized district heating supply services are provided to 37% of Ukrainian families, and account for a large share of their expenses in urban areas, in many cases exceeding 20% of the total housing and utility expenses.

[6] Like many other energy system models, TIMES-Ukraine provides an intertemporal optimization based on the perfect foresight.

Table 1
Actual supply and potential of the bioenergy in Ukraine.

Biomass type	2015				2050
	Actual production, Mtoe	Theoretical potential, M t[a]	Share available for energy sector, %	Economic potential, Mtoe	Economic potential, Mtoe
Cereals' straw	–	35.14	30	3.65	5.48
Rape straw	–	3.10	40	0.43	0.65
Corn grain production waste (stems, cores)	–	30.3	40	2.32	3.48
Sunflower seed production waste	–	21.2	40	1.22	1.22
Secondary agricultural waste (sunflower husks)	–	1.9	41	0.27	0.27
Total agricultural potential	**0.65**	**91.64**	-	**7.90**	**11.10**
Wood biomass (firewood, logging waste and residues, splinters)		8.8	41	1.03	2.08
Wood biomass (maintenance logging of forest bands, dead-wood)		11.0	58	1.80	1.03
Total wood	**0.79**	**14.80**	-	**2.41**	**3.11**
Biodiesel	–	-	-	0.19	0.19
Bioethanol	–	-	-	0.54	0.54
Total biofuel	**0.00**	–	–	**0.73**	**0.73**
Biogas from by-products of the agri-food sector (manure + food industry)	0.01	1.6 B m^3 CH_4	50	0.68	2.38
Biogas from solid waste landfills	–	0.6 B m^3 CH_4	34	0.18	0.59
Biogas from waste water	–	1.0 B m^3 CH_4	23	0.19	0.39
Total biogas	**0.01**	**3.2 B m^3 CH_4**		**1.05**	**3.37**
Poplar, miscanthus, acacia, alder, willow, rapeseed	–	11.5	90	4.40	13.19
Corn (biogas)	–	3.3 B m^3 CH_4	90	2.58	10.30
Total energy crops	-	-	-	**6.97**	**23.49**
Peat	–	-	-	0.28	0.28
Grand total, Mtoe	**1.45**	-	-	**19.34**	**42.07**
Share of biomass in TPES, %	**1.7**	-	-	-	-

Notes: Considering the significant environmental impact of peat extraction, this paper does not include peat into the set of available energy sources.
[a] I f not specified otherwise.
Source: Based on [7] and data provided by the Bioenergy Association of Ukraine.

energy prices, the optimal technology mix, etc. Based on such data, the cost of the selected policy pathways, most efficient technologies, as well as required energy system transformations can be identified and analysed. In the next section, we provide a detailed discussion of the baseline and policy scenarios set up.

4. Baseline and policy scenarios

In this section, we provide an overview of the business as usual (BaU) pathway and two policy scenarios, which include reductions in GHG emissions by 68% and 83% in 2050 relative to the 2010 level. We focus on the macroeconomic, demographic and energy price assumptions that underlie these scenarios, as well as discuss the resulting energy mix and emission profiles of the BaU and policy pathways. The BaU scenario is based on the current energy policy efforts and serves as a reference for model calibration. Policy scenarios are imposed on top of the BaU. We also discuss the consistency of the identified emission reductions with Ukraine's fair contribution toward the 2.0 °C and 1.5 °C global mitigation efforts.

4.1. Baseline scenario

In the baseline scenario, we assume an average annual GDP growth rate of around 3.5% over 2021–2050, with higher growth rates associated with construction, other services and selected manufacturing industries (Table C.1, Appendix C). The share of services in the aggregate GDP moderately increases by 3% points and reaches 55.7% in 2050. For the demographic forecast, we assume −0.5% annual average population growth, which corresponds to the central scenario provided by the Ukrainian Institute of Demography and Social Studies (Table C.2, Appendix C). It is assumed that domestic and world energy prices follow the International Energy Agency's New Policies scenario [32].

The BaU scenario is developed under the assumption of no fundamental changes in the energy system, i.e. current trends continue and no new policies are implemented [33]. Thus, the fuel mix and energy demand are fully defined by the demand drivers. Gradual replacement of technologies still takes place, as the lifetime of existing equipment terminates. The cost of new technologies that replace the old ones decreases in time, while their efficiency increases. Even under such assumptions, considering the initially high carbon intensity of the national economy, GHG emissions significantly increase under the BaU path – by around 27% in 2050 relative to the 2010 level (Fig. 2). Most of this increase is coming from the industrial emissions, while emissions from the power and heat generation is almost the same in 2012 and 2050.[7]

A 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 around 2025, therefore GHG emissions grow faster during this transition phase (2020–2025), compared to the 2015–2020 period.[8] At the same time, maintenance of the highly energy-intensive economy like the Ukrainian one would require significant expenses in the long run. Due to the high level of depreciation, significant investments are required to replace the existing technologies even without any major upgrades – a total of around 835 B € over the 2020–2050 time frame.

TPES[9] under the BaU path is being dominated by fossil fuels, mainly by coal (41.5% share in 2050) and natural gas (30.8%), followed by nuclear energy (15.6%) (Fig. 3). The share of RES in the baseline moderately increases by 5.4% points since 2015 and reaches 7.6% in 2050. While solar- and wind-based generation grow substantially over time, together they represent less than 37% of all RES (Fig. 3). In the

[7] For the case of municipal solid waste representation in the model, we assume net zero CO_2 emissions, but positive N_2O and CH_4 emissions.
[8] The state sovereignty restoration assumption is captured via changes in demand drivers.
[9] In this study, TPES is estimated based on the energy balance accounting framework, i.e. no conversion rates for renewable electricity are applied.

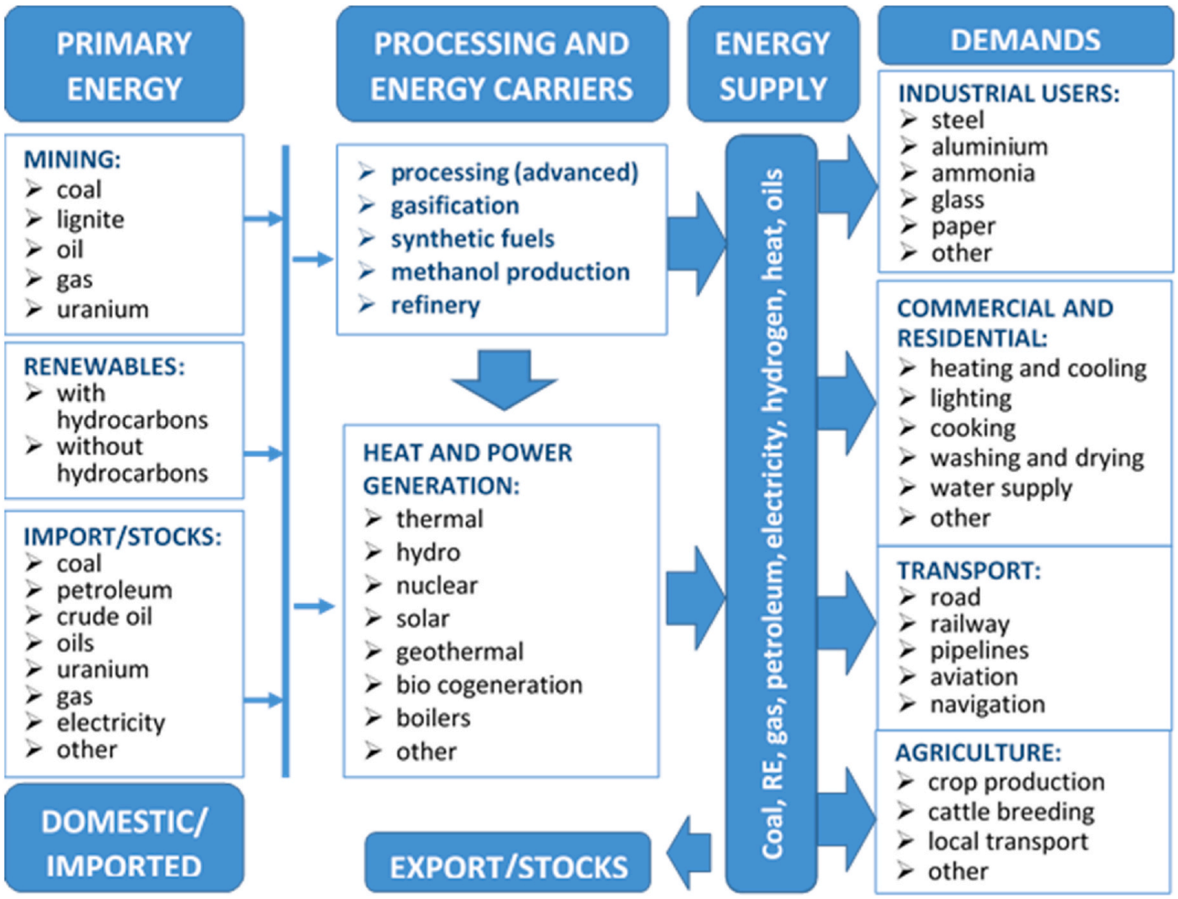

Fig. 1. Representation of the energy system in TIMES-Ukraine model. *Source:* Reprinted by permission from Springer Nature: [4], Copyright (2018). *Notes:* The figure provides a schematic representation of the energy system in the TIMES-Ukraine model. An actual representation of the energy system within the modelling framework is much more detailed and includes over 1600 technologies. For a more detailed description of the TIMES-Ukraine model, an interested reader is referred to Refs. [7,29]. "RE" stands for renewable energy.

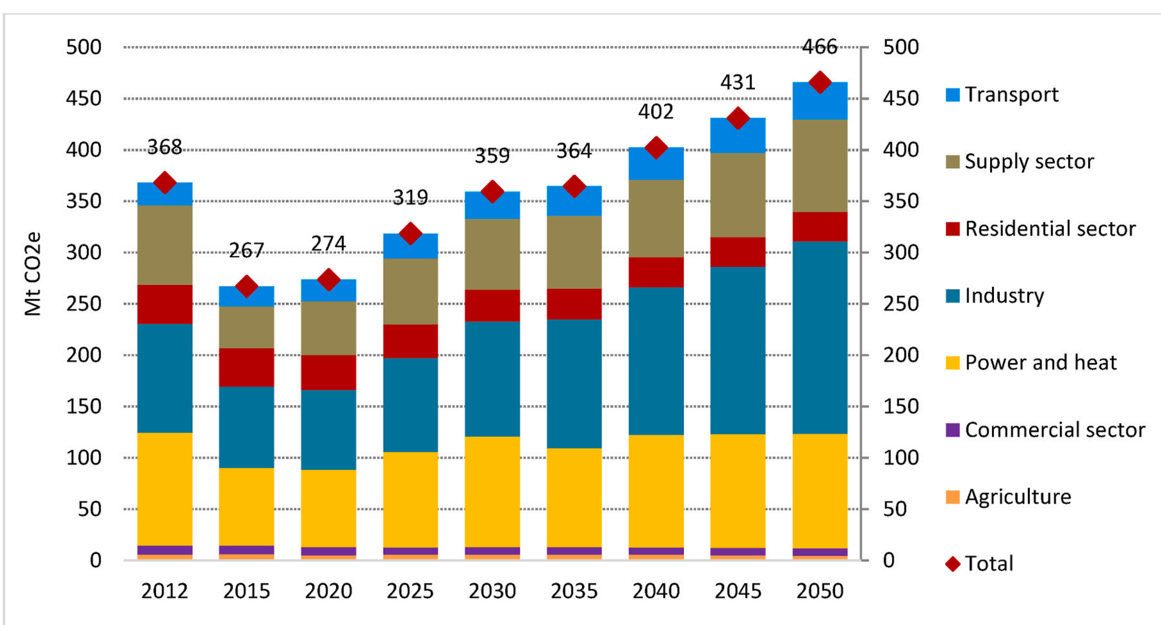

Fig. 2. GHG emissions by sectors under the BaU scenario. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* Stacked bars report GHG emissions decomposed by sectors for selected years. Red diamonds represent total GHG emissions in a selected year.

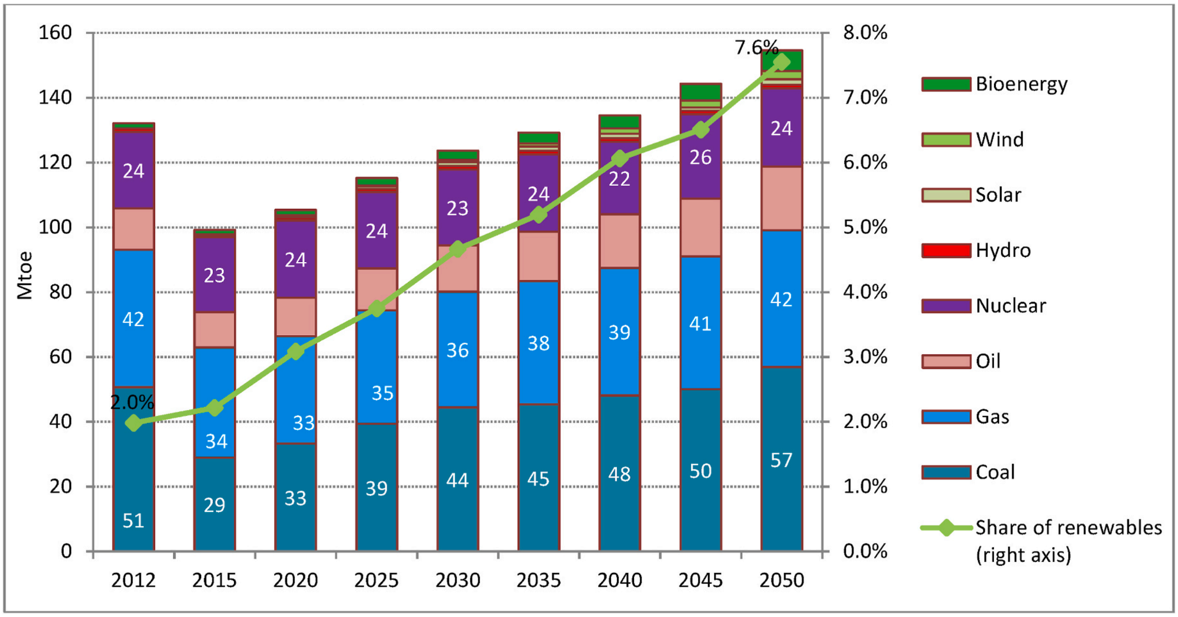

Fig. 3. TPES and the share of renewables in the baseline scenario. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* TPES is reported on the primary vertical axis of the figure and is represented using stacked bars. Share of renewables is reported on the secondary vertical axis of the figure and is represented with a green line.

baseline scenario, biofuels still dominate the RES supply mix, accounting for 4.6% of TPES in 2050 – a moderate increase of 1.9% points since 2015.[10]

In terms of the composition of the biomass-based energy supply in the baseline scenario, industrial waste-sludge plays a major role in the long run, contributing over 60% to TPES (Fig. 4). Industrial waste-sludge includes a combination of agricultural and industrial waste, such as straw, forestry waste, wood and paper products waste, sunflower waste, etc. This type of waste is used for electricity and heat generation only, either through direct combustion (e.g. on farms) or by producing pellets/briquettes. Wood products is the second-largest contributor with the share varying between 40% and 50% (at the beginning of the period) and 16% and 18% in 2045–2050. Bioenergy crops start gaining a significant share after 2030, reaching 20% in the biomass-based TPES in 2050. Other types of biomass-based energy sources, such as liquid biofuels, biogas and bio rapeseed, do not play a major role under the BaU assumptions, as their aggregate contribution does not exceed 5% in any given year (Fig. 4).

In terms of uses, by 2050 around 43% of all biomass-based energy is consumed by power and heat generation, followed by the commercial sector with 35% of total consumption (Fig. D.1, Appendix D). In the latter case, most biomass is combusted by commercial users to produce heat. The remaining 22% is redistributed between agriculture (12%), industrial sector (7%) and supply sector (4%). The share of biomass used by the residential and transport sectors is close to zero in the baseline scenario in 2050 (Fig. D.1, Appendix D). In the case of the residential sector, the share of biomass is substantially decreasing over time – from 36% in 2015 to 0% in 2045, as households move away from the use of both traditional and non-traditional biomass-based energy.[11] While in absolute terms the bio-based energy supply under the baseline scenario increases by around four times between 2012 and 2050, reaching 6.3 Mtoe at the end of the analysed period, it is far from reaching its economic potential. As was discussed in Section 2, the economic potential of the biomass-based energy generation in 2050 is estimated to be around 42.1 Mtoe (Table 1), while under the baseline scenario only 15% of these are used. In the case of some biofuels, the energy potential is underutilized even more under the BaU. For instance, this is the case of biogas, with only 0.3% of its economically feasible potential being used by 2050. Thus, under the baseline scenario, without implementation of any stringent climate policies, such as carbon pricing, renewable share targets or environmental regulations, only a small share of the biomass-based energy potential is used, leaving a major opportunity for the increase in the biomass supply within more ambitious climate mitigation pathways.

4.2. Climate mitigation scenarios

Two GHG emission reduction scenarios are considered in this study. In addition to the timely implementation of the existing and drafted national legislations (as in the baseline scenario), both policy scenarios also include more stringent climate mitigation measures consistent with keeping global warming below 2 °C (Table 2).[12] Scenario 1 is broadly consistent with Ukraine's fair contribution toward keeping global warming below 1.5 °C within both 2030 and 2050 time frames. Cumulative emissions (carbon budget) over corresponding periods under two fair-sharing frameworks are provided in Table 2. Only under the [26] approach and the 2018–2050 time frame does Scenario 1 have somewhat higher cumulative emissions (5% difference) than the 1.5 °C-consistent effort. At the same time, compared to the [27]

[10] To take into account the necessity for the storage and backup capacities within the modelled scenarios, we specify a required share of batteries and balancing capacities in the model (as a share of the solar and wind capacity). In 2020, the battery requirement is 1% of solar and wind capacity, while the share of balancing capacity is 10% (for both solar and wind capacity). In 2050, these shares are 10% (for battery requirement) and 5% (for balancing capacity), respectively.

[11] In the applied modelling framework, traditional biomass is represented within a variety of biomass-based energy sources.

[12] Within the implemented policy scenarios, emission reduction targets are imposed and the model finds the least-cost trajectory to meet these targets and other constraints by adjusting the energy generation mix. Carbon pricing is not used to achieve the mitigation targets.

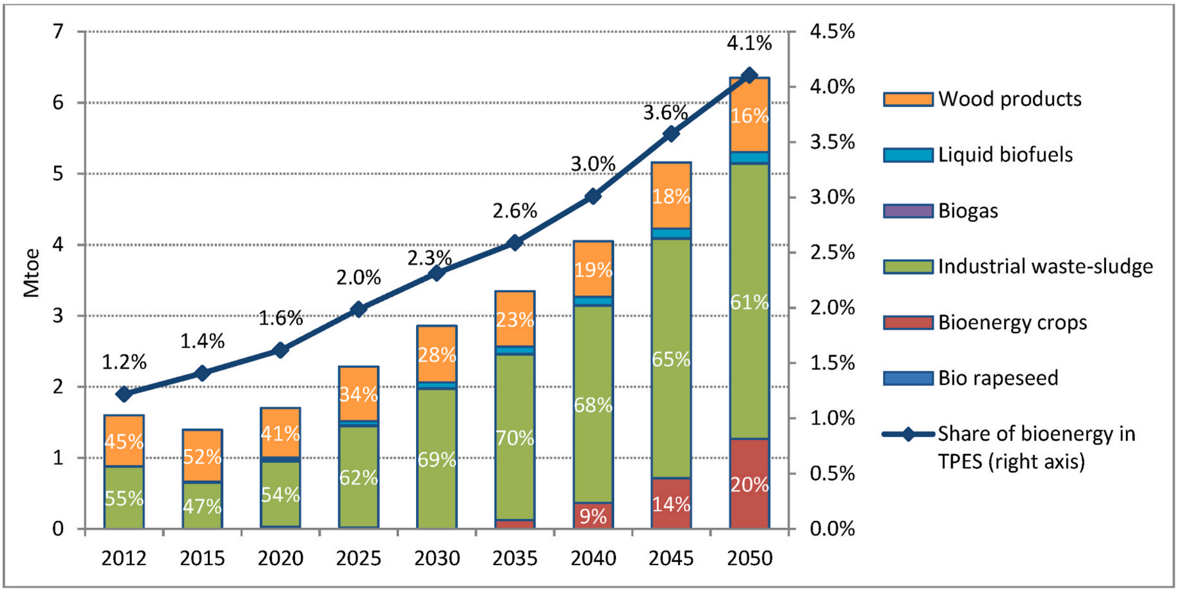

Fig. 4. TPES composition of the biomass-based energy sources in the baseline scenario. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* TPES of the biomass-based energy sources is reported on the primary vertical axis of the figure and is represented using stacked bars. Share of the bioenergy in the country's TPES is reported on the secondary vertical axis of the figure and is represented with a dark blue line.

Table 2
Ukraine's climate mitigation efforts under different equity principles and scenarios developed in the paper, carbon budgets over 2015–2030 and 2015–2050, billion tCO_2-eq.

Allocation approach	Timeframe	2 °C-consistent	1.5 °C-consistent	Scenario 1	Scenario 2	Baseline
Average over five allocation approaches from [27]	2018–2030	4.0	3.4	2.8	2.8	4.7
	2018–2050	8.5	6.3	5.9	6.1	11.8
Average over six allocation approaches from [26]	2018–2030	4.3	3.5	2.8	2.8	4.7
	2018–2050	8.2	5.6	5.9	6.1	11.8

Notes: Carbon budget estimates include emissions from energy and industrial sectors only. For the CAT 2 °C scenario we use the level of emissions that corresponds to the limit between 2 °C-compatible and insufficient. For the CAT 1.5 °C scenario we use the level of emissions that corresponds to the limit between 1.5 °C-Paris Agreement compatible and 2 °C-compatible. Emission trajectories reported in Refs. [26,27] are for the selected years and thus are linearized (between reported years) to estimate carbon budgets. Pre-2020 emission levels for carbon budget estimates under all scenarios are taken from the TIMES-Ukraine model.
Source: Developed by authors based on [26,27] and TIMES-Ukraine model estimates.

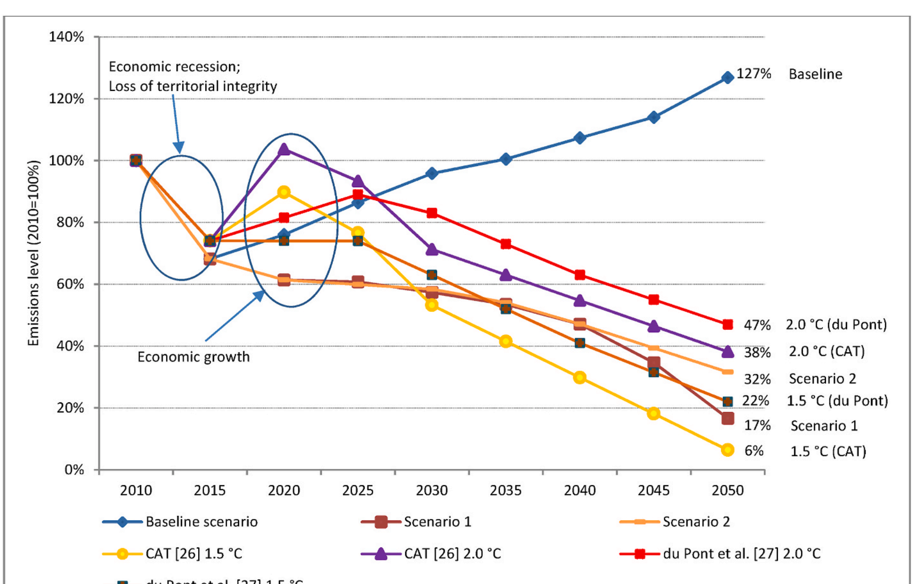

Fig. 5. GHG emission profiles under different modelled scenarios and assumption of Ukraine's fair contribution to the climate change mitigation. *Source:* Developed by authors based on [26,27] and TIMES-Ukraine model estimates. *Notes:* All emission levels of the represented scenarios are indexed to 100% in the 2010 reference year. Blue ovals with corresponding comments indicate specific time periods with rapidly changing emission trends. Emission scenarios reported on the figure represent either the modelled scenarios (Baseline scenario, Scenario 1 and Scenario 2) or scenarios adopted from the literature with a corresponding identification of the source (all other depicted scenarios).

Ukraine's fair contribution, Scenario 1 carbon budget is 6% lower than the 1.5 °C-consistent estimate. Scenario 2 was designed with a somewhat lower level of mitigation efforts, but still consistent with keeping global warming below 2 °C. Given that Ukraine is a developing country and the implementation of the 1.5 °C-consistent scenario (Scenario 1) would require significant investments, one might consider Scenario 2 as an unconditional climate mitigation target and Scenario 1 as a conditional target (depending on availability of support by the international community).

Both Scenario 1 and Scenario 2 are much more ambitious than the Ukraine's first nationally determined contribution (NDC) target, which is aimed at keeping the GHG emissions under 60% of the 1990 level [34]. In our BaU scenario, GHG emissions in 2030 are around 41% of the 1990 level, thus already fulfilling Ukraine's first NDC commitment. It should be noted that Ukraine is currently revising its NDC target toward a higher level of ambition [7], while some existing national strategic documents also set more stringent climate mitigation goals (e.g. Ref. [35]) compared to the Ukraine's first NDC.

Fig. 5 reports the comparison of GHG emission profiles by scenarios and under different assumptions of Ukraine's fair contribution to the global climate mitigation efforts. Consistent with the allocation of carbon budgets (Table 2), in 2030 and 2050 Scenario 1 has lower emission levels than both 1.5 °C- and 2.0 °C-consistent estimates of the [27] and 2.0 °C-consistent of [26]. By construction, in Scenario 1 we impose emission trajectories from Scenario 2 as an upper bound and identify a specific reduction target for emissions in 2050. As a result, due to the fact that more efficient and cheaper technologies are available in the model starting from 2030 (based on the current technological projections), Scenarios 1 and 2 mainly differ in emission trajectories in a post-2035 period.

One particular point that should be highlighted in terms of the emission trajectories interpretation is a high variation in emissions during 2010–2020 – first a sharp decline and then an increase in emissions is observed in most scenarios (Fig. 5). This specific trajectory kink is caused by two factors – sharp economic recession and loss of territorial integrity due to the war conflict with Russia. As a result, Ukraine's GDP has reduced by 15% during the 2013–2015 period [36]. Between 2020 and 2025 different assumptions among scenarios are made regarding the restoration of Ukraine's territorial integrity. In the case of TIMES-Ukraine scenarios, we assume that territorial integrity is restored by 2025, which impacts emission trajectories. Considering that carbon budgets (Table 2) are estimated starting from 2018, this difference in emission trajectories during the beginning of the period has limited impact on the comparison of emission profiles. Neither of the emission scenarios take into account economic and environmental impacts of COVID-19.

5. The role of the biomass in Ukraine's climate mitigation policies

To explore the role of the biomass in Ukraine's climate mitigation efforts, we first consider climate mitigation targets under Scenarios 1 (S1) and 2 (S2) without imposing any additional constraints on biofuels apart from the general cost assumptions (Appendix A [7]). We impose emission reduction targets for each modelled year and estimate resulting investment needs, TPES mix, electricity generation mix, implied carbon prices and other indicators for each of the two scenarios. We then group eight biomass-based energy sources represented in the TIMES-Ukraine model into four categories – woody biomass; biogas; bioliquids; and biowaste (Table E.1, Appendix E). For each of the two policy scenarios we run eight combinations of bioenergy constraints. Table 3 below represents these options.

Assessment of the scenarios with constrained biomass-based energy availability is motivated by several considerations. *First,* as will be discussed in more detail in Section 6, there are multiple regulatory, market and infrastructure-related obstacles that currently exist in Ukraine and could significantly limit the realization of the biomass potential. An applied modelling framework does not explicitly capture all the existing administrative and market constraints, e.g. by assuming a complete availability of the investment resources, fair and competitive market conditions, etc. In reality, this might not be the case and the biomass-based energy producers might not only continue facing the existing obstacles, but also experience new challenges. In this case, biomass-constrained scenarios could help to understand the cost of the existing and potential obstacles.

Second, in the current policy assessment we impose an aggregate emissions reduction target without providing any additional specific support for individual technologies. In this context, we are able to

Table 3
Scenario matrix for the decomposition of biomass potential by technologies.

No.	Scenarios/options	Constraints on bioenergy technologies				Emission targets
		Woody biomass	Biogas	Bioliquids	Biowaste	
1.	Baseline (BaU)	BaU	BaU	BaU	BaU	NA
2.	Scenario 1 (S1)	Unconstrained				S1
3.	Scenario 2 (S2)	Unconstrained				S2
4.	FR	BaU	BaU	BaU	BaU	S1/S2
5.	BDGLOth	BaU	BaU	BaU	S1/S2	S1/S2
6.	BDGOth	BaU	BaU	S1/S2	S1/S2	S1/S2
7.	BDOth	BaU	S1/S2	S1/S2	S1/S2	S1/S2
8.	BD	Unconstrained	BaU	BaU	BaU	S1/S2
9.	BG	BaU	Unconstrained	BaU	BaU	S1/S2
10.	BL	BaU	BaU	Unconstrained	BaU	S1/S2
11.	BW	BaU	BaU	BaU	Unconstrained	S1/S2

Notes: The table provides an overview of the modelled scenarios set up that are used to decompose the biomass potential by technologies represented in the model. The first three scenarios in the table correspond to the BaU and two policy scenarios (without any additional constraints imposed on the bioenergy). Option "FR" corresponds to the case when all biomass-based energy technologies are constrained at the BaU level. The next three options (Nos. 5–7 in the table) consequently relax constraints on the biomass-based energy technologies, putting them at the corresponding policy scenario level (S1/S2). For instance, the "BDGLOth" option relaxes constraint on biowaste, "BDGOth" in addition to biowaste relaxes constraint on bioliquids, finally, "BDOth" additionally relaxes constraint on biogas. It should be noted that under options Nos. 5–7 constraints are not fully relaxed, but capped at the corresponding policy scenario level, this allows us to decompose the impact of the constraint on all biomass-based energy technologies (under option "FR") into contributions by each technology. At the same time, such a set up does not allow us to account for possible substitution between biomass-based energy technologies, e.g. it could be the case that if we constrain biowaste supply, supply of the woody biomass could exceed the policy scenario level, thus partially substituting the lost (restricted) volumes of the biowaste supply. To investigate such interactions, we explore four additional scenarios (Nos. 8–11 in the table), where we constrain bioenergy technologies one by one (at the BaU level), but do not put any constraints on the three remaining biomass-based energy technologies.
Source: Developed by authors.

identify the least-cost solution to achieve the mitigation target. However, this might not necessarily be true in the actual policymaking process. Specific support measures or targets could be introduced for selected technologies (e.g. feed-in tariffs for wind post-2030 or targeted share of solar generation in the electricity mix for the selected year). This could lead to the non-optimal choice of the energy supply mix and a lower than estimated share of biomass-based energy.

Third, biofuels' supply can be impacted by future competition with food-related crops [37]. Increasing demand for food – both domestic and exported – can limit the availability of land for growing dedicated energy crops and thus constrain the future bioenergy supply.

Fourth, like all other renewable energy sources, increasing bioenergy supply has its trade-offs. For instance, bioenergy plantations may adversely impact biodiversity and aerosol concentrations in the atmosphere, as well as lead to indirect land use changes [38]. Consideration of these potential effects of the bioenergy expansion might lead to the decision to limit the supply of this source of energy. It should be noted, however, that some recent advancements in the production practices can lead to reductions in the environmental impacts of the bioenergy supply. For instance Ref. [39], proposes a method that reduces the environmental impact of the biogas production from purpose-grown phytomass [40]; shows that Spirulina can serve both as a tool for waste-water management and as a feedstock for biorefining.

Finally, several studies report there is a significant lack of information about biofuels in society and that respondents prefer other renewable energy sources over biofuels. For instance, as shown in Ref. [41], this is the case for Greece. Radics et al. [42] also identify a significant lack of knowledge about liquid biofuels in North Carolina and Tennessee, suggesting the need for a wider communication of benefits and risks from the use of bioenergy to promote this transportation fuel. While similar studies have not been conducted for the case of Ukraine, low societal support of bioenergy could be another factor limiting the future availability of the bioenergy sources in the country.

Considering all these potential risks to the expansion of the bioenergy supply in Ukraine, it is important to understand what the economic costs are of the constrained bioenergy availability. It is also crucial to know what are the key bioenergy technologies that are the most promising in the case of Ukraine and which should be prioritized from the climate mitigation perspective.

As simulations suggest, in order to reach the emission reductions under Scenario 1, Ukraine's energy sector has to go through major transformations, as the share of renewables in TPES reaches 38.3% in 2050, a 36.3 percentage-point increase from the 2012 level (Fig. 6). Bioenergy plays a key role in this long-term energy transition, as over 50% of all renewable energy is supplied by biofuels, while the biofuels TPES exceeds 20.5 Mtoe in 2050 – more than gas and coal combined (Fig. 6).

Under a somewhat less ambitious mitigation scenario (Scenario 2), the role of bioenergy is still significant, with the share in TPES of 17.8% in 2050 (Fig. F.1, Appendix F). The share of bioenergy in renewables under Scenario 2 is virtually the same as under Scenario 1 (59.3% vs 59.5%, respectively – average over the 2020–2050), indicating that within the set of renewable generation technologies, biofuels represent an option with lower mitigation costs, compared to other renewable technologies.

In absolute terms, volumes of the bioenergy supply under both Scenario 1 and Scenario 2 increase dramatically compared to the 2015 levels – by 14.7 and 12.2 times, respectively (Fig. 7; Fig. F.2, Appendix F). Thus between 51% and 40% of the economically feasible bioenergy potential (Table 1) is utilized in 2050. Most of the bioenergy within both policy scenarios is coming from three sources – wood products, industrial waste-sludge and bioenergy crops (Fig. 7; Fig. F.2, Appendix F). While in the case of Scenario 2 the composition of biomass-based energy supply by years closely follows the BaU scenarios, under the more ambitious Scenario 1 the bioenergy mix changes more significantly, especially in the post-2040 period. With higher emission reduction costs, it is becoming more economically feasible to grow bioenergy crops and by 2050 a large share of the industrial waste-sludge feedstock is substituted by bioenergy crops, thus making the latter category a key contributor to the bioenergy mix (Fig. 7). A smaller portion of the industrial waste-sludge is substituted by wood products, which also show a major supply increase under Scenario 1 – more than doubling in absolute terms in 2050 compared to Scenario 2.

Decomposition of the bioenergy supply by uses suggests that in both Scenarios 1 and 2, 50% of all biomass is consumed by the power and heat generation sector, making it by far the largest biomass demander (Figs. G.1, G.2; Appendix G). An upscaling in biomass use is also observed for industry, agriculture and transport sectors. In the latter case, more ambitious climate mitigation targets make the use of the liquid biofuels economically feasible, while under the BaU scenario the share of the transport sector in the total biomass use is negligible. The commercial sector, on the other hand, shows a significant reduction in biomass use under policy scenarios (compared to BaU), as a direct biomass combustion by this sector (in the BaU) is substituted by the biomass-based centralized heat and electricity generation.

In terms of the aggregate implementation costs (total system costs (TSC)),[13] Scenario 1 is 13.4 B € or 1.8% more expensive than the BaU scenario, while Scenario 2 adds 6.4 B € or 0.9% compared to BaU. Constraining the bioenergy supply at the BaU scenario level more than doubles (147% increase) additional TSC under Scenario 1 and more than triples it (219% increase) under Scenario 2 (Fig. 8). In both policy scenarios biogas does not play a major role in the bioenergy supply mix (Fig. 8). The importance of the woody biomass significantly increases with a higher mitigation target – while under Scenario 2 only 19.5% of the increasing TSC are associated with woody biomass, under Scenario 1 this share increases to 36.8%. At the same time, the role of biowaste decreases with a transition toward higher ambitious mitigation scenario (Fig. 8).

In terms of the average emission reduction costs, estimated by dividing an increase in TSC by a reduction in GHG emissions over the period 2020–2050,[14] all bioenergy constraints under Scenario 1 lead to a 14.3 €/tCO_2-eq. increase in the abatement costs (from 9.9 €/tCO_2-eq. for the unconstrained case to 25.2 €/tCO_2-eq.) (Fig. H.1, Appendix H). Under the Scenario 2, corresponding increase in abatement costs is 10.8 €/tCO_2-eq. – more than tripling of the mitigation costs relative to the unconstrained case (Fig. H.1, Appendix H). While, as discussed earlier, biogas availability does not have any significant impact on the mitigation costs, unavailability of even one of the three remaining bioenergy sources (woody biomass, bioliquids and biowaste) increases the cost of emissions reduction per tCO_2-eq. by at least 35%.

When bioenergy supply is capped at the baseline scenario level (with all bio constraints), around half of the constrained supply is substituted by wind and solar energy, with a higher contribution of wind among these two renewable sources. The other half is being compensated by increasing nuclear and natural gas supply. This is the case for both policy scenarios.

Negative impact of the bioenergy constraints increases with more ambitious climate mitigation targets. For instance, in the case of the electricity and heat generation sector, which is the major user of biomass, the marginal price of CO_2 increases by 2.4 times (from 11.8 €/tCO_2-eq. to 28.1 €/tCO_2-eq.) if bioenergy is constrained in 2040 under

[13] Total system costs are used to measure the aggregate costs of the baseline and policy scenarios. Total system costs represent all costs (operational and investment expenditures) of the energy system operation discounted to the 2015 reference year and summed over the corresponding period of time. A discount rate of 5% is used.

[14] Changes in both indicators are measured relative to the BaU scenario level.

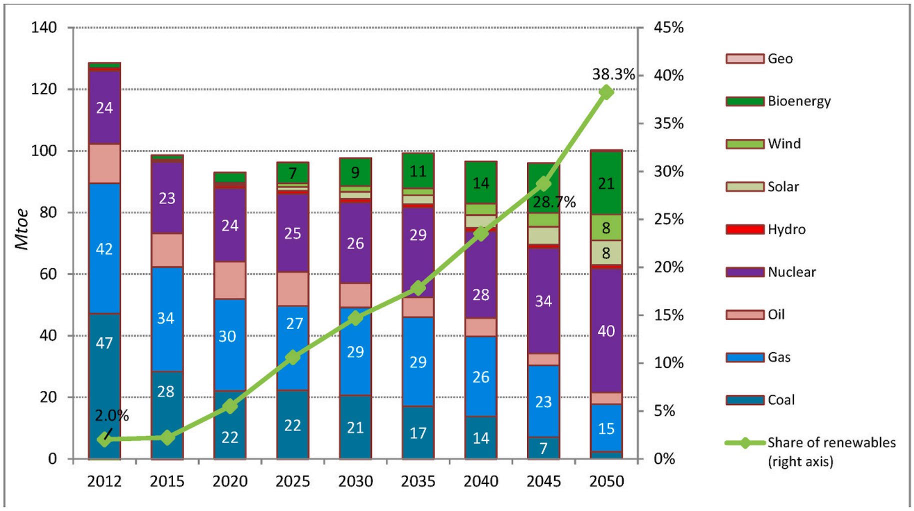

Fig. 6. TPES and the share of renewables under the Scenario 1. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* TPES is reported on the primary vertical axis of the figure and is represented using stacked bars. Share of renewables is reported on the secondary vertical axis of the figure and is represented with a green line.

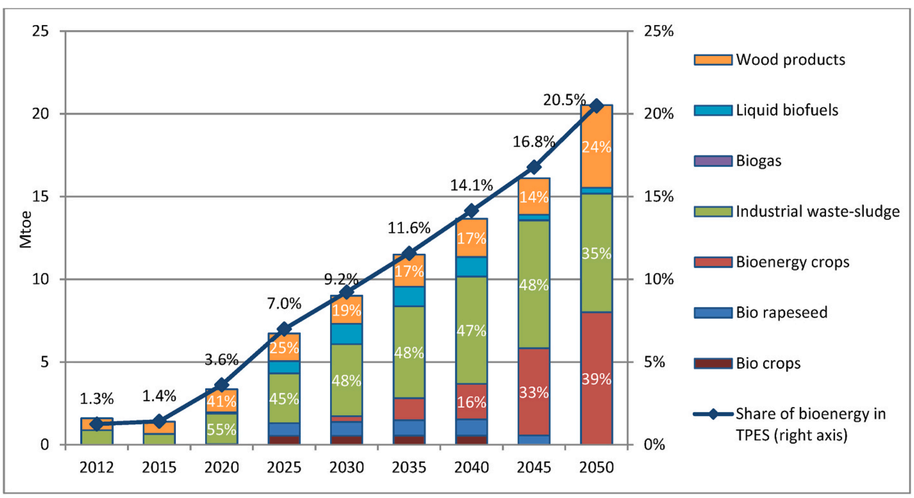

Fig. 7. TPES composition of the biomass-based energy sources under the Scenario 1. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* TPES of the biomass-based energy sources is reported on the primary vertical axis of the figure and is represented using stacked bars. Share of the bioenergy in country's TPES is reported on the secondary vertical axis of the figure and is represented with the blue line.

Scenario 1 (Fig. H.2, Appendix H). At the same time, a much more ambitious reduction target during the 2045–2050 period[15] leads to a more dramatic impact of bioenergy constraints on the marginal abatement cost, as the price of CO_2 increases by 18.3 times (from 86.1 €/tCO_2-eq. to 1574.9 €/tCO_2-eq.) (Fig. H.2, Appendix H), thus indicating a more significant role of biomass under stringent climate change mitigation targets. This result is consistent with a 100% renewable scenario analysed in Ref. [19] for the case of Ukraine, where the authors show that the share of solid biomass in the electricity generation mix becomes significant only in the post-2035 period.

We further explore interactions between different bioenergy sources, by constraining three out of four biofuels at the Baseline level and leaving one bioenergy source unconstrained (Scenarios 8–11 in Table 3). This allows us to assess whether there is any substitution within bioenergy sources or is it the case that most of the lost (constrained) supply of biofuels would be substituted by the non-biomass-based technologies. Simulations suggest that neither biogas nor bioliquids could provide any substantial contribution toward substituting other biofuels, as less than 4% of the lost (constrained) bioenergy TPES is being substituted by either of these two sources (Fig. 9). On the other hand, woody biomass and biowaste could play a major role in substituting other biofuels, as under both policy scenarios between 40% and 59% of the lost (constrained) bioenergy supply is substituted by these sources (Fig. 9).

While our assessment suggests that further development of the biomass-based energy generation in Ukraine could play a key role in the achievement of the ambitious climate mitigation targets, a number economic, political and technological constraints could prevent this from happening. As a result, a much more expensive climate mitigation option would need to be implemented, which would significantly increase the climate policy costs. As of the end of 2020, the future of the biomass-based energy generation in Ukraine remains highly uncertain. In the next section, we review some of the key challenges that the bioenergy sector faces and provide policy recommendations that could help to overcome these obstacles.

[15] A much more ambitious reduction in emissions relative to the baseline level and compared to the previous periods (i.e. before 2045). A simple average of the marginal CO_2 prices over the 2045–2050 period is estimated and reported.

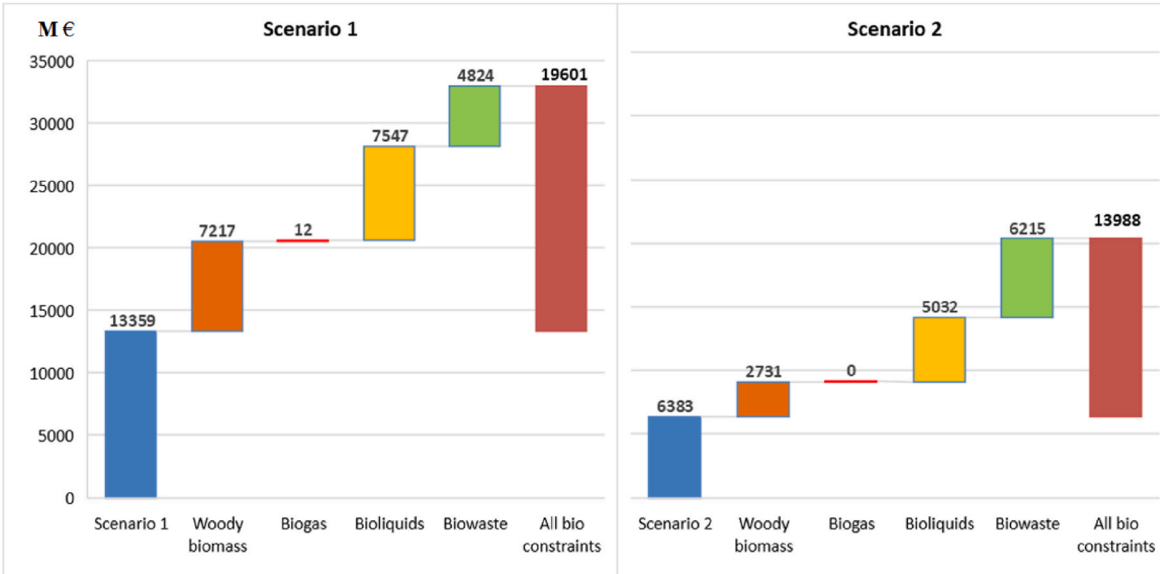

Fig. 8. Impact of the bioenergy constraints on the total system costs – aggregate over 2020–2050, M € (difference relative to the Baseline scenario). *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* The figure shows the impact of the bioenergy constraints on the total system costs (aggregate over 2020–2050) relative to the baseline scenario. Blue bars represent increases in total system costs in Scenarios 1 and 2 respectively (relative to BaU) without any constraints on bioenergy. Orange, red, yellow and green bars represent increases in total system costs when a corresponding bioenergy type (i.e. woody biomass, biogas, bioliquids or biowaste) is constrained at the BaU level. Pale red bar (far right on the chart) represents an increase in total system costs when all bioenergy types are constrained at the BaU level.

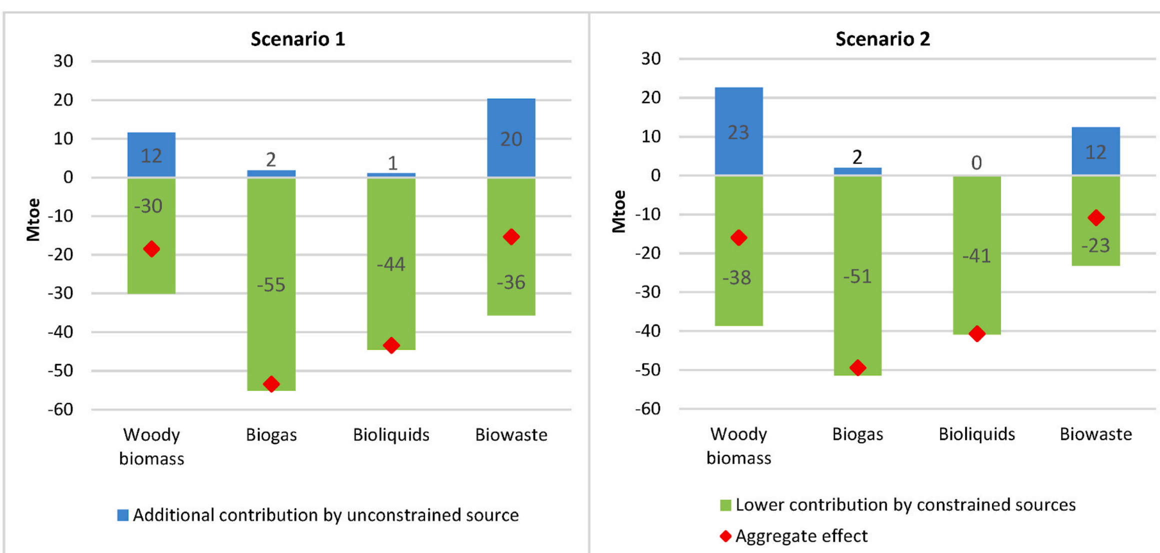

Fig. 9. Interactions between different bioenergy sources under constraining of one source at a time – difference in TPES over 2020–2050, Mtoe. *Source:* Developed by authors using TIMES-Ukraine model. *Note:* Each bar represents the case where the TPES of three bioenergy sources is constrained at the BaU level, while the TPES of the fourth bioenergy source (identified by the name of the bar) is unconstrained. The green part of the bar corresponds to the lower TPES (BaU relative to the policy scenario level) of the three constrained sources (aggregate). The blue part of the bar corresponds to the additional TPES (relative to the policy scenario level) of the unconstrained bioenergy source. Red rectangles correspond to the aggregate change in TPES of all bioenergy sources relative to the policy scenario level.

6. Conclusions

Despite all the attractive features of the biomass-based energy generation, biomass energy potential in Ukraine remains highly underexplored. As of 2015, less than 7.5% of the economically feasible potential of biomass was utilized. Apart from the potential biomass-related constraints discussed in the previous section, there is a number of existing regulatory, market and infrastructure-related obstacles that could prevent a wider deployment of the biomass in Ukraine. Some of these obstacles include the following:

- ➢ *Financial constraints* (poor access to the affordable financing options). This challenge is partially addressed with financial support of the international financial organizations that have developed programmes aimed at increasing energy efficiency and the share of RES; however, higher engagement of the domestic banking institutions is needed.
- ➢ *Lack of knowledge and expertise* sufficient for the development of the small-scale biomass projects. To overcome this barrier, wider information campaigns describing practical steps to use biomass are needed.
- ➢ *Imposition of the CO_2 tax on the biomass-based combined heat and power plants.* Despite the fact that biomass is carbon-neutral fuel, biomass-based combined heat and power plants (BioCHPs) in Ukraine have to pay taxes on CO_2 emissions. To solve this issue, BioCHPs have to be exempt from the CO_2 tax.
- ➢ *Poor regulation of the dedicated energy crops' market.* While most energy crops are formally present in the classifier of agricultural crops, market participants report that the classifier does not work as expected and none of the energy crops are treated as agricultural. Plantation investors are not included in the category of "agricultural producer" before the sale of the first harvest, so dedicated energy crop producers cannot claim certain advantages that agricultural producers are eligible for [43].
- ➢ *Non-transparency of the procedures for connecting to the grids.* Currently, the grid connection depends on the technical condition of the grid itself, as well as on the ability to reach an agreement with regional distribution companies. The national energy system operator "Ukrenergo" should ensure a stricter control over the rules' implementation by project developers and regional distribution companies.
- ➢ *Poor regulation of current waste management practices.* More strict financial responsibility for unprocessed waste is required. Companies having waste, such as animal manure, that do not process the manure correctly are subject to a fine. The size of the fine for corporate enterprises is around €3360–€4380/year, and for private entrepreneurs €1110–€2130/year. Sometimes companies prefer to pay a fine instead of implementing measures to dispose of the livestock waste. For comparison, in the EU, farmers violating legislation on waste processing are fined by reductions in Common Agricultural Policy payments, facing much more stringent measures and incentives for the proper disposal of livestock waste, compared to the case of Ukraine.

Some of these issues could be partially addressed by an increase in the CO_2 taxes – currently the level of the CO_2 tax in Ukraine is around 0.3 €/tCO_2-eq. [44].

In general, our results support an assumption that biomass could play a major role in the future of Ukraine's climate mitigation efforts, contributing to the TPES more than wind and solar combined. Though, if enabling conditions for the fulfilment of the biomass potential in Ukraine is not implemented, limiting the biomass potential, the Ukrainian energy system could face significant extra costs along the way to reaching the climate mitigation targets. According to the simulation results, availability of the bioenergy supply could reduce the cost of the climate mitigation policies by 14.0–19.6 B € and lower an average cost of emissions reduction by 10.8–14.3 €/tCO_2-eq., over the 2020–2050 period. While biogas availability does not have any significant impact on the mitigation costs, unavailability of any of the three other bioenergy sources (woody biomass, bioliquids and biowaste) increases the cost of emissions reduction per tCO_2-eq. by at least 35%. The negative impact of the biomass availability constraints rapidly increases over time and with more ambitious climate mitigation targets. In the case of electricity and heat generation, the marginal price of CO_2 increases by 2.4 times if bioenergy is constrained in 2040 and by 18.3 times for the 2045–2050 period under Scenario 1.

While our analysis provides a detailed quantitative assessment of the role of biomass in Ukraine's long-term energy transition, trying to take into account the best available information, there are a number of limitations and potential extensions to our approach that should be discussed. *First,* while the TIMES-Ukraine model represents the energy sector at a high level of detail, the model does not represent interactions with other sectors – in particular, agriculture. Although, based on the available data, most of the dedicated energy crops in Ukraine would be using marginalized lands (with low agricultural productivity) [28], there could be some competition with agriculture-related lands and thus an additional impact on food markets. We do not take into account such interactions. *Second,* in our assessment we focus on the impacts on the energy sector only, while possible implications at the macro level or impacts on other sectors (outside energy) are not considered. Linking the TIMES-Ukraine model to macroeconomic models, such as a computable general equilibrium model, could provide such assessment (e.g. see Ref. [7] for such a model link example). Implementation of the two-way model linkage would also allow for a more precise assessment of the structural shifts and changes in the energy demand. It should be noted, however, that some previous studies for Ukraine have reported moderate positive implications of the biogas development projects [45]. *Third,* a regional dimension of the biomass supply and biomass-based energy generation remains unexplored in our analysis. Considering that biomass-based generation facilities could be a high-priority option for the distributed generation, effects of the biomass-based projects could be highly heterogeneous by regions. *Finally*, the consideration of the various policy options toward the promotion of the biomass-based generation technologies requires more attention. In this paper, we identify a list of obstacles and policy options to promote the future use of biomass in the energy sector. Naturally, some of the discussed policies would be more efficient than others and would have a higher level of priority. Assessing and identifying such options would provide valuable information to the policymakers.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Key cost and technological assumptions for the bioenergy production technologies

Table A.1
Cost and technological assumptions for biomass-based cogeneration

Indicator	New	Used
Capital expenditure, €/$kW_{electr.}$	532	250
Operating expenses, €/$kW_{electr.}$	20	20
Coefficient of performance, %	87.2	87.2

Notes: prices are reported in the constant €2015.
Source: adopted from Ref. [29].

Table A.2
Cost and technological assumptions for biomass-based thermal power plants

Indicator	2015	2020	2025	2030	2035	2040	2045	2050
Wood biomass								
Capital expenditure, €/$kW_{electr.}$	2800	2800	2800	2600	2500	2400	2200	2000
Operating expenses, €/$kW_{electr.}$	30							
Coefficient of performance, %	24	24	25	26	28	29	30	31
Installed capacity utilization factor, %	50							
Lifetime, years	30							
Biomass from waste of agricultural and food industry								
Capital expenditure, €/$kW_{electr.}$	3500	2900	2800	2700	2600	2500	2300	2100
Operating expenses, €/$kW_{electr.}$	30							
Coefficient of performance, %	23	23	24	24	25	27	28	29
Installed capacity utilization factor, %	50							
Lifetime, years	30							
Biogas								
Capital expenditure, €/$kW_{electr.}$	4500	4400	4300	4200	4100	4000	3900	3800
Operating expenses, €/$kW_{electr.}$	30							
Coefficient of performance, %	42	42	42	43	43	43	44	44
Installed capacity utilization factor, %	90							
Lifetime, years	30							

Notes: Prices are reported in the constant €2015.
Source: Adopted from Ref. [7].

Table A.3
Cost and technological assumptions for biomass combined heat and power plants

Indicator	2015	2020	2025	2030	2035	2040	2045	2050
Wood biomass								
Capital expenditure, €/$kW_{electr.}$	3500	3400	3300	3200	3100	3000	2900	2800
Operating expenses, €/$kW_{electr.}$	50							
Coefficient of performance, %	20	20	20	20	20	20	21	21
Installed capacity utilization factor, %	50							
Lifetime, years	35							
Biomass from waste of agricultural and food industry								
Capital expenditure, €/$kW_{electr.}$	3500	3400	3200	3100	2900	2900	2800	2800
Operating expenses, €/$kW_{electr.}$	55							
Coefficient of performance, %	19	19	19	19	19	19	20	20
Installed capacity utilization factor, %	50							
Lifetime, years	35							
Household waste								
Capital expenditure, €/$kW_{electr.}$	5500	5400	5200	5100	5000	4800	4500	4500
Operating expenses, €/$kW_{electr.}$	55							
Coefficient of performance, %	25	25	25	25	25	25	26	26
Installed capacity utilization factor, %	50							
Lifetime, years	35							
Energy crops								
Capital expenditure, €/$kW_{electr.}$	3500	3400	3300	3200	3100	3000	3000	3000
Operating expenses, €/$kW_{electr.}$	50							
Coefficient of performance, %	20	20	20	20	20	20	21	21
Installed capacity utilization factor, %	50							
Lifetime, years	35							

Notes: Prices are reported in the constant €2015.
Source: Adopted from Ref. [7].

Table A.4
Cost and technological assumptions for the biomass-based residential boilers

Indicator	2015	2020	2025	2030	2035	2040	2045	2050
Wood biomass								
Capital expenditure, €/kW$_{electr.}$	150	145	142	140	138	136	136	136
Operating expenses, €/kW$_{electr.}$	7							
Coefficient of performance, %	64	64	64	64	64	65	65	65
Installed capacity utilization factor, %	50							
Lifetime, years	35							
Waste of the agricultural and food industry								
Capital expenditure, €/kW$_{electr.}$	400	350	320	300	280	270	260	250
Operating expenses, €/kW$_{electr.}$	7							
Coefficient of performance, %	62	62	62	62	63	63	63	64
Installed capacity utilization factor, %	50							
Lifetime, years	35							

Notes: Prices are reported in the constant €2015.
Source: Adopted from Ref. [7].

Table A.5
Cost and technological assumptions for the biomass-based heat generation industrial boilers

Indicator	2015	2020	2025	2030	2035	2040	2045	2050
Wood biomass								
Capital expenditure, €/kW$_{electr.}$	145	142	140	138	136	134	134	145
Operating expenses, €/kW$_{electr.}$	7							
Coefficient of performance, %	83							
Installed capacity utilization factor, %	60							
Lifetime, years	40							
Waste of the agricultural and food industry								
Capital expenditure, €/kW$_{electr.}$	270	260	250	240	230	220	220	270
Operating expenses, €/kW$_{electr.}$	7							
Coefficient of performance, %	80							
Installed capacity utilization factor, %	60							
Lifetime, years	40							

Notes: Prices are reported in the constant €2015.
Source: Adopted from Ref. [7].

Appendix B. Basic structure of the energy system in the TIMES-Ukraine model

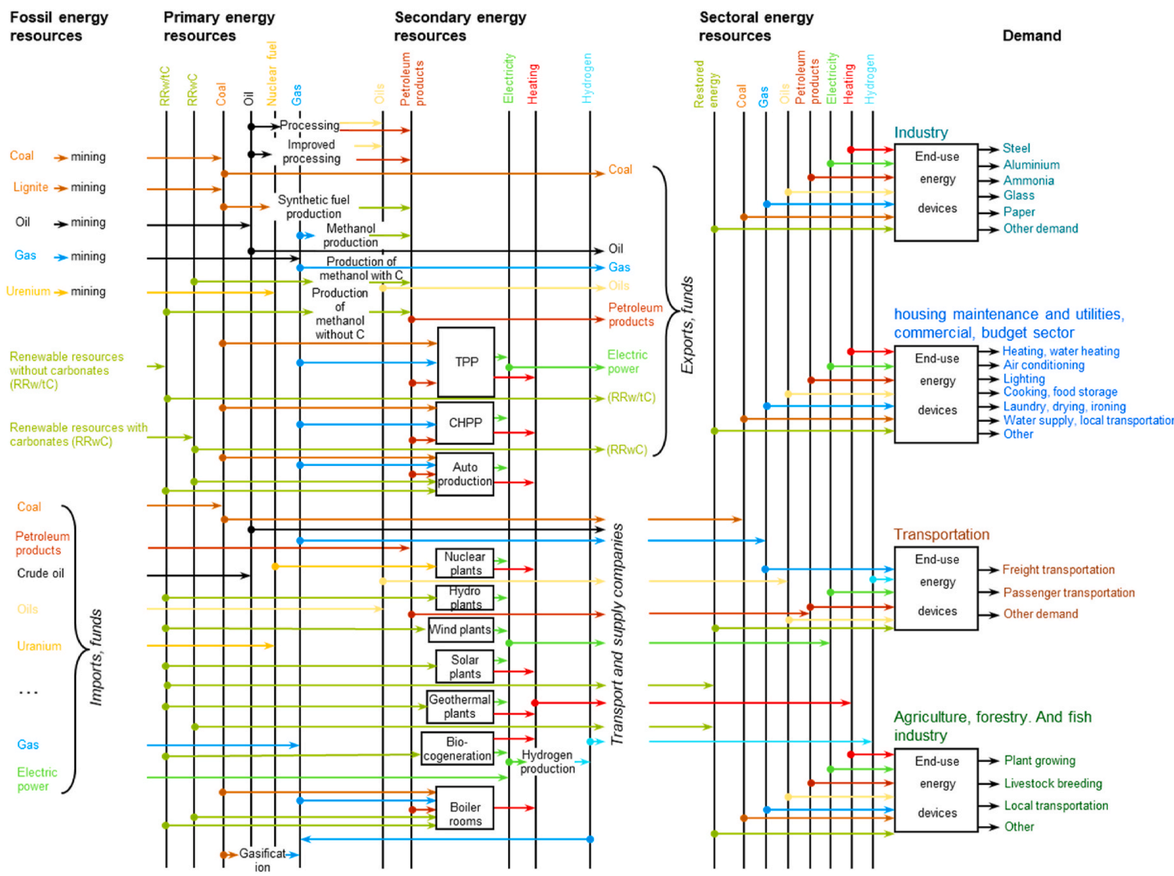

Fig. B.1. Representation of the energy system in the TIMES-Ukraine model. *Source:* Developed by authors.

Appendix C. Economic and demographic assumptions for the baseline scenario

Table C.1
Economic assumptions for the baseline scenario, average over period, %

Indicator	2021–2030	2031–2040	2041–2050
GDP growth rate			
Aggregate	3.8	3.5	3.2
Mining and quarrying	2.0	1.2	0.6
Manufacturing	4.5	4.2	3.8
Industry	3.5	3.2	2.9
Construction	5.0	4.3	3.9
GDP composition			
Services	52.7	54.3	55.7
Agriculture	9.3	8.2	7.3

Source: Developed by authors.

Table C.2
Demographic assumptions for the baseline scenario

Indicator	2018		2030	2040	2050
Population, million	42.4	39.7		37.7	35.6
Average life expectancy, both genders, years	72.2	73.9		75.3	76.7
Average population age, both genders, years	40.5	42.7		44.4	45.4
Share of working-age population, both genders, %	51.1	48.4		47.5	43.0
Number of retired per working persons, both genders, persons	0.99	1.14		1.24	1.49
Share of rural population, %	32.6	31.6		30.2	28.6

Notes: Population numbers are aligned with reported data provided by the State Statistics Service of Ukraine and do not included the annexed territory of the Republic of Crimea. GDP forecasts do not take into account the impact of COVID.
Source: Developed by authors using inputs provided by experts from the Institute of Demography and Social Studies of the National Academy of Sciences of Ukraine.

Appendix D. Consumption of the biomass-based energy by sectors under the baseline scenario

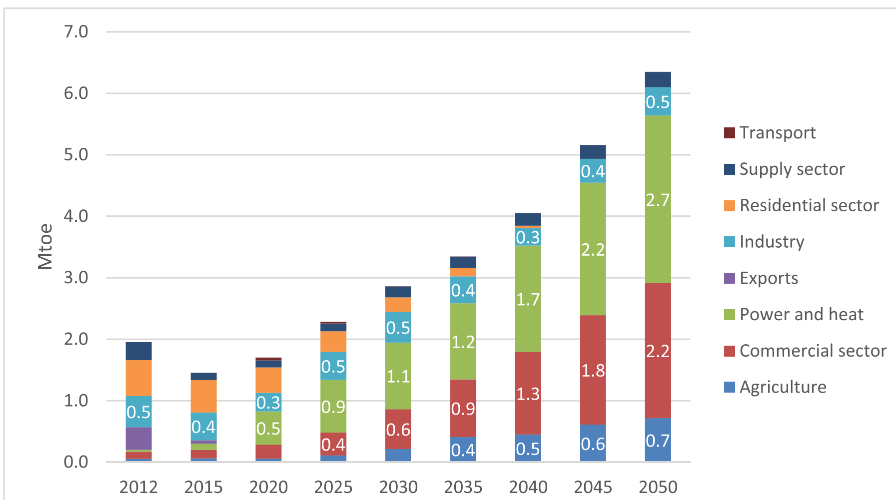

Fig. D.1. Consumption of the biomass-based energy by sectors under the baseline scenario. *Source:* Developed by authors using TIMES-Ukraine model.

Appendix E. Mapping between energy sources and categories for the decomposition analysis

Table E.1
Mapping between biomass-based energy sources represented in the TIMES-Ukraine model and aggregate biomass-based energy categories for the decomposition analysis

	Woody biomass	Biogas	Bioliquids	Biowaste
Bio crops			+	
Bio energy crops	+			
Bio rapeseed			+	
Liquid biofuel			+	
Biogas		+		
Industrial waste-sludge				+
Municipal waste				+
Wood products	+			

Notes: Biomass-based energy sources represented in the TIMES-Ukraine model are listed in the first column, while aggregate biomass-based energy categories are listed in the first row. Mapping cases are indicated with "+" symbol.
Source: Developed by authors.

Appendix F. Total primary energy supply under Scenario 2

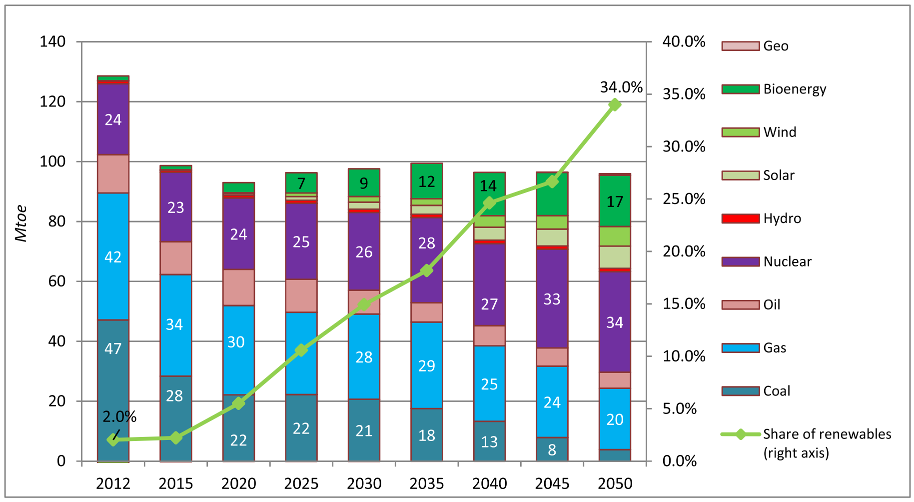

Fig. F.1. TPES and the share of renewables under Scenario 2. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* TPES is reported on the primary vertical axis of the figure and is represented using stacked bars. Share of renewables is reported on the secondary vertical axis of the figure and is represented with a green line.

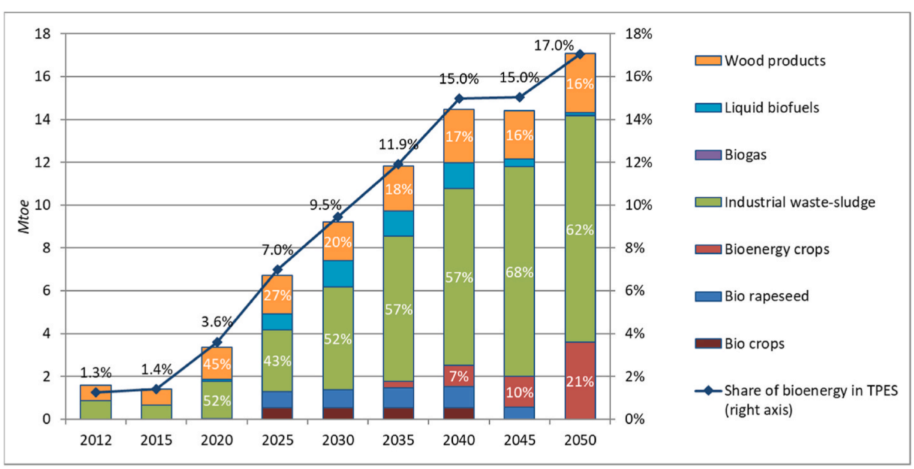

Fig. F.2. TPES composition of the biomass-based energy sources under Scenario 2. *Source:* Developed by authors using TIMES-Ukraine model. *Notes:* TPES of the biomass-based energy sources is reported on the primary vertical axis of the figure and is represented using stacked bars. Share of the bioenergy in country's TPES is reported on the secondary vertical axis of the figure and is represented with the blue line.

Appendix G. Consumption of the biomass-based energy by sectors under Scenarios 1 and 2

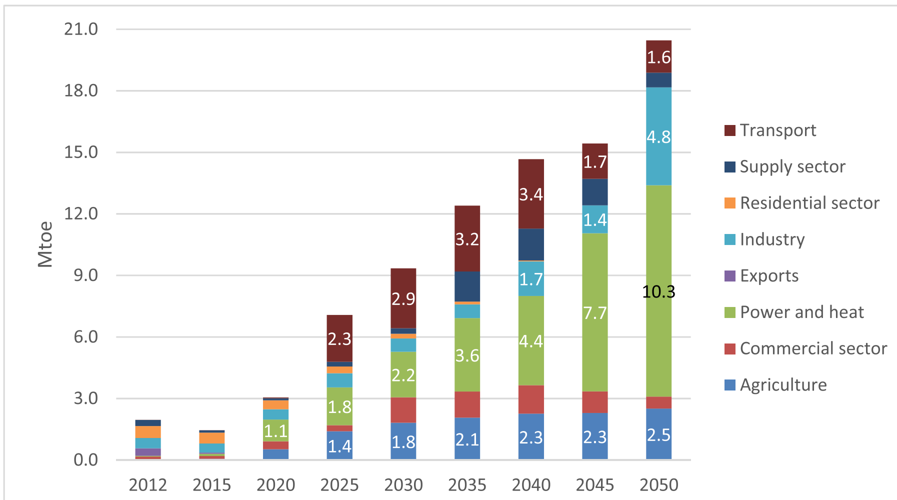

Fig. G.1. Consumption of the biomass-based energy by sectors under the Scenario 1. *Source:* Developed by authors using TIMES-Ukraine model.

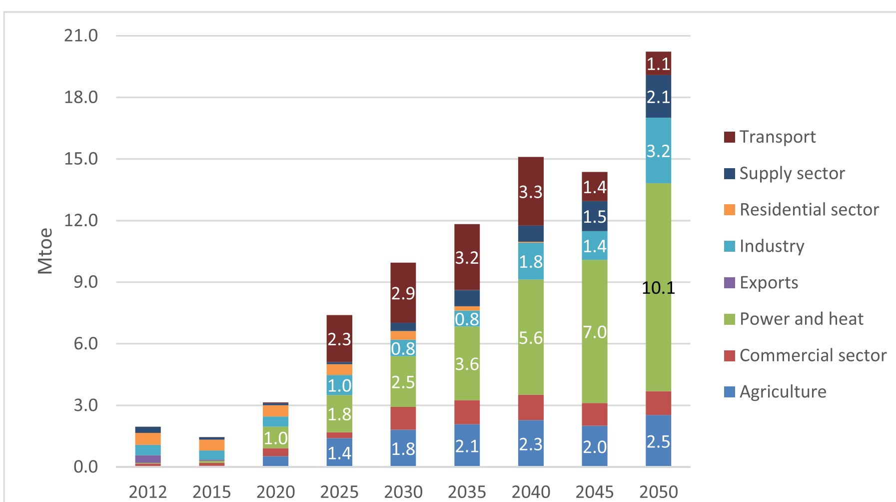

Fig. G.2. Consumption of the biomass-based energy by sectors under the Scenario 2. *Source:* developed by authors using TIMES-Ukraine model.

Appendix H. Impact of the bioenergy constraints on the GHG abatement costs

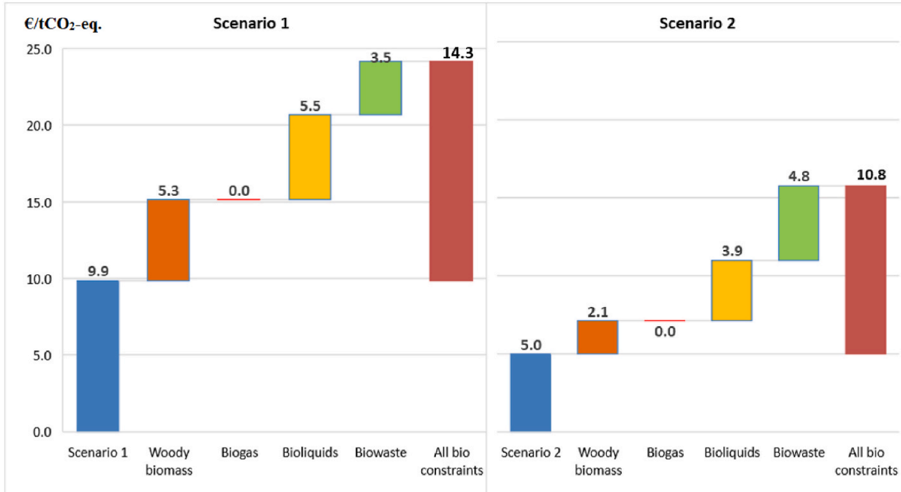

Fig. H.1. Impact of the bioenergy constraints on the GHG abatement costs – average over 2020–2050, €/tCO_2-eq. (difference relative to the Baseline scenario). *Source:* Developed by authors using TIMES-Ukraine model. *Note:* GHG abatement cost is estimated by dividing an increase in the TSC (relative to the Baseline scenario) by the GHG emission reductions (relative to the Baseline scenario) over the 2020–2050 time frame. Blue bars represent increases in abatement costs in Scenarios 1 and 2, respectively (relative to BaU), without any constraints on bioenergy. Orange, red, yellow and green bars represent increases in the abatement costs when a corresponding bioenergy type (i.e. woody biomass, biogas, bioliquids or biowaste) is constrained at the BaU level. The pale red bar (far right on the chart) represents an increase in abatement costs when all bioenergy types are constrained at the BaU level.

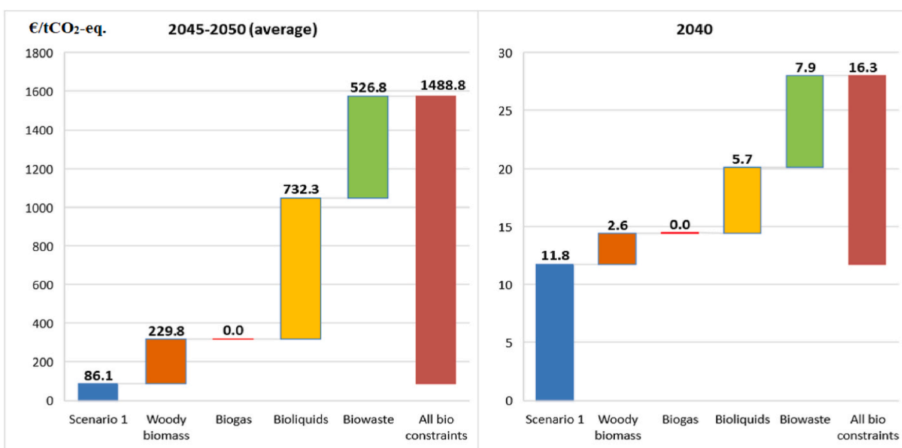

Fig. H.2. Marginal cost of emission reductions in the electricity sector under Scenario 1, €/tCO_2-eq. *Source:* Developed by authors using TIMES-Ukraine model. *Note:* For the 2045–2050 marginal cost of emission reductions a simple average of 2045 and 2050 is taken. Blue bars represent increases in abatement costs in Scenarios 1 and 2, respectively (relative to BaU), without any constraints on bioenergy. Orange, red, yellow and green bars represent increases in the abatement costs when a corresponding bioenergy type (i.e. woody biomass, biogas, bioliquids or biowaste) is constrained at the BaU level. Pale red bar (the most right on the chart) represents an increase in abatement costs when all bioenergy types are constrained at the BaU level.

Credit author statement

Maksym Chepeliev: Conceptualization, Supervision, Visualization, Writing - Original Draft, Writing - Review & Editing. **Oleksandr Diachuk:** Methodology, Software, Formal analysis, Visualization. **Roman Podolets:** Methodology, Software. **Galyna Trypolska:** Writing - Original draft preparation.

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