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Sotnyk, Iryna; Sasse, Jan-Philipp; Trutnevyte, Evelina

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Decarbonizing Ukraine's electricity sector in 2035: Scenario analysis

Iryna Sotnyk [a,b,*], Jan-Philipp Sasse [a], Evelina Trutnevyte [a]

[a] Renewable Energy Systems group, Institute for Environmental Sciences (ISE), Section of Earth and Environmental Sciences, University of Geneva, Uni Carl Vogt, Boulevard Carl Vogt 66, CH-1211, Geneva, Switzerland
[b] Department of Economics, Entrepreneurship and Business Administration, Sumy State University, Kharkivska 116, 40007, Sumy, Ukraine

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ABSTRACT

In this study, we considered the case of decarbonizing Ukraine's electricity sector that has significant import dependence, high energy and carbon intensity, and an unprecedented destruction of electricity facilities due to ongoing war. Using a newly built UKRAINE-EXPANSE model, which covers 24 Ukrainian oblasts (regions) and five neighboring countries at high temporal and spatial resolution, we offered four cost-optimal scenarios for the national electricity sector in 2035. Considering the targets of the current National Energy and Climate Plan and the Updated Nationally Determined Contribution of Ukraine to the Paris Agreement, we analyzed the structure of the installed capacities, annual electricity generation, storage, transmission, and trade with neighboring countries and calculated sustainability impacts (greenhouse gas and air pollution emissions, employment, land use, and total system costs). We showed that in 2035, the undamaged total installed capacity (as of May 2024) should be increased by 2.7–3.2 times while supplying up to 16.3 % higher electricity demand compared to the pre-war period. Nuclear and gas power would still remain the primary electricity sources in 2035, supported by intensive growth in wind power, pumped hydropower storage, bioenergy and expansion of transmission grids. Implementing environmentally friendly scenarios with 30 % of renewable generation and/or no hard coal power would require only 5 to 13 % higher total system costs compared to the least cost scenario, which could be socially and politically acceptable.

1. Introduction

Considering the international Sustainable Development Goals [1] and the global threat of climate change [2], achieving carbon neutrality is today's priority for many countries worldwide, such as countries of the European Union for 2050 [3], China for 2060, or India for 2070 [4, 5]. The first step to reaching carbon neutrality of the whole economy is a transition to a zero-carbon electricity system, especially using renewable energy sources [6], which primarily generate electricity (solar photovoltaic (PV), wind power, hydropower, etc.). Zero-carbon electricity can then be used to decarbonize transportation and heating through electrification. The national electricity sectors are thus expected to be the locomotives of the transition to carbon neutrality.

Energy transition, in general, is of utmost importance for Ukraine since the country heavily depends on imported energy, has a high energy and carbon intensity of the gross domestic product, and faces accumulating problems with electricity provision due to the ongoing Russia's war of aggression against Ukraine and destruction of domestic infrastructures [7,8]. As a member of the European Energy Community and a contributor to the Paris Agreement, Ukraine is also obliged to reach carbon neutrality by 2050 [81]. To tackle this goal, the government developed and adopted the National Energy and Climate Plan until 2030 (NECP) [9], the National Emission Reduction Plan from Large Combustion Plants [10], the National Action Plans for Energy Efficiency and Renewable Energy until 2030 [11,12], the Ukraine 2050 Low Emission Development Strategy [13] and other specialized documents. The ongoing Russian aggression, however, adds significant uncertainty and shapes further needs of Ukraine's electricity sector. First, it questions the feasibility of earlier energy system scenarios [14–16] and strategies [17–19] and requires updated solutions for rebuilding the electricity sector in the post-war period. Second, an important shortcoming of Ukraine's electricity system, which became crucial in wartime, is its high centralization of installed capacity. The legacy from the Soviet period, namely, large nuclear, thermal, and hydropower plants generating great quantities of electricity for own and neighboring regions, are now targeted by Russians. Therefore, along with the

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[*] Corresponding author at: Renewable Energy Systems group, Institute for Environmental Sciences (ISE), Section of Earth and Environmental Sciences, University of Geneva, Uni Carl Vogt, Boulevard Carl Vogt 66, CH-1211, Geneva, Switzerland.
E-mail address: iryna.sotnyk@unige.ch (I. Sotnyk).

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decarbonization of the national electricity sector [20–22], issues of regional decentralization of electricity capacities become urgent and strategically significant [23,24]. Third, as the electricity system infrastructures will be rebuilt in the post-war period, there will be an opportunity to transition to zero-carbon, renewable and decentralized energy sources without the need to prematurely phase-out existing technologies.

To provide insights into the future opportunities for Ukraine's electricity sector when building and/or reconstructing its capacities at the state and regional levels, we modeled Ukraine's electricity sector using a newly developed spatially and temporally explicit UKRAINE-EXPANSE model, adapted from the previous model versions in Switzerland [25–27] and Europe [28–30]. Previous modeling of Ukraine's energy sector mostly used the whole system models TIMES-UKRAINE [31–33] and DESTINEE [24], which do not cover spatio-temporal detail that is relevant for renewable energy sources and hence are known to underestimate the potential role of these sources [34,35]. Unlike these models, UKRAINE-EXPANSE reflects the regionalized and temporal analysis of electricity demand, generation, storage, transmission, and import and export. Furthermore, in addition to the assessment of the total system costs and greenhouse gas emissions like in TIMES-UKRAINE, UKRAINE-EXPANSE also quantifies other relevant sustainability impacts, such as air pollution emissions, employment, and land use [28,29]. Using this new model, we developed and analyzed four scenarios for Ukraine's electricity sector in 2035 by applying various decarbonization and technology-specific constraints to reflect the targets set in NECP [9] and the Updated Nationally Determined Contribution (NDC2) of Ukraine to the Paris Agreement [5].

2. Methods

2.1. Ukraine-expanse model

To build UKRAINE-EXPANSE, we adapted existing EXPANSE models for Switzerland [25–27] and Europe [28–30], and complemented them with some data assumptions from the PyPSA-Eur model. UKRAINE-EXPANSE is a spatially- and temporally-resolved, bottom-up, single-year optimization model, which optimizes electricity demand, generation, storage, transmission, import and export in terms of both installed capacities and generation of the United Energy System of Ukraine and its neighboring countries in 2035. In Ukraine, the model analyses 24 Ukrainian oblasts (administrative regions) in terms of generation and demands and 11 nodes for modeling storage and transmission in the regions (Fig. 1). Due to the lack of reliable statistical data, we excluded Crimea and part of the territories of Luhansk and Donetsk regions occupied by Russia before February 2022 from consideration. In addition, Kyiv city and Kyiv region were accounted together as the Kyiv region. UKRAINE-EXPANSE also covers 5 neighboring countries (Poland, Slovakia, Hungary, Romania, and Moldova), modeled as single-country nodes for import and export analysis (Fig. 1).

UKRAINE-EXPANSE includes 17 electricity generation technologies (onshore and offshore wind power, solar PV, biogas, woody biomass, agricultural and municipal waste, energy crops, small hydropower, run-of-the-river hydropower, geothermal, gas, hard coal, lignite, oil, nuclear plants, and hydropower dams), three storage options (pumped hydropower storage, power-to-hydrogen, and batteries), and two types of transmission (alternating current for Ukraine's domestic lines and, for modeling purpose, direct current for neighboring countries). Three-hour time resolution for the whole year 2035 for supply-demand balancing at a regionalized scale is applied to ensure a good compromise [25,38] between the need for high temporal resolution for modeling renewable energy sources and the computational tractability of modeled scenarios. The model balances electricity generation, storage, and transmission under the inelastic demand assumption at each node and time step, while electricity generation and demand are modeled at the oblast level.

The sustainability impacts of various scenarios on greenhouse gas (GHG) emissions, air pollution (as particulate matter PM_{10} emissions), direct electricity sector jobs, direct land use, and total system cost are processed for the different scenarios bottom up, using indicators per unit of installed capacity or generation. The methodology for calculating these indicators is presented in [25,28,29,39,40].

2.2. Data

The datasets for the study were formed based on the European EXPANSE model [28,29] and PyPSA-Eur model [41] workflows, as well as data from ENTSO-E [42], Eurostat [43], NPC "Ukrenergo" [44], and the State Statistics Service of Ukraine [45,46]. In addition, we used recent publications on economic and technical indicators of power systems and electricity technologies [47–50], as well as energy data from the World Resources Institute [51], International Energy Agency [52], European Commission [53], Joint Research Centre of the European Commission [54,55], United Nations Economic Commission for Europe [56], International Renewable Energy Agency [57], and others. The Ukrainian data was collected based on regional information [42,58–64]. The technology potentials in 2035 were set based on earlier studies [58–64] while assuming that electricity capacities on coal would not exceed their current level.

The ongoing war caused the closing of the recent energy data in Ukraine to the public. Thus, for this study, we estimated the available electricity capacities as of May 2024, based on the data of Kyiv School of Economics (KSE) regarding damage assessments across sectors of the

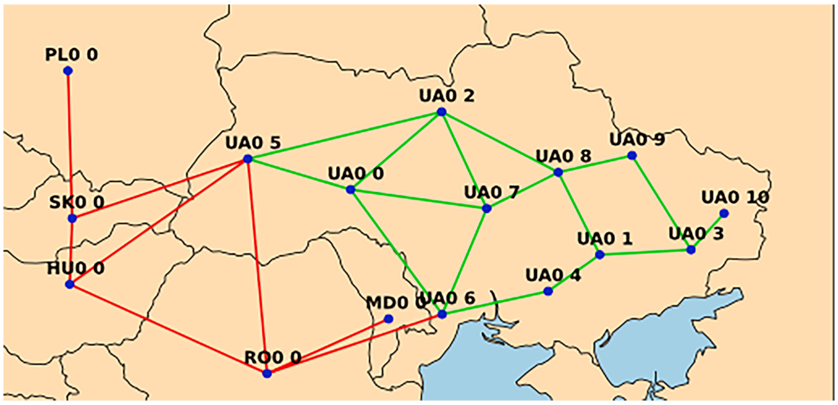

Fig. 1. Spatial structure of UKRAINE-EXPANSE. Green lines and UA0 points show the representation of the Ukrainian nodes for balancing supply, demand, storage and transmission. They reflect grid bottlenecks within Ukraine. Red lines and remaining points show the interconnections (Net Transfer Capacities [36,37]) with neighboring countries, modeled as single-country nodes.

national economy [65,66], ecodozor.org database on emergencies at energy facilities [67], the UNDP [68] and official reports from news agencies of UNIAN [69] and UKRINFORM [70] regarding the destruction of the Ukrainian power facilities. The assessment of the current capacity levels was carried out in several steps. First, we created a database of regional electricity capacities for 22 types of considered electricity technologies based on pre-war official data from 2018 to 2021 [45,46]. Then, we reduced the volumes of generation capacities by type and region based on the irreversibly lost generating capacities, whose restoration would take at least 3–5 years (e.g., Kakhovska hydropower dam, Trypilska thermal power plant). Next, based on the analysis of total economic losses estimated by KSE [65,66], we ranked and grouped the regions into five categories according to the degree of destruction. For each group, we assumed a certain percentage of reduction in electricity capacities:

- for Donetsk, Kharkiv and Luhansk – by 90 %;
- for Zaporizhzhya, Kherson, Kyiv and Mykolayiv – 70 %;
- for Chernihiv, Sumy, Dnipropetrovsk and Odesa – 50 %;
- for Khmelnytskiy, Zhytomyr, Poltava, Vinnytsya, Ivano-Frankivsk, Lviv and Rivne – 30 %;
- for Kirovohrad, Cherkasy, Ternopyl, Chernivtsi, Volyn and Zakarpattya – 20 %.

The UKRAINE-EXPANSE model adapted the technical and economic parameters, such as lifetime, specific investments, annualized capital and variable costs, fuel costs, CO_2 intensity, efficiency, and specific sustainability impacts of different technologies (direct employment, PM_{10} emissions, and land use) from the EXPANSE model [25] (see Supplementary Material). The weighted average cost of capital was set at 5 % based on recommendations of the European Commission and recent studies [33,71].

The electricity demand for selected countries in 2035 was assumed based on Ukraine's NECP [9], the National Energy and Climate Plan of Moldova [72], and the data from Demand Time Series 2025–2040 for Slovakia, Poland, Romania, and Hungary [73]. The demand for Ukraine was set at 180.8 TWh (16.3 % higher than in 2018), which was the average value calculated for 2035 based on the electricity demand forecasted in NECP [9]. The peak demand was set at 28.8 GW and the average demand was assumed to be at 20.6 GW per hour. The demand was allocated for each region proportionally to its pre-war values. The study assumed no new nuclear power and fossil fuel capacities in the future facilities [9,74].

2.3. Scenarios

We analyzed four cost-optimal scenarios for Ukraine and its neighboring countries in 2035, combining different decarbonization and technology constraints. The MinCost scenario minimized the total system cost without applying any constraints. COAL0 scenario assumed no hard coal facilities to generate electricity in 2035 according to the NECP target for thermal power plants in Ukraine in 2030 [9,10,13,16]. RES30 % scenario covered minimum annual volumes of electricity generation (30 % in the electricity mix) from green power sources: hydropower dams and pumped hydropower storage (assumed at least at 10.3 TWh/year), and other renewable sources (solar PV, wind power, biogas, woody biomass, agricultural and municipal waste, energy crops, small hydropower, and geothermal power, assumed at least at 45.5 TWh/year in total) based on the averaged estimations for 2035 calculated from NECP [9]. The fourth scenario COAL0+RES30 % involved the combination of COAL0 and RES30 % constraints. Also, we considered Ukraine's decarbonization target indicated in NECP and the Updated Nationally Determined Contribution (NDC2) to the Paris Agreement [5,16] by extrapolating it for 2035. This target reflected Ukraine's obligation to reduce GHG emissions by 70 % (or down to 29.7 Mt CO_2) in 2035 if aiming for 1.5°C temperature limit [75].

3. Results

3.1. Comparison of scenarios in terms of installed capacities

All four developed scenarios rationalized the current electricity generation and storage capacities and radically transformed their structure. Compared to the undamaged electricity facilities as of May 2024, the growth of capacities until 2035 would be 2.7–3.2 times. However, despite the assumed 16.3 % increase in electricity demand by 2035 as compared to 2018, the scenarios suggested a reduction in the total installed generation and storage capacities from 57 GW in 2018–2021 to 45.9–54.3 GW in 2035 or by 4.7 % to 19.5 % (Fig. 2). The most significant decline (by 19.5 %) in the total installed capacity was observed in the MinCost scenario, while scenarios with COAL0 constraint showed lower levels of capacity reduction (by 11.7 %) due to the noticeable growth of wind power (offshore and onshore) and agricultural waste in the capacity mix to substitute hard coal. RES30 % scenario had the lowest decline because of even higher shares of weather-dependent renewable technologies, such as onshore and offshore wind power. The increasing volumes of green sources in scenarios with constraints also needed additional storage technologies or peak plants as backup since renewable technologies have lower capacity factors than conventional technologies.

The structure of installed capacities by technologies also varied significantly among the scenarios, while it was similar for the scenarios with COAL0 constraint. It meant that RES30 % constraint was satisfied by default while introducing the COAL0 constraint. The list of technologies with essential capacities observed across MinCost and RES30 % scenarios included hard coal, hydropower dams, pumped hydropower storage, solar PV, nuclear power, wind power (onshore and offshore), biogas and gas. The options with COAL0 constraint (COAL0 and COAL+RES30 %) added up to 2.9 GW to agricultural waste, 3.6 GW and 1.5 GW to facilities with onshore and offshore wind plants, respectively, compared to the MinCost scenario. Solar PV, hydropower dam and nuclear power capacities stayed at the same level for all scenarios, except for RES30 % scenario, with only a slight deviation for hydropower dams due to the maturity and wide use of these technologies in Ukraine already and due to the pre-war tremendous growth in solar PV encouraged by high feed-in tariffs. The value of electricity capacities using gas was stable for all scenarios but increased by 21.6 % compared to the pre-war level. Onshore and offshore wind capacities increased steadily with the introduction of COAL0 and RES30 % constraints from 8.8 GW and 1.6 GW in MinCost scenario to 15.5 GW and 4.3 GW in RES30 % scenario, respectively.

In terms of conventional technologies, nuclear power capacity varied from 11.8 GW (21.7 % in total capacities) in RES30 % scenario to 13.8 GW (27.4–30.0 %) in other scenarios. Scenarios without COAL0 constraint suggested 4.7 GW (10.2 % for MinCost and 8.7 % for RES30 % scenarios) of capacities on hard coal to compensate for nuclear power in the RES30 % scenario and for renewable technologies in the MinCost scenario due to the low assumed cost of coal facilities compared to renewable technologies and nuclear power when environmental costs were not considered and due to the assumption on non-extension of current hard coal capacities. All scenarios demonstrated the increasing share of gas capacities from the current (undamaged) 0.8 GW to 3.3 GW to replace hard coal facilities and balance inflexible nuclear and renewable capacities. In addition, since gas combustion generated lower emissions than hard coal and since gas is a close substitute to coal, scenarios offered significant increments in gas capacities to reach decarbonization targets.

Contrary to the most significant conventional technologies analyzed above, agricultural waste did not play essential role in MinCost and RES30 % scenarios. As for biogas, its capacity increased from 0.3 GW in MinCost scenario to 0.7 GW in RES30 % scenario and to 1 GW in options with the COAL0 constraint. Woody biomass, energy crops, municipal waste, and small hydropower kept the same capacity level in 2035 as

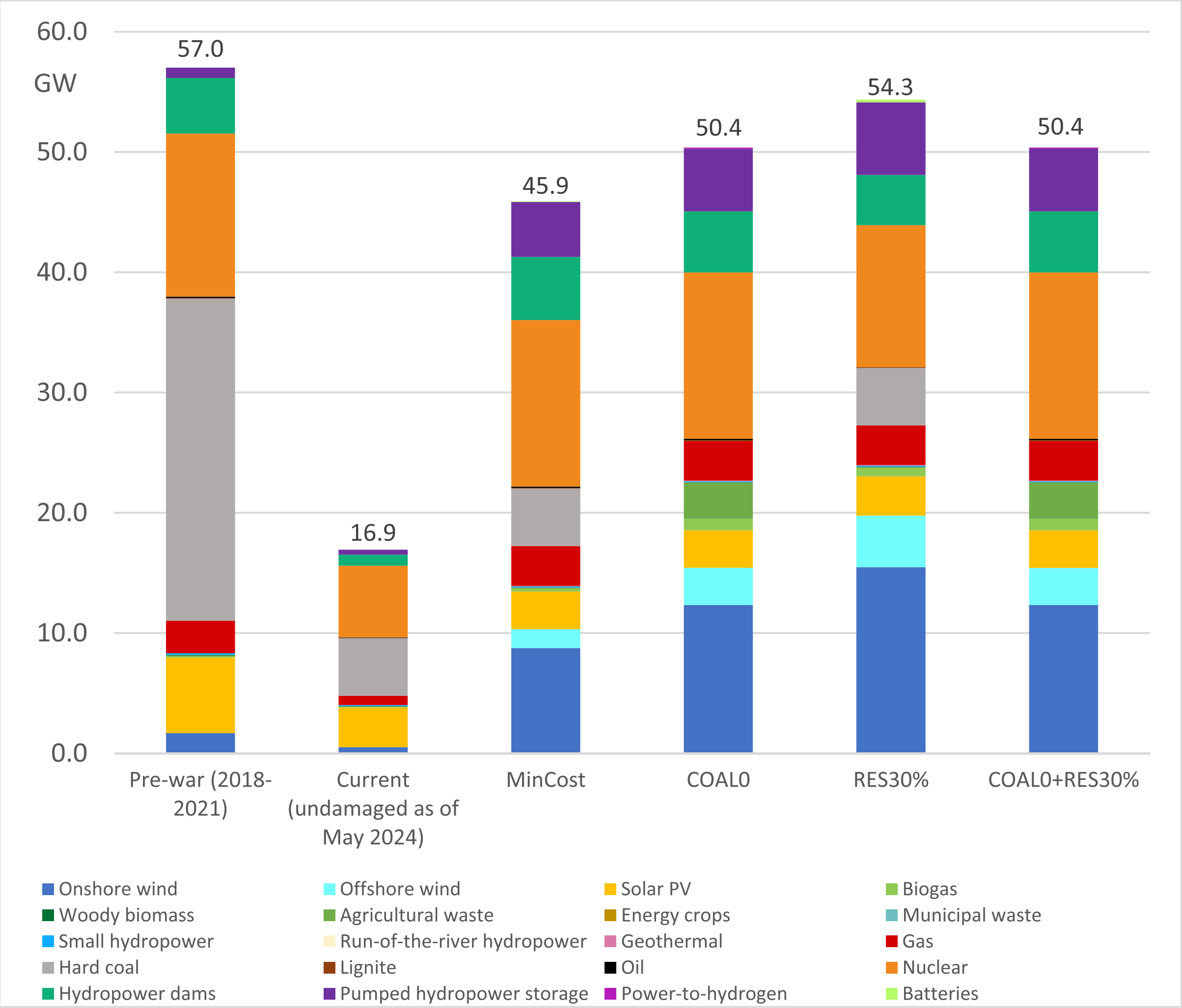

Fig. 2. Structure of the installed electricity capacity in Ukraine by scenario in 2035, GW.

compared to the current one in all scenarios, while geothermal, lignite, and oil plants were slightly increased but did not overcome the threshold in 0.1 GW.

As for storage technologies, all scenarios suggested increased capacities of pumped hydropower storage by 5.1 – 6.7 times from the pre-war 0.9 GW up to 4.6–6.0 GW. In addition, the RES30 % constraint indicated the highest need for pumped hydropower storage growth, due to temporal inflexibility of weather-dependent renewable generation. Pumped hydropower storage could compensate these drawbacks. Today, the United Energy System of Ukraine already has a sharp deficit of balancing capacities already [76], and growing pumped hydropower storage facilities are needed. As battery technology is not widely used in Ukraine and is expected to remain more expensive in 2035 than pumped hydropower storage, each scenario depicted only minor development of batteries (0.2 GW for the RES30 % and close to 0 GW for other options) with differentiation in their amount due to regional needs. Power-to-hydrogen technology, although modeled as a storage option, was practically not used in MinCost and RES30 % scenarios while reaching only 0.1 GW in COAL0 and COAL0 + RES30 % options. Electricity trade with neighboring countries moderated the storage needs too as explained in Chapter 3.2.

Every scenario suggested increasing the capacity of transmission grids inside the country, but to a different extent and in different locations. Overall, scenarios required updating six node pairs (Fig. 1): UA0 0 and UA0 6, UA0 2 and UA0 7, UA0 2 and UA0 8, UA0 4 and UA0 6, UA0 8 and UA0 9, and UA0 10 with UA0 3. They connect respectively Vinnytsya, Khmelnytskiy, and Chernivtsi oblasts with the Odesa region; Zhytomyr, Kyiv and Chernihiv with Kirovohrad and Cherkasy oblasts; Zhytomyr, Kyiv and Chernihiv regions with Poltava; Kherson and Mykolayiv with Odesa; Poltava with Kharkiv and Sumy; Luhansk with Donetsk oblasts. All scenarios showed 1.5 – 2 times increase in transmission capacities between UA0 0 and UA0 6 nodes, 1.2 – 1.5 times increase between UA0 2 and UA0 7 nodes, and 1.7 – 2 times increase between UA0 4 and UA0 6 nodes. In addition, the transmission capacities should be increased between UA0 10 and UA0 3 nodes, as well as between UA0 8 and UA0 9 nodes by 20 % for RES30 % and 30 % for MinCost scenarios. Moreover, the growth of transmission capacities was required between nodes UA0 2 and UA0 8 by 20 % for RES30 % scenario. In general, each scenario needed grid extension in at least three different node pairs while MInCost scenario added two more and RES30 % added three more node pairs, respectively.

In terms of electricity import and export, modeling results showed the necessity of increasing capacity of grids joining Ukraine with its neighboring countries to the maximum possible values. All scenarios suggested growth of up to 75 MW of transmission capacity between UA0 5 and RO0 0 connecting Western Ukraine with Romania, and the same extension was offered for the node pair UA0 6 (Odesa) and RO0 0 (Romania). The transmission capacity between Western Ukraine (node UA0 5) and Slovakia (node SL0 0) should be increased up to 650 MW. The transmission grid between Western Ukraine (UA0 5) and Hungary (HU0 0) required capacity growth to 450 MW.

3.2. Comparison of scenarios in terms of electricity supply mix

Like the installed capacity, the electricity supply mix in these four scenarios was ensured mainly by hydropower dams, pumped hydropower storage (charge and discharge), solar PV, nuclear power and wind power (onshore and offshore), biogas and gas. Scenarios without COAL0 constraint added 26.9 – 28.5 TWh/year from hard coal to the mix, and options with this constraint involved 16.2 TWh/year generated from agricultural waste to partially substitute hard coal (Fig. 3). The RES30 % constraint required +11.7 TWh/year of onshore and +6.6 TWh/year of offshore wind power in the mix compared to the MinCost scenario. In COAL0 and COAL0+RES30 % scenarios, the growth of electricity generation from the wind power was humbler: +5.2 TWh/year for onshore and +3.2 TWh/year for offshore wind technologies again aimed to replace the hard coal. Among the scenarios, nuclear power was still the key contributor to the electricity generation, followed by hard coal (for scenarios without COAL0 constraint), wind power (for all scenarios) and agricultural waste (for options with COAL0 constraint). The other mentioned technologies played a far smaller role.

In terms of conventional technologies, electricity volumes produced from nuclear plants differed essentially in the RES30 % scenario (98.6 TWh/year) compared to other options (115.6–116.2 TWh/year) since nuclear power was substituted by hard coal and renewables in this scenario. In addition, the absence of constraints also caused the highest volume of electricity generation from nuclear power in the context of cost minimization. That is, RES30 % constraint did not encourage nuclear power but rather coal use. In addition, the MinCost scenario had even higher electricity volumes generated from hard coal (28.5 TWh/year). Gas played a far less important role in the supply mix than nuclear power and hard coal, with fluctuations among the scenarios (8.5–9.5 TWh/year). RES30 % scenario provided the lowest electricity generation from gas, which amounted to 8.5 TWh/year. Electricity from lignite did not exceed 0.4 TWh/year among scenarios while oil power (0.2 TWh/year) appeared in all scenarios except for the RES30 %.

In terms of other technologies, solar PV generation had the highest value of 3.7 TWh/year for RES30 % scenario while others scenarios indicated 3.2 TWh/year from solar PV. Hydropower dams generated 9.6–9.9 TWh/year within MinCost and scenarios with COAL0 constraint while RES30 % scenario reduced these volumes to 8.4 TWh/year due to hydropower-coal replacement. Additionally, the electricity volumes

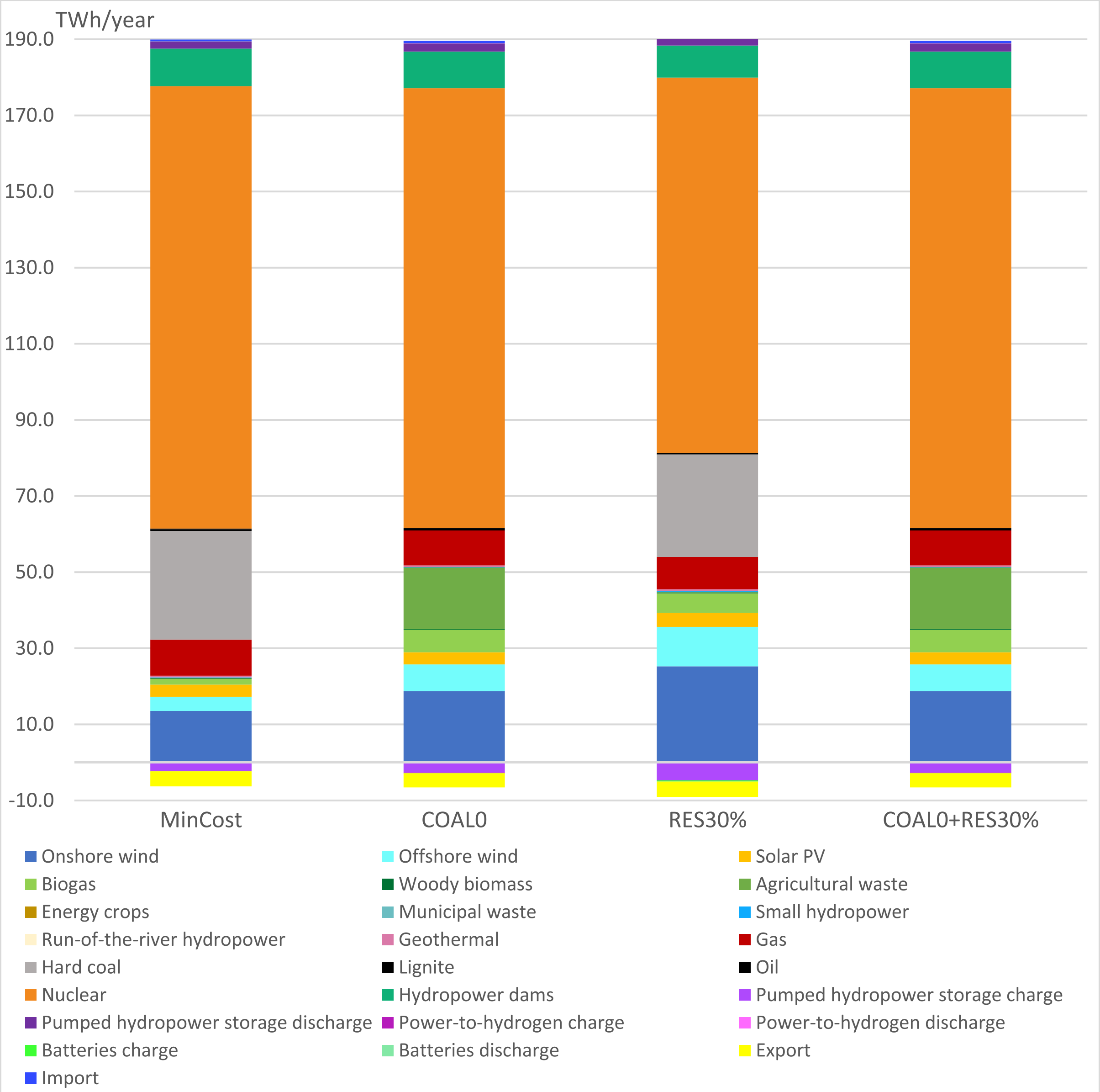

Fig. 3. Structure of annual electricity generation, storage, import and export volumes in Ukraine by scenarios in 2035, TWh/year.

generated from biogas varied from 1.5 TWh/year in MinCost scenario to 6 TWh/year for scenarios with COAL0 constraint. Electricity generation from this source was 5.2 TWh/year in RES30 % scenario, again due to the higher share of hard coal and wind power compared to COAL0 and COAL0+RES30 % scenarios. The contribution of other generation technologies did not overcome the threshold of 0.5 TWh/year for geothermal power and 0.2 TWh/year for woody biomass and small hydropower. Values for municipal waste, energy crops, and run-of-the-river hydropower were near zero.

Depending on the scenario, pumped hydropower storage discharged 1.9–3.1 TWh/year and demonstrated the highest values for the RES30 % scenario, followed by COAL0 and COAL0+RES30 % scenarios (2.1 TWh/year). On the contrary, pumped hydropower storage charged 2.3–4.7 TWh/year with the maximum values for the RES30 % scenario and the minimum ones for the MinCost scenario. The higher pumped hydropower storage charge and discharge amounts were characteristic of scenarios with constraints in order to support the flexibility of the electricity system. The batteries had far lower scores: 0.3 TWh/year for charging and 0.2 TWh/year for discharging in RES30 % scenario. Their contribution in other scenarios was close to zero. On the contrary, power-to-hydrogen as an electricity storage technology showed 0.2 TWh/year for charging and 0.1 TWh/year for discharging in scenarios with COAL0 constraint while other options indicated almost zero electricity volumes. That is, introduction of COAL0 constraint moved to replacing batteries with power-to-hydrogen technologies to storage electricity. Overall, the low values for these two technologies were due to the high costs and substitution by pumped hydropower storage, as well as interconnection with the neighboring countries.

The trade with neighboring countries did not vary significantly among the scenarios: from 0.4 TWh/year of import for MinCost to 0.6 TWh/year for scenarios with COAL0 constraint. It is worth noting that export flows consistently exceeded imports for all options, fluctuating from 3.7 TWh/year for COAL0 and COAL0 + RES30 % scenarios to 3.9–4.0 TWh/year for MinCost and RES30 % scenarios, respectively. The RES30 % constraint increased the need for electricity export while COAL0 constraint required the highest volumes of its import along with significant export volumes, presenting an opportunity for electricity trade.

3.3. Sustainability impacts of scenarios

In terms of the environmental impacts of these four selected scenarios of Ukraine's electricity sector in 2035 (Table 1), the distributions of GHG and PM_{10} emissions showed different tendencies among scenarios. For example, including COAL0 constraint led to a >7–7.5-fold reduction in GHG emissions compared to the RES30 % and MinCost scenarios. At the same time, PM_{10} emission volumes stayed approximately at the same level for all scenarios with no >4 % deviation and minimized in the MinCost scenario. In all scenarios, GHG emissions were below 29.7 Mt CO_2/year, meaning the NECP and NDC2 target of a 70 % reduction in GHG emissions in 2035 was already met by default in the MinCost scenario. Considering this result, there was no need to create a separate scenario to account for the decarbonization target of Ukraine's electricity sector. The level of GHG emissions in all scenarios indicated that the current damage to Ukraine's energy infrastructure opened up new opportunities to achieve decarbonization of the sector, even with minimal reconstruction costs.

Table 1
Overall sustainability impacts of the developed scenarios for Ukraine's electricity sector in 2035.

Scenario	GHG emissions, Mt CO_2/ year	Air pollution emissions, ktPM_{10}/year	Direct electricity sector jobs, annualized	Direct land use, km^2	Total system cost, BEUR/ year
1 MinCost	27.8	7.4	37′924	201.0	10.4
2 COAL0	3.7	7.8	47′525	503.8	11.7
3 RES30 %	26.0	7.7	45′358	267.2	10.9
4 COAL0 + RES30 %	3.7	7.8	47′526	503.8	11.7

In terms of employment effects, a comparison of scenarios showed that the COAL0 constraint provided the highest employment impact of over 47 thousand working places in the sector or a 25.3 % increase compared to the MinCost scenario (Table 1). Introducing the RES30 % constraint alone led to a 19.6 % increment in employment. Including constraints enhanced growth in the number of jobs because electricity generation from wind power, bioenergy and other renewables to replace hard coal required the development of new regional infrastructures to produce and install the equipment, ensure its proper operation and maintenance, security control, waste disposal, training of specialists for each subsector, etc.

In terms of direct land use, on the one hand, it can be considered as an economic effect due to the importance of land for agricultural purposes and industrial facilities. On the other hand, land use for constructing and operating power plants affects the environment by changing the ground and water quality, biodiversity level, recreational potential of the territory, etc. As for the four selected scenarios (Table 1), MinCost involved the minimal need for the land area for its implementation, while the RES30 % scenario referred to land use that was 32.3 % higher than the minimum amount. Scenarios with COAL0 constraint required the most extensive land use that was 2.5 times higher than the minimum amount. Thus, including constraints in the model noticeably added to the required land use for implementing scenarios. The observed impact of constraints could be explained by high specific land use for renewable technologies.

The distribution of total system cost among scenarios was the following (Table 1): the MinCost scenario provided the minimal system cost of 10.4 BEUR/year; the RES30 % scenario was more costly with 10.9 BEUR/year (4.8 % higher); the COAL0 and COAL0 + RES30 % scenarios were the most expensive with 11.7 BEUR/year (12.5 % higher than MinCost). The observed results showed that constraints' contribution to cost was quite humble and raised the total system cost by 12.5 % as the maximum. The specific cost characteristics of individual technologies can explain these results. For example, hydropower dams and pumped hydropower storage have one of the lowest investment, fixed and variable operation and maintenance costs among the studied technologies, and no fuel cost. As the hydropower potential in Ukraine is highly used, these technologies contribute to cost minimization as mature technologies. Renewable technologies (onshore and offshore wind power and solar PV) have higher operation and maintenance costs and investment costs for wind power facilities. That is why implementing these technologies requires modestly more expenditures. Power plants based on nuclear fuel and hard coal are characterized by higher investment and operation and maintenance costs compared to renewable technologies, and they also have fuel costs of 8 EUR/MWh_{el} (nuclear power) or 21 EUR/MWh_{el} (hard coal). Technologies using agricultural waste and biogas have even higher investment and operation and maintenance cost compared to the hard coal, as well as much higher fuel costs of 45 EUR/MWh_{el} (agricultural waste) and 31 EUR/MWh_{el} (biogas). The combination of the considered costs contributes to the increment of the total system cost by adding renewable and coal constraints to the scenarios.

4. Discussion

The conducted analysis showed the need for increasing the current undamaged capacities by 2.7–3.2 times in 2035. However, compared to the pre-war period, the total installed capacity in all scenarios for 2035 should decline due to capacity structure rationalization despite a 16.3 %

increase in assumed electricity demand. This finding is confirmed by other studies, which also indicated the need to modernize and rationalize Ukraine's electricity assets [15,16,23,77]. At the same time, all scenarios allowed for achieving decarbonization goals by involving more renewable technologies (primarily wind power) and possibly also nuclear power. While the electricity generation from nuclear power and its combination with gas prevailed in scenarios for 2035, onshore and offshore wind power, solar PV, hydropower dams, biogas and pumped hydropower storage facilities (including their use for balancing solar PV and wind power capacities) played a significant role in electricity generation too, along with agricultural waste technology in scenarios without hard coal. The list of technologies identified as key ones aligns with NECP [9] and other program documents. It is worth noting that solar PV contributed modestly to the increase in electricity generation in 2035, while electricity generation from wind energy grew severalfold among scenarios. This result is confirmed in NECP [9]. The predominance of wind power development over solar energy can be attributed to the significantly higher untapped potential of wind energy in Ukraine, huge war-induced wind power capacity losses, and the market saturation of solar PV due to its rapid expansion under favorable feed-in tariffs over the past 15 years. All analyzed scenarios for the short term (2035) kept a large share of interchangeable conventional fuel capacities (nuclear power and gas, as well as hard coal for scenarios without COAL0 constraint) in the electricity industry, 34 to 48 %, depending on the scenario.

Both the MinCost and RES30 % scenarios assumed the continuation of electricity generation from hard coal at a level of 26.9–28.5 TWh/year, combined with some nuclear power. The ceasing of hard coal in scenarios with COAL0 constraint and MinCost increased the share of nuclear power to 63 %. This indicator was more balanced in the RES30 % scenario, where the share of capacities on hard coal was maintained at 15 %, nuclear power accounted for 54 %, and there was diversity in renewable sources. These findings align with the works [23,24] and the modeling conclusions presented in the NECP [9], which state that the complete phasing out of coal generation in Ukraine by 2035 could be infeasible. Having said that, our COAL0 and COAL0 + RES30 % scenarios show how cola phase out could be achieved, mostly by a combination of wind power, hydropower, and agricultural waste. Overall, in scenarios with the RES30 % constraint, the distribution of electricity generation and the structure of installed capacities are in line with the results obtained using the TIMES-UKRAINE model and presented in the NECP, confirming the validity of our research findings.

Given the short time remaining until 2035, Ukraine can be expected to continue to bet on nuclear power and reduce coal capacity, considering the NECP and NDC2 goals. With Ukraine's desire to join the European Union, the need to implement the European Union's directives motivates developing and implementing national decarbonization plans without the wide use of environmentally unfriendly coal. Implementing scenarios with a zero hard coal share and increased role of green power sources would require additional costs and larger land areas to place electricity generation installations but would also provide more employment in the sector.

The increase in electricity demand in 2035, despite lower overall installed generation capacity compared to the pre-war period, necessitates the expansion of domestic grids, as argued in other studies [15,16,32,77]. All scenarios foresee the development of transmission grids mostly in central, southwestern and southern regions of Ukraine, adding eastern and northern oblasts in some scenarios. The extended renewable generation determined the growth in export volumes due to decreasing flexibility of electricity production with such technologies. Therefore, to balance the national system, electricity import would need to rise accordingly, but to a far lesser extent than export. Because of this, all scenarios required a maximum increase in the capacity of transborder transmission grids between Western and Southern Ukraine and five neighboring countries, which is a finding that is in line with recent studies [77]. Further system flexibility in 2035 would be provided by 5.1 to 6.7 times higher capacity of pumped hydropower storage as compared to the pre-war period and minor development of batteries, while power-to-hydrogen almost was not integrated to keep system costs low.

Overall, the developed UKRAINE-EXPANSE model presents a new approach to regionalized electricity system modeling and analysis, involving 24 administrative units of Ukraine and five neighboring countries and considering 22 generation, storage, and transmission technologies. Unlike the previous TIMES-UKRAINE model, including different types of energy and economy sectors [14–16,32,33], UKRAINE-EXPANSE focuses on the electricity industry and on a single year, but at higher spatial and temporal resolution. The in-depth focus on electricity is an advantage of the study and, at the same time, its limitation as the electricity sector is considered separately from industries which may affect its operating efficiency. Moreover, modeling of cost-optimal scenarios only in UKRAINE-EXPANSE as well as in TIMES-UKRAINE does not ensure full coverage of state and regional policies, and real-world dynamics [34]. In addition, we considered 2035 as a research horizon while it can be significantly extended in future studies.

Finally, the main limitation currently is the lack of precise, up-to-date open data on the current, undestroyed regional installed capacities and the generation mix in Ukraine to build scenarios. Hence the model relies on assumptions that account for the destruction of infrastructure caused by Russia's war of aggression against Ukraine from 2022 to 2024 [77]. Due to ongoing Russian attacks, the inaccessibility of power infrastructure in occupied regions, and the removal of publicly available data, it remains impossible to accurately assess regional damage and update the model accordingly. However, once the war ends and a thorough assessment of the damage to regional power capacities is possible, the model can be quickly adjusted to support the post-war reconstruction of Ukraine's electricity industry.

5. Conclusions

Modeling the transformation of the electricity industry is essential to form feasible national and regional programs for decarbonization, green energy transition, and post-war reconstruction in Ukraine. In this study, we modeled four cost-optimal regionalized scenarios for Ukraine's electricity sector development in 2035 by considering several constraints on hard coal, renewable technologies and GHG emissions connected to Ukraine's NECP and NDC2. We found it possible to satisfy the increased country's electricity demand in 2035 while reducing pre-war total installed capacity. The policy focused on cost efficiency for now would suggest preserving a high nuclear power share in electricity generation, while utilizing some of the remaining undestroyed hard coal facilities. Phasing out hard coal entirely and essentially increasing the share of renewable technologies would raise total system costs by 4.8 to 12.5 % compared to the least-cost scenario, which could be socially and politically acceptable as practice in other countries shows [34,78,79].

Ceasing hard coal would ensure further economy's decarbonization and leave space for renewable energy development. The growing share of inflexible weather-dependent renewable technologies and a high share of nuclear power would necessitate increasing system flexibility by extending power grids (especially in central, southwestern and southern regions, adding eastern and northern oblasts in some scenarios) and electricity transborder export-import (including grids in western and southern oblasts). As before the war, Ukraine in 2035 would remain a net electricity exporter, having increased its export capacity.

Policy incentives, such as the feed-in tariffs applied by the state, positively affect green energy development, but they also create a burden on the state budget [80] and cannot alone ensure the achievement of national decarbonization goals. Therefore, Ukraine should improve its electricity sector's policy, adhering to the principles of rational allocation and decentralization of power facilities in the regions, creating economic incentives for renewable energy deployment and energy efficiency improvements, introducing green auctions for various renewable technologies, and providing investment support for projects to modernize and expand transmission grid capacities in the post-war period. This will give the country a real chance to achieve the goals of its NECP and NDC2, to update obsolete and restore destroyed power infrastructures, reducing the energy and carbon intensity of the national economy.

CRediT authorship contribution statement

Iryna Sotnyk: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Jan-Philipp Sasse:** Software, Methodology, Data curation. **Evelina Trutnevyte:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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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Supplementary materials

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