WAR AND ENERGY: CAN WAR-INDUCED ELECTRICITY INFRASTRUCTURE LOSS DRIVE SUSTAINABILITY IN UKRAINE?*

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The relevance of the research

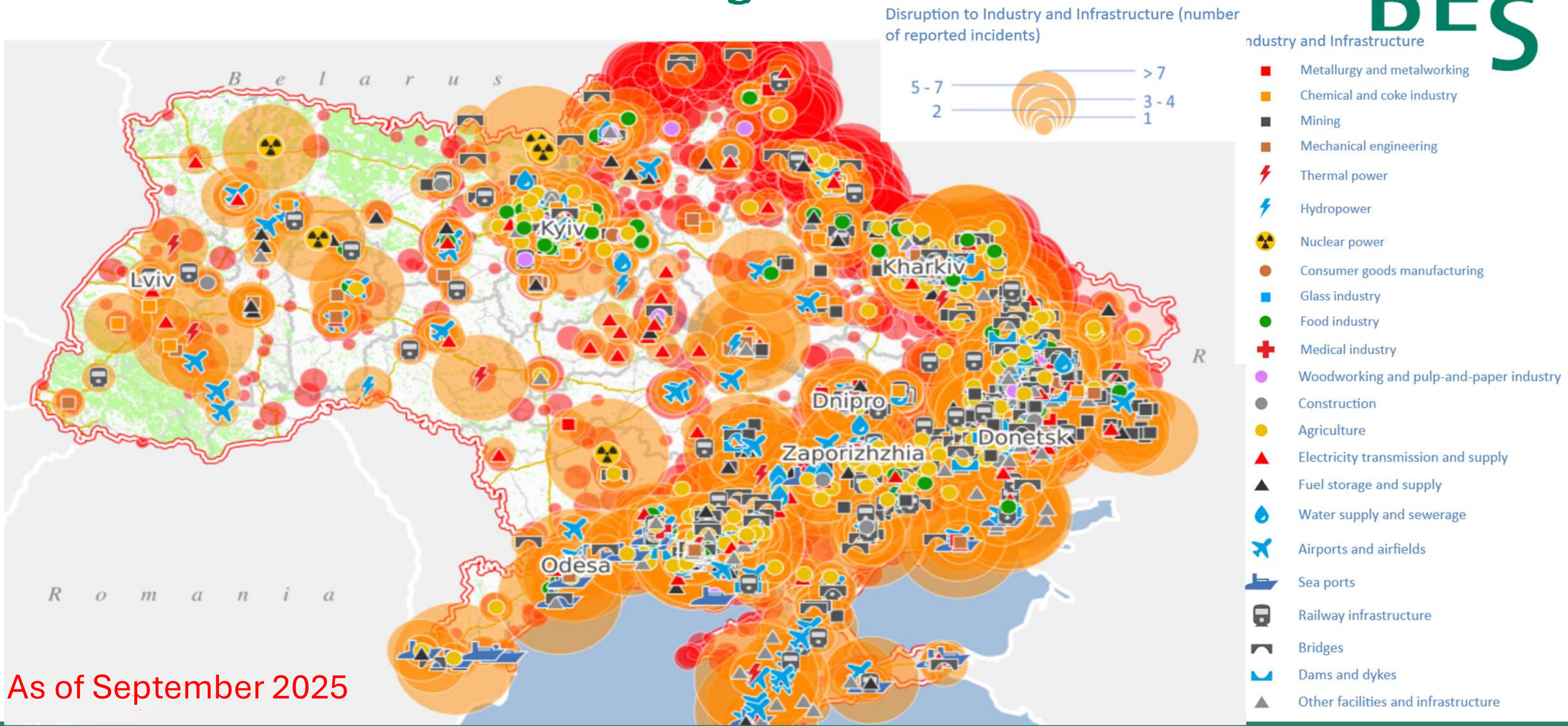
- Since Russia’s invasion in February **2022**, Ukraine has faced **unprecedented infrastructure destruction**. The electricity sector has been a primary target, aiming to cut electricity, water, heating and internet, and create a humanitarian catastrophe. Near frontlines, damage reaches **70–100%**.
- As a member of the European Energy Community and a contributor to the Paris Agreement, Ukraine installed a national target to reach carbon neutrality by **2050**.
- Besides **decarbonization**, issues of **regional decentralization** of electricity capacities become urgent and strategically significant.

The crisis presents an opportunity to reshape the electricity sector during its post-war reconstruction based on the "building back better" principle.

Structure of the presentation

- Overview of current electricity infrastructure destruction in Ukraine
- Results of scenario modeling for electricity sector development in Ukraine in 2035
- Estimation of the impacts of key factors on electricity sector development and policy implications

Infrastructure destruction during the war



As of September 2025

Source: https://www.ecodozor.org

Movement of air targets over the territory of Ukraine, 30.10.2025

On the night of **October 30, 2025**, Russia launched over **600** drones and **52** missiles into Ukraine, of which the air defense shot down **623** targets, including **592** drones and **31** missiles.

Direct hits were recorded at **20** locations, including **16** missiles and 63 drones.

Source: https://24tv.ua/

War realities in Ukraine

Anti-drone nets on roads in the Donetsk region

Source: https://kyiv24.news/

Russian drone "Shahed" in the center of Kyiv

Electricity infrastructure destruction during the war in Ukraine

- Since **February 24, 2022**, Russia has destroyed more than **50%** of Ukraine's electricity infrastructure. Only in **2024**, as a result of Russian attacks, **10 GW** of generation capacity was lost. The total damage is estimated at **$ 12.1 bln** as of **December 2024**.
- **Thermal generation:** Up to **70%** of thermal power generation capacities have been destroyed or occupied, and **87%** of coal-fired CHP plants are irreversibly lost.
- **Hydropower generation:** Severe losses, including the complete destruction of the **Kakhovka** HPP (**0.3 GW**) and major damage to other plants of the Dnipro cascade.

Source: KSE, 2024

Electricity infrastructure destruction during the war in Ukraine

- **<u>Nuclear power plants</u>:** Almost half of Ukraine's nuclear capacity (**Zaporizhzhia** NPP, **6 GW**) remains under occupation. Russian strikes on October 30, 2025, damaged key substations, disrupting external power lines to **South Ukraine** NPP (**3 GW**) and **Khmelnytskyi** NPP (**2 GW**) and forcing **Rivne** NPP (**2.8 GW**) to halve its output.
- **<u>Renewable energy sources</u> :** More than **90%** of wind power and about **50%** of solar power capacity have been taken out of operation or occupied.
- **<u>Electricity export-import flows</u>**: Ukraine shifted from a net exporter to a net importer of electricity. In **2024**, imports reached **4.4 GWh** — **five** times higher than in **2023**.

Source: KSE, 2024; Suspilne, 2025

The socio-economic dimension of war

- **8.2 mln internally displaced persons** (IDPs) in Ukraine; **6.3–6.5 mln** Ukrainians are abroad as temporary or long-term migrants.
- **37%** of the population lives below the **poverty** line; among IDPs, **64%** live in poverty.
- **Energy poverty** is rising: over **30%** of households spend more than **10%** of their income on energy.
- **Human capital** is projected to decline by **6–7%** by **2035** due to the loss of labor force, education, and health.



Source: UNDP, 2025; Eurostat, 2025; The World Bank, 2025

Is destruction always a loss — or can it be a turning point?

- **Restoration of damaged/destroyed capacities:**
  - as of **July 2025**, **over** **50 %** of the damaged electricity generation capacities have been restored;
  - in 2024, **4 GW** of damaged capacities were restored, and an additional **3 GW** are planned for restoration in 2025.
- **Commissioning of new renewable energy capacities:**
  - **2022-2023 – 0.7 GW,**
  - **2024 – 1 GW.**

Source: Pravda, 2025; Interfax, 2025; Ukrainepost, 2025

The research gap

- The previous publications considering modeling of Ukraine's energy sector mostly used the macro **models TIMES-UKRAINE, DESSTINEE and PLEXOS**, which do not reflect the **regional** infrastructure of the United Energy System of Ukraine and, therefore, do not optimize electricity generation, storage, and transmission in the **spatial context** according to decarbonization targets.
- This lack is addressed by applying the spatially-explicit, bottom-up, single-year optimization **UKRAINE-EXPANSE model**, allowing cost-optimal **regional differentiation** in generation, storage, and transmission technologies and assessment of their impacts for Ukraine in **2035.**

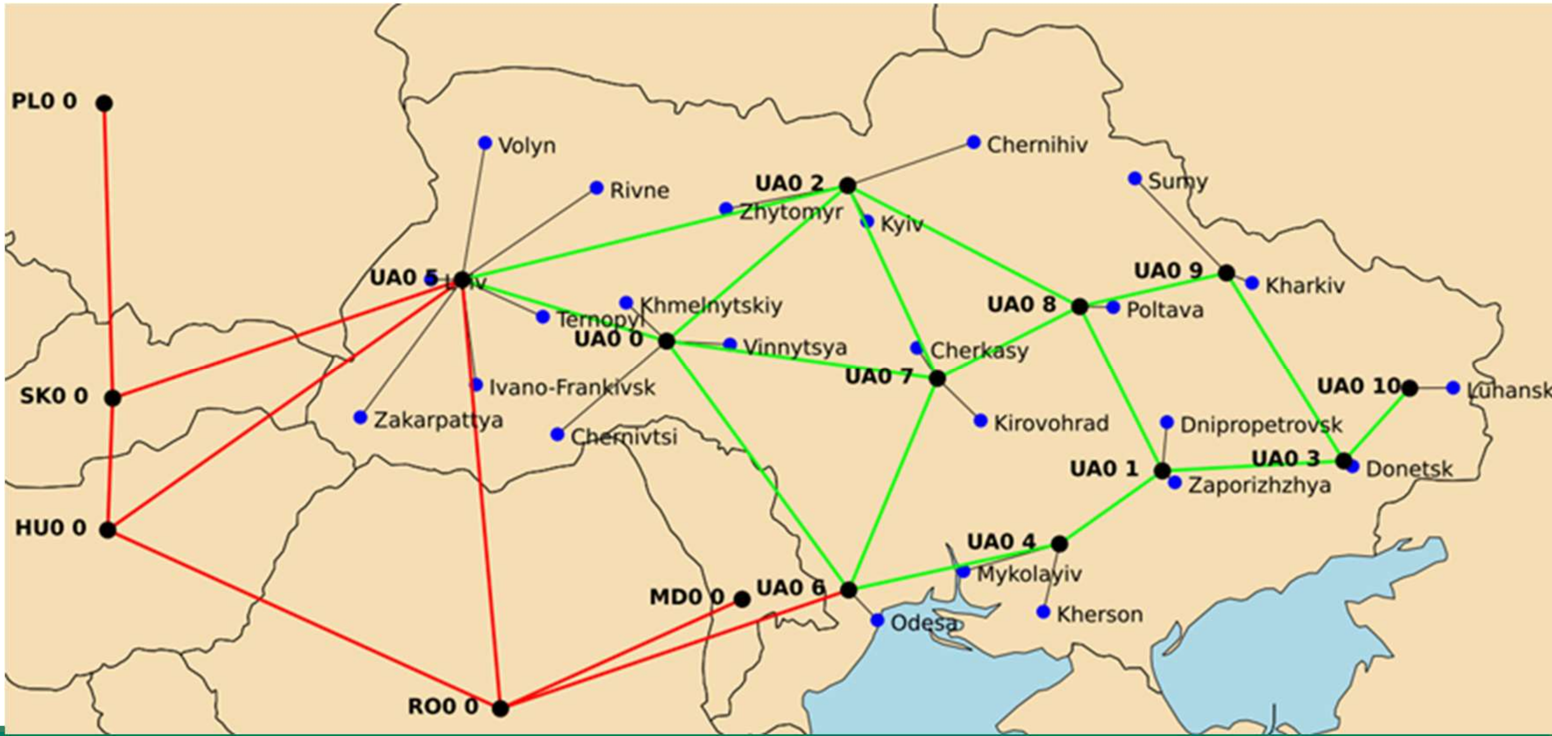
The aim of the research

The research aims to provide cost-optimal pathways for rebuilding Ukraine’s electricity sector by 2035, integrating:

- regional parameters,
- infrastructure destruction scenarios,
- electricity demand fluctuations,
- discount rate variations,
- and the national decarbonization targets.

Methods: Spatial structure of UKRAINE-EXPANSE model

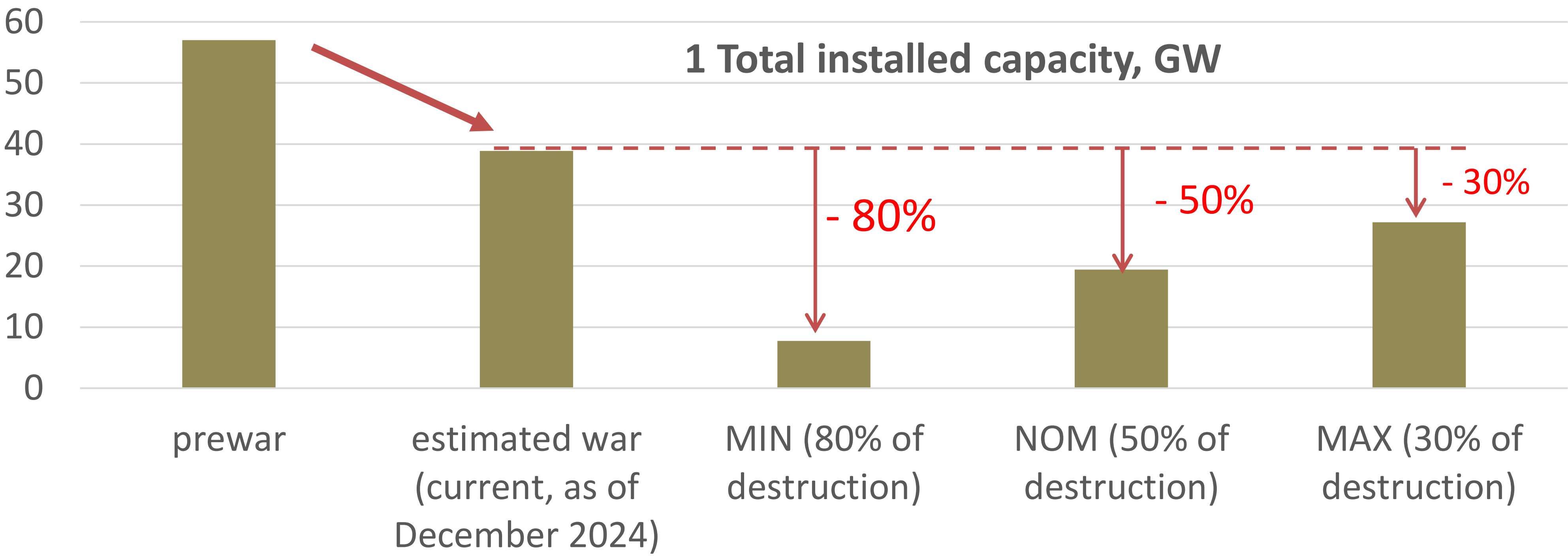
- The UKRAINE-EXPANSE model covers five neighboring countries (Poland, Slovakia, Hungary, Romania, and Moldova) presented as single-country nodes and **24** Ukraine's administrative regions linked to **11** nodes.
- The territories of Crimea, Luhansk and Donetsk regions occupied by Russia before 2022 were excluded from consideration

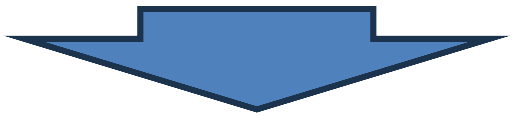


Methods: List of technologies considered in the model

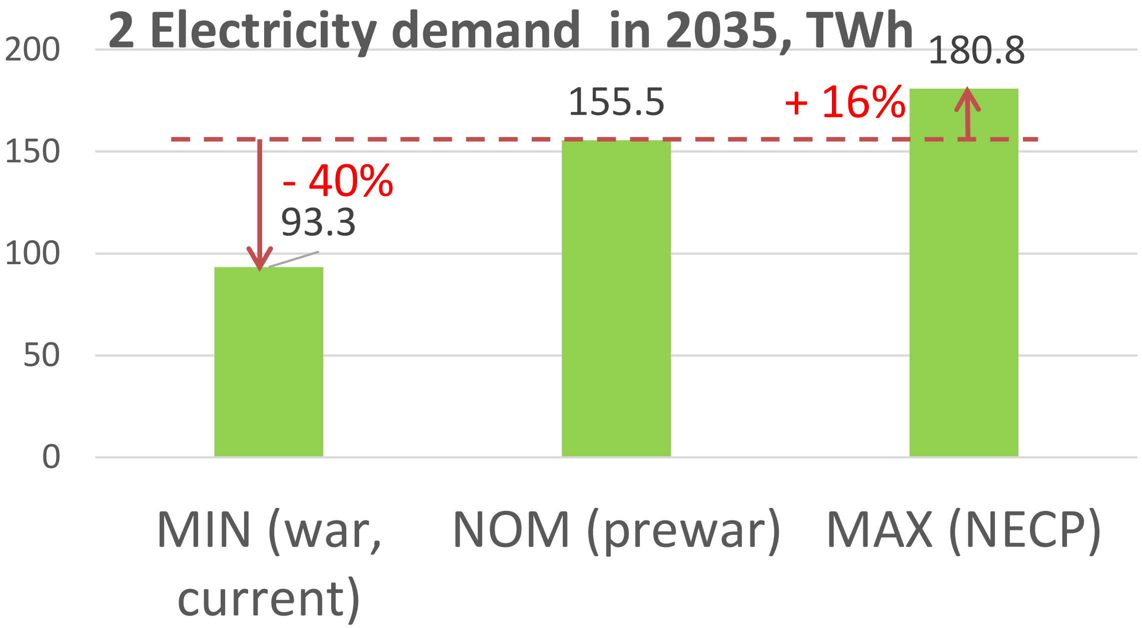
Technology type	Number of technologies	Characteristics of technologies
Generation	17	onshore and offshore wind power, solar PV, biogas, woody biomass, agricultural and municipal waste, energy crops, small hydropower, run-of-the-river hydropower, geothermal, gas, hard coal, lignite, oil, nuclear plants, and hydropower dams
Storage	3	pumped hydropower storage, power-to-hydrogen, and batteries
Transmission	2	alternating current for Ukraine's domestic lines and, for modeling purpose, direct current for neighboring countries

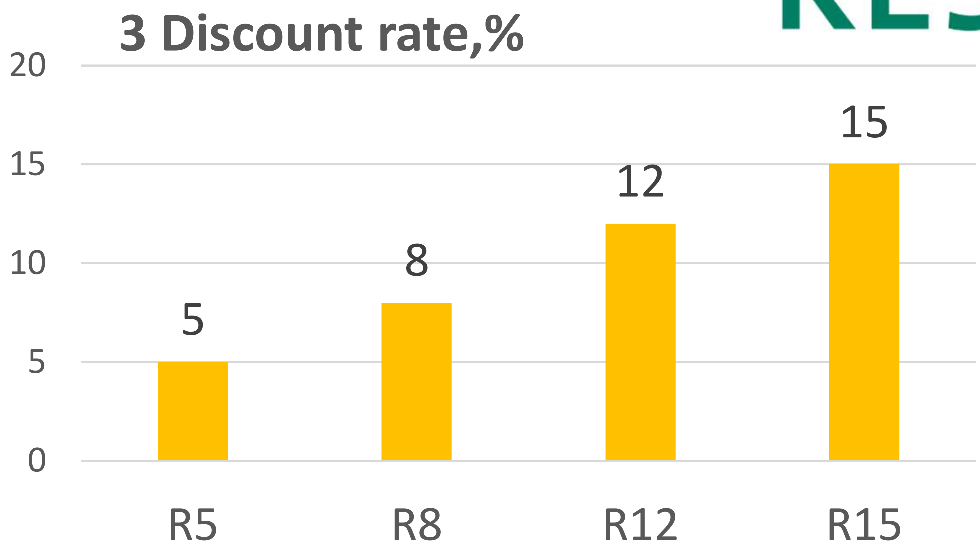
Methods: Key assumptions in the model





Methods: Key assumptions in the model



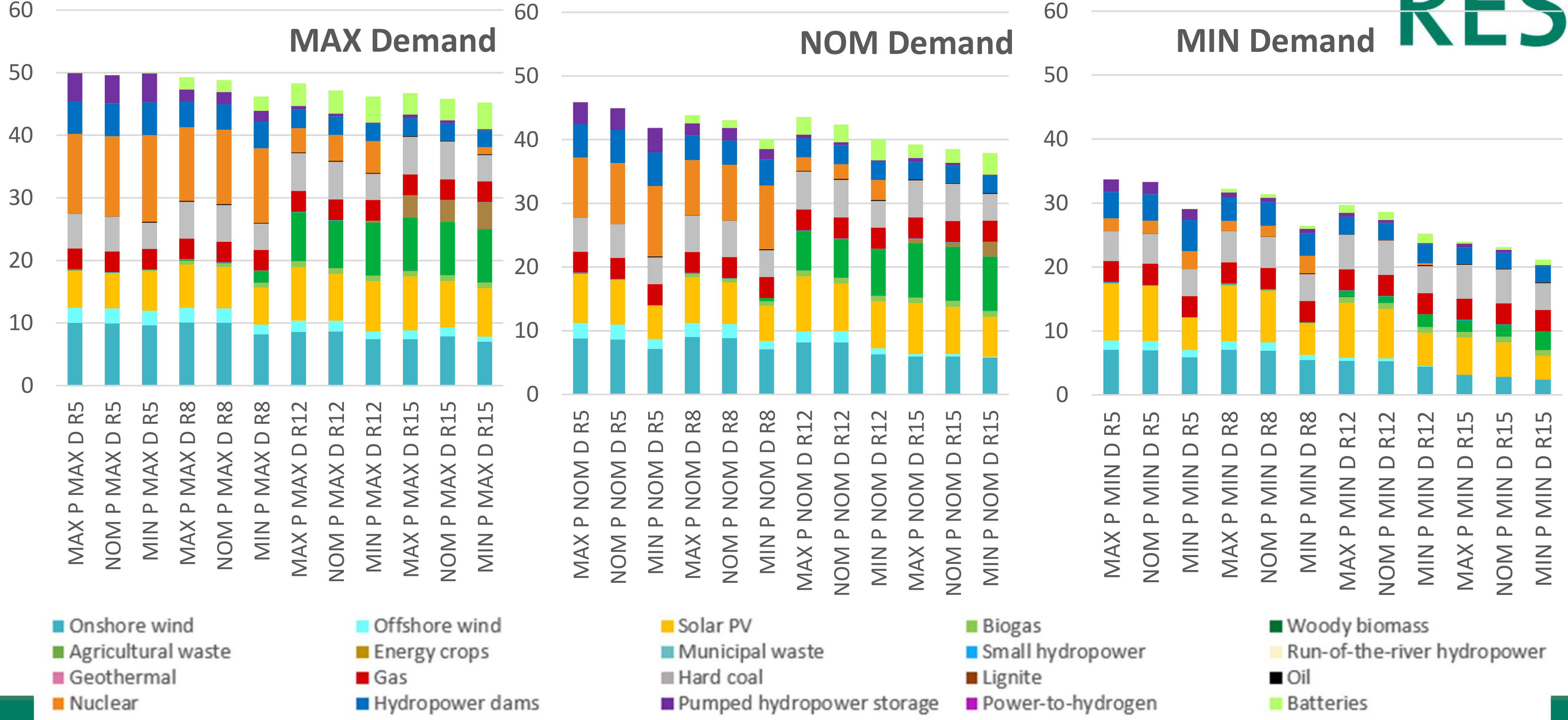


4 Maximum 29.7 Mt CO_2 emissions by 2035 (-70% compared to 2018 level)

5 No new capacities on hard coal and nuclear power (limited to the current level)

36 cost-optimal scenarios

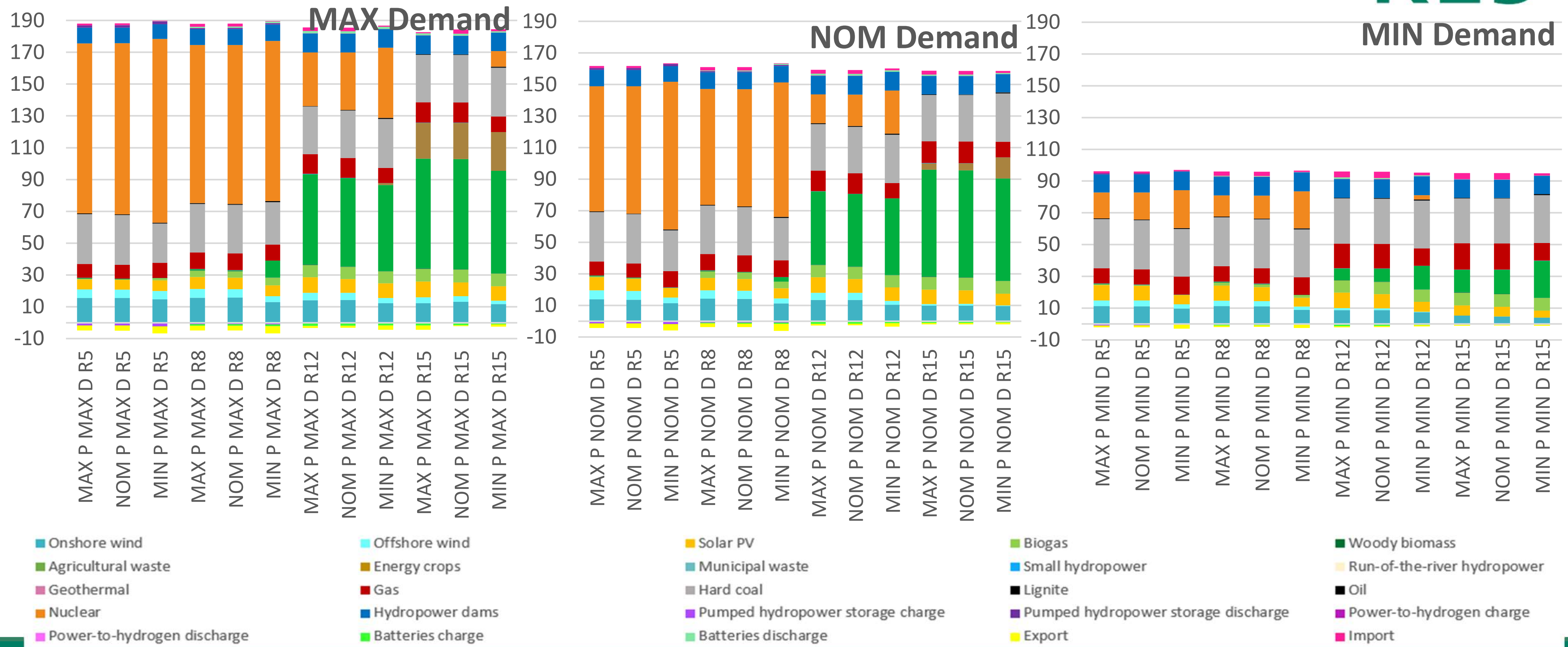
Results: Structure of electricity generation and storage installed capacities in Ukraine in 2035 by scenarios, GW



Results: Structure of electricity generation and storage installed capacities in Ukraine in 2035 by scenarios

- The **total installed electricity capacity** by 2035 is **12–63%** below pre-war levels among scenarios, despite **electricity demand** increasing by **16%** in some cases.
- **Hard-coal** capacity ranges **4–6 GW**; **nuclear powe**r installation depends on discount rates due to high investment cost.
- **Gas-fired** capacity remains stable at **3 GW** across all scenarios.
- **Bioenerg**y installed electricity capacity rises at high discount rates (**agricultural waste and energy crops**).
- **Wind power** facilities vary up to **12 GW**, **solar PV** capacity ranges **4-9 GW** among scenarios.
- **Pumped hydropower storage** capacity declines with higher discount rates; **batteries** replace it in some scenarios.

Results: Structure of electricity generation volumes in Ukraine by scenarios in 2035, TWh



Results: Structure of electricity generation volumes in Ukraine by scenarios in 2035

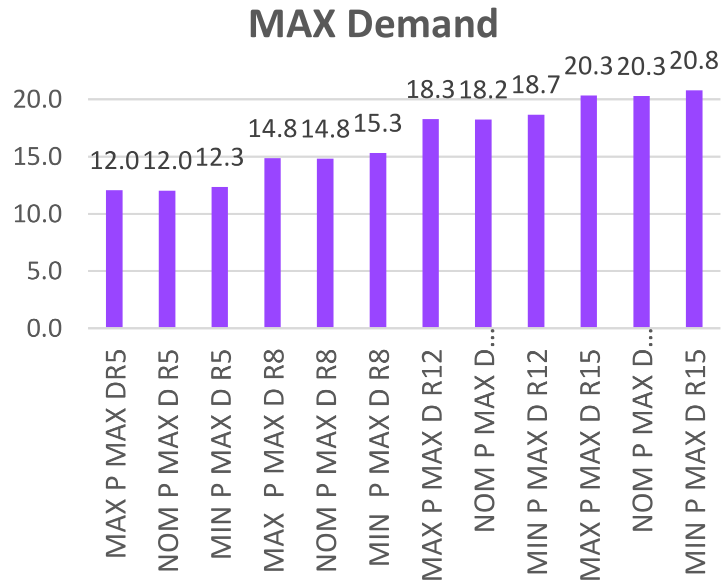
- Electricity generation from **nuclear power** ranges **0–116 TWh**; it is replaced by bioenergy sources (**agricultural waste** - up to **69 TWh**, **biogas** - up to **8 TWh** and **energy crops** - up to **24 TWh**) in scenarios with high discount rates.
- **Hard coal** remains a stable contributor to the electricity generation (**25-31 TWh**), while generation on **gas** fluctuates between **9-17 TWh**.
- **Hydropower dam** generation remains almost steady (**10-12 TWh**).
- **Wind power** generation increases with demand; electricity from **onshore wind** reaches up to **16 TWh** and from **offshore wind** ranges **0-7 TWh** (depending on demand and discount rate).
- **Solar PV** generation (**4-10 TWh**) is affected by infrastructure destruction rather than demand or discount rate.
- **Electricity trade changes**: low discount rates increase exports, while high discount rates encourage imports.

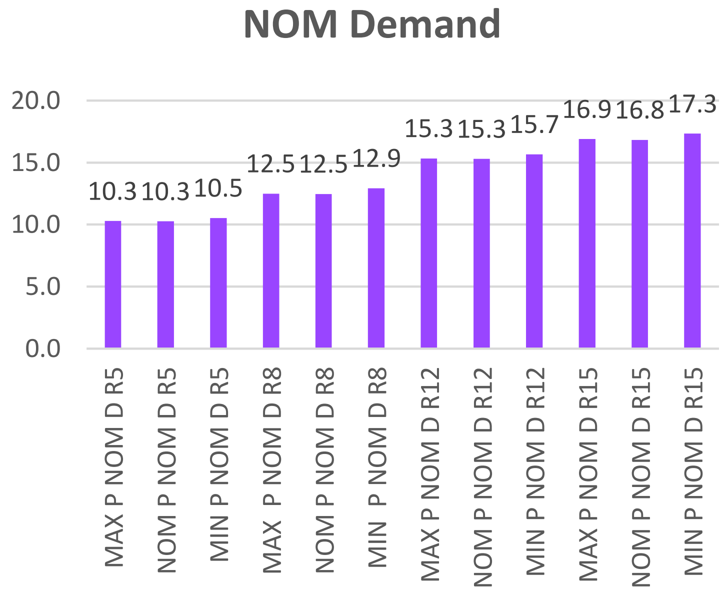
Results: Decarbonization pathways of scenarios in 2035

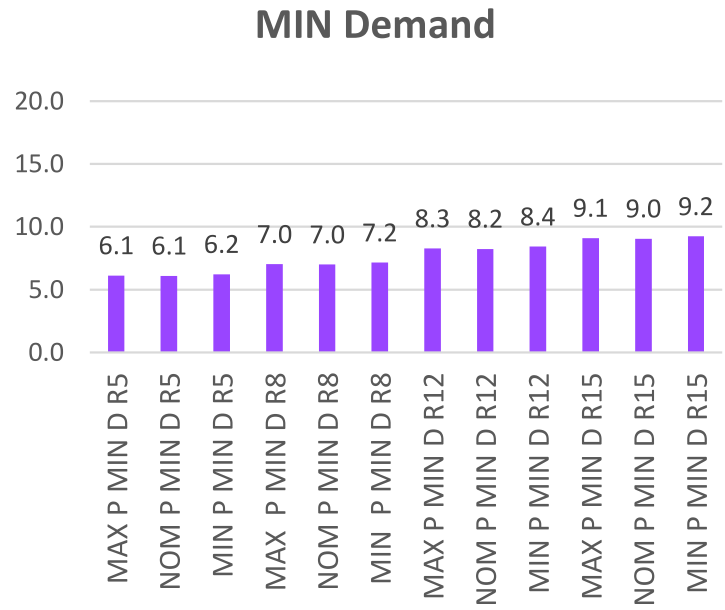
- All scenarios show increasing **green power share in installed electricity capacity** (**46–71%** vs **23%** pre-war) and reducing **carbon-based** technologies share (down to **15–38%**).
- **Green electricity generation share** varies within **19–76%**; while **including nuclear energy**, it accounts for **50-82%**.
- **Electricity generation share** from **fossil-based technologies** fluctuates within **19–50%.**

Ukraine's electricity sector recovery will be driven predominantly by the expansion of non-carbon energy sources

Results: Total system cost by scenarios in 2035, BEUR/year







- **Among scenarios with MIN demand, the growth in total cost is 1.5 times**
- **Among scenarios with NOM and MAX demand, the growth in total cost is 1.7 times**

Results: Regression analysis of key scenario factors

The following *regression model* was used:

$$Y = \beta_0 + \beta_1 \cdot \text{Demand} + \beta_2 \cdot \text{Discount\_rate} + \beta_3 \cdot \text{El\_installed\_capacity} + \varepsilon,$$

where Y – dependent variable indicating the contribution of a specific electricity technology (or group of technologies) to the installed capacity or electricity generation mix;

Demand – total electricity demand, TWh;

Discount_rate – discount rate, unit share;

El_installed_capacity – current electricity installed capacity (depending on the destruction level), GW;

β_0 , β_1 , β_2 , β_3 – regression coefficients to be estimated;

ε – random error term.

Results: Role of the discount rate

- A **1% increase** in **discount rate** leads to:
  - ✓ **–0.9 GW (–2.19%)** and **–7.58 TWh (–4.72%)** in **nuclear power**;
  - ✓ **–0.43 GW** and **–0.71 TWh** in **wind energy** (capital-intensive and uncertain output);
  - ✓ **+0.95 GW (+2.65%)** and **+7.26 TWh (+4.75%)** in **bioenergy** (acts as a substitute for nuclear power).

Higher discount rates shift investment **away from capital-intensive** (nuclear, wind) **toward flexible bioenergy** technologies.

Results: Role of electricity demand

- A **+1 TWh increase** in **electricity demand** leads to:
  - ✓ **+0.11 GW (+0.49%)** and **+0.45 TWh (+2.56%)** in **wind energy;**
  - ✓ similar upward effects in **agricultural waste (bioenergy)**;
  - ✓ **+0.07 GW** and **+0.61 TWh** (within system limits) in **nuclear power.**

Rising electricity demand stimulates **green technology expansion**, constrained by **decarbonization targets** and limited growth in carbon-based generation.

Results: Effect of infrastructure destruction

- Preserving **1 GW** of existing capacity enables:
  - ✓ **+0.1 GW**, and **+0.11** and **+0.18 TWh** in **solar PV and wind power;**
  - ✓ **+0.08 GW** and **+0.14 TWh** in **carbon-based** technologies.

Less destruction → more balanced growth across renewables and conventional generation.

However, **the effect remains secondary** compared to the discount rate and electricity demand.

Results: Key determinants of electricity technology deployment

Main regression findings:

- **Discount rate** – consistently the most significant factor across models.
- **Electricity demand** – highly significant in most models, especially for **wind energy**.
- **Current installed capacity** (proxy for infrastructure destruction) – limited significance, relevant mainly for **solar PV, wind, and coal**.

Implication: Investor sensitivity to the **cost of capital** is a decisive element for new capacity deployment.

Modeling outcomes: policy implications

RES

- Smart restructuring of destroyed electricity infrastructure (with a predominant shift toward renewables) is feasible, not full rebuilding.
- The sector's development will be shaped by financial conditions (discount rates) and electricity demand, while the extent of network destruction will have an ambiguous impact.
- Policymakers should focus on creating favorable financial conditions for investors in low-carbon energy through state guarantees and preferential loans
- The policies should prioritize decentralized generation and EU integration to enhance the country's energy security.

Conclusions

- Green, resilient and cost-optimal recovery is achievable.
- High discount rates limit nuclear power use and boost bioenergy development.
- Future policies must align finance, demand and low-carbon goals.
- EU integration and flexible storage are key for the electricity sector’s development.
- Decentralized generation advancement will contribute to energy independence and resilience of the sector.

Limitations of the study and prospects for further research

- UKRAINE_EXPANSE focuses on the electricity industry. The latter is considered separately from industries which may affect its operating efficiency.
- Modeling cost-optimal scenarios do not ensure 100% of covering state and regional policies influencing the choice of technologies.
- We considered 2035 as a research horizon while it can be significantly extended in future studies.

Limitations of the study and prospects for further research

- The model applies aggregated parameters of regional electricity demand, which may not fully reflect demographic changes, industrial recovery, or migration dynamics.
- The model should be further refined to expand the set of uncertainty parameters (fuel prices, infrastructure recovery, climate risks, and geopolitical factors).

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