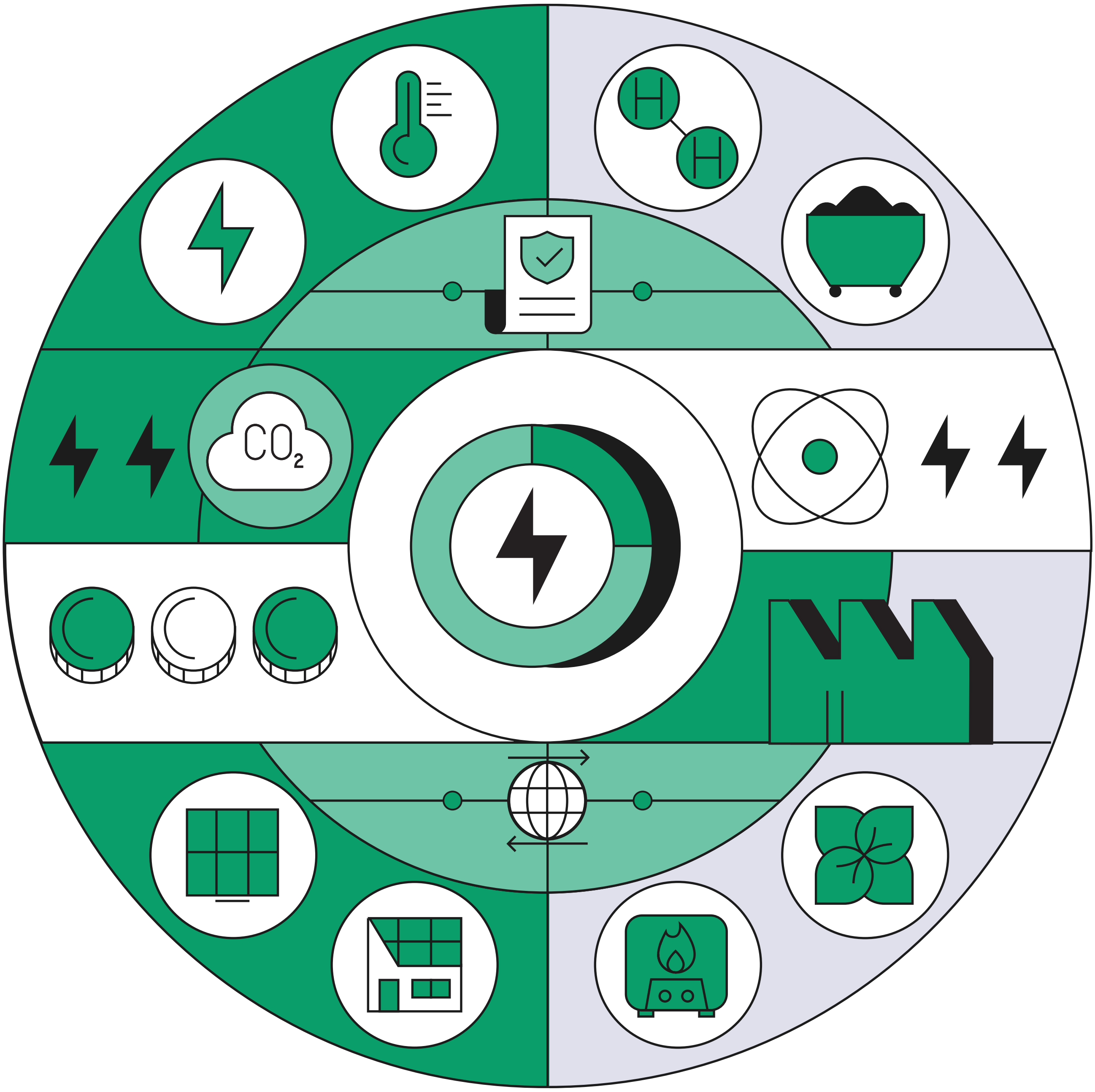
Ukraine against darkness

Pathways to a resilient and decentralised power system in Ukraine until 2030



Instrat Policy Paper 04/2024
Oleksii Mykhailenko
Igor Piddubnyi

instrat CEL

Kyiv, November 2024

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All errors are ours.
Usual caveats apply.

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in the current version let's erase this completely. The results presented in the report are based on the non-public version of the model containing non-disclosed data, which for security reasons not available under open license. The non-public version of the model, its input and output data are available at a request.

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Key findings and numbers

20% less

gross electricity demand is estimated in Ukraine in 2030 under the conservative scenario representing geography within the current frontline - contrary to assumptions used in governmental strategic documents.

5.4 GW

additional generating capacity is required until 2026, comprising 3.5 GW of solar PV, 0.7 GW of wind, 1.1 GW new fast-start gas supported with 2.8 GW of repaired coal-fired power and CHP plants and 0.6 GW expansion of cross-border capacity.

EUR 12.5 bn

of investment required until 2030 to replace lost generation capacity under Victory pathway, and reduce to EUR 9.3 bn under Frontline pathway with lower demand. Out of these, EUR 4.3 bn is required already during 2025 2026.

up to 12.8 GW

new generating capacities are required until 2030 under the Victory pathway scenario, complemented by 0.9 GW of new gas units in addition to 7.4 GW repaired and 3 GW unoccupied capacities.

7.5 GW

is the potential of behind-the-meter solar PV in Ukraine until 2030, with 1.8 GW deployed in the next 2 years and 1 GW each year afterwards.

15.8 GW

theoretical maximum of behind-the-meter PV capacity the Ukrainian power system can absorb without reducing its nuclear baseload by year 2030. However, such capacity will lead to suboptimal system costs, increased curtailment of utility-scale plants and miniscule gain of 1 percentage point in RES share.

5.8x

increase in the ramping up flexibility requirement is expected in the Ukrainian power system in 2030 compared to 2021.

3 GW less PV

can be accommodated by the Ukrainian power system if export capacity was not available.

50% more

investment cost required to replace destroyed coal generation with a mix of new renewables and flexible gas generation compared to baseline scenario with repairs. However, switching to gas generation enables integration of more wind energy to the system.

38% of RES

in total electricity generation can be achieved by 2030 within the most ambitious scenario as well as ensuring improved security of supply.

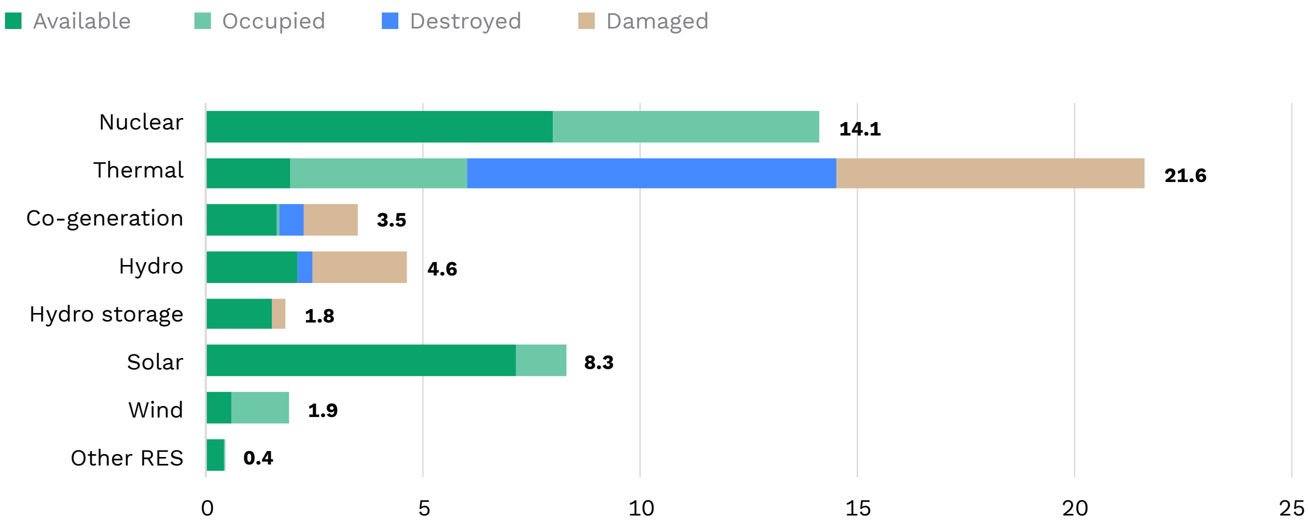
up to EUR 11.4 bn more

could be the investment cost of scenario with adding new nuclear baseload compared to cost-optimal mix with repairs of damaged generation. Decentralised scenario which replaces all damaged generation with new gas and renewables would cost EUR 4.2 bn less under Victory pathway and EUR 7 bn less under Frontline, compared to adding new nuclear baseload.

Introduction

(1) Since Russia's full-scale invasion began in February 2022, Ukraine's energy system has faced unprecedented challenges. Targeted attacks on critical infrastructure and power plants have plunged millions into darkness, endangering essential services like heating and water supply during harsh winters. By summer 2024, only 40% of the nation's installed capacity remained operational, with 60% of the capacity occupied, damaged, or destroyed, creating a significant gap between available capacity and demand. Ongoing Russian bombardments continue to weaken the remaining flexible coal and hydro capacities, with nuclear power plants also under-threat.

FIGURE 1. Extent of damage to generating capacities as of mid-2024 [GW]



Instrat & CEL estimates, based on UNDP (2023), Ministry of Energy (2024), Kharchenko (2024), Susplilne Media (2024), experts' interviews.

(2) Amid this ongoing bombing campaign, Ukraine's top priority is securing a stable energy supply. For the 2025-2030 period, Ukraine aims to transition to a more resilient, decentralised power system. Given limited wartime investment, the government has primarily focused on repairing damaged generation. Still, Ukraine remains committed to renewable energy as a means to bolster its power system against military threats.

In response to attacks, the Ukrainian government is prioritising decentralised energy generation from both renewable and fossil fuel sources to enhance grid resilience. Distributed generation reduces vulnerability by diversifying power sources, potentially ensuring reliable supply even if some sites are compromised. During 2022-2024, the government has adopted several key strategic documents to guide energy sector development:

- Energy Strategy of Ukraine 2050 (ESU 2050) – on 21/03/2023
- National Energy and Climate Plan until 2030 (NECP 2030) – on 25/06/2024
- Strategy of distributed generation development until 2035 (SDGD) – on 18/07/2024
- National Renewable Energy Action Plan until 2030 (NREAP 2030) – on 13/08/2024

While ESU 2050 remains classified, the NECP modelling is based on Ukraine's pre-war RES targets, which were made binding through the 2022/02/MC-EnC Decision of the Ministerial Council of the Energy Community. NREAP has adopted a 29.4% target for renewable energy in the electricity sector by 2030, as set forth by NECP. NREAP and SDGD outline policy measures to support decentralised generation, including renewable energy auctions with contracts for difference, subsidised (soft) loans for prosumers and small – to medium-scale developers, and support for new balancing and ancillary services assets.

In parallel, the government is advancing plans to expand the Khmelnytska nuclear power plant with four new units: two of Soviet-Russian design and two Westinghouse AP1000 units, with a projected construction timeline of 3-4 years. This project has faced criticism from industry experts due to concerns over the feasibility of the timelines, misalignment with the decentralisation goal, limited domestic supply chain capabilities, and military risks. The draft law supporting this nuclear expansion has stalled in parliament, as questions remain about the quality of the underlying feasibility study. Uncertainty persists over Ukraine's actual need for additional baseload capacity and whether these nuclear projects align with the urgent need to focus on decentralised generation.

(3) Private investment in utility-scale renewables remains limited and hampered by regulatory constraints. In the past two years, only 374 MW of wind, 81 MW of utility-scale PV, and 35 MW of bioenergy capacity have been commissioned[1]. Developers face difficulty securing financing without a guaranteed offtake. The corporate PPA market is constrained by high uncertainty and the risk of supply disruptions, as customers are wary of long-term contracts with fixed electricity prices that factor in high capital costs due to wartime risks. Wholesale price volatility and low capture prices for PV further limit investment.

1 Sources: UWEA, EUEA, NEURC, https://ua-energy.org/

(4) Rising energy prices for consumers, low PV panel prices, and the risk of supply interruptions may drive a rapid deployment of consumer-side distributed generation. At least 300 MW of PV under feed-in tariffs were installed by households in 2022-2023. We believe that growth in behind-the-meter (BtM) generation in Ukraine is inevitable, primarily driven by PV, given falling equipment costs, significant cost savings, ease of installation, and access to subsidised loans through government and international programs.

(5) While BtM PV deployment is driven by consumer savings, it may not represent the most cost-effective solution for the grid as a whole. In systems with limited flexibility and high baseload, BtM PV can cannibalise capture prices, cause curtailment of utility-scale renewables, and increase the need for peaking capacities. Poland's experience is instructive: between 2020 and mid-2024, prosumer PV capacity grew by nearly 11.5 GW (ARE, 2024), while RES curtailment surged from 8.4 GWh in 2022 to 194 GWh in just four months of 2024, with 64% of this curtailment in solar (Clyde & Co 2024). Ukraine's reliance on inflexible nuclear (50%) makes integrating additional PV even more challenging.

Our research aims to investigate an optimal path for Ukraine's power sector, focusing on short – and medium-term energy needs during wartime. We concentrate on the outlook through 2030 and the role of commercially available decentralised energy technologies. Specifically, we examine whether BtM PV can be an effective addition to the system and assess the theoretical maximum BtM PV capacity that Ukraine's current grid can accommodate by 2030. We aim to support discussions on Ukraine's energy sector needs and inform public policy directions.

1. How do we model the Ukrainian power system?

To evaluate power system performance under different scenarios, we used power system modelling capable of simulating hourly supply and demand balance throughout the year. Specifically, we employed the open-source PyPSA-Eur framework[2], adapted to the Ukrainian power sector based on Instrat's experience in using PyPSA for modelling of the Polish energy system (Instrat, 2024). Given that much of Ukraine's power system data is classified or limited due to wartime restrictions, we relied on historical data and industry expertise to make informed assumptions. Our modelling approach combines tailored demand estimates with a custom-built power system optimization model, providing a comprehensive analysis of Ukraine's energy dynamics.

1.1. PyPSA-UA – power system model

This report presents the results of scenario-based analyses conducted using the PyPSA-UA model, developed by the Open Energy Transition team and commissioned by Instrat and CEL. PyPSA (Python for Power System Analysis) is an open-source power system modelling tool that identifies and simulates cost-optimal development pathways. The version of the PyPSA-UA model used to inform the report's findings covers Ukraine's electricity sector down to key DSO regions with a simplified high-voltage (220-750 kV) grid topology. The model simulates the dispatch at full hourly resolution (all 8760h/a) and assesses cost-optimal investment needs, with both generation profiles and optimal installed capacities as outputs.

Modelling is based on a range of data and assumptions, including the current generation structure of the Ukrainian energy sector, existing transmission grid topology, future prices of fossil fuels, the cost of investment in new power plants, and the electricity demand at any given hour of the year. We have also considered certain technical constraints, such as operating parameters of power plants and transmission capacities based on their historic performance.

More detailed information on the model's selected assumptions and operation principles can be found in Appendix A. The version of the model with the publicly available data and assumptions is published on the GitHub platform under an open licence, free of charge, allowing its development and replication by the expert community. This report is based on non-public data and sensitive information, and it will not be disclosed on GitHub. Please contact the authors should you have questions regarding accessing the non-public inputs.

2 https://pypsa-eur.readthedocs.io/en/latest/

1.2. Power demand model

Electricity demand time series are a crucial input for power sector models, as varying assumptions about the hourly profile and annual magnitude of demand can lead to different outcomes even by similar models. A common approach is to use available historical data from Transmission System Operators (TSOs) and project it forward. However, this top-down method has limitations, particularly in cases like Ukraine's, where gross demand includes both grid losses and self-consumption of power stations. Self-consumption varies widely—1-2% for solar PV, wind, and hydro, 5-6% for nuclear, and 10-15% for thermal generators. Gross demand also accounts for behind-the-meter generation, appearing as reduced demand. With a growing share of renewables, relying on historical hourly demand data, which reflects a fixed power mix with embedded losses, may overestimate future demand. For this reason, net demand is a more accurate input for power models. Additionally, Ukraine's power system has also experienced a significant demand reduction due to migration, loss of territories, and industrial damage. Using pre-2022 historical data to forecast future consumption could be misleading, as it would fail to capture these structural shifts.

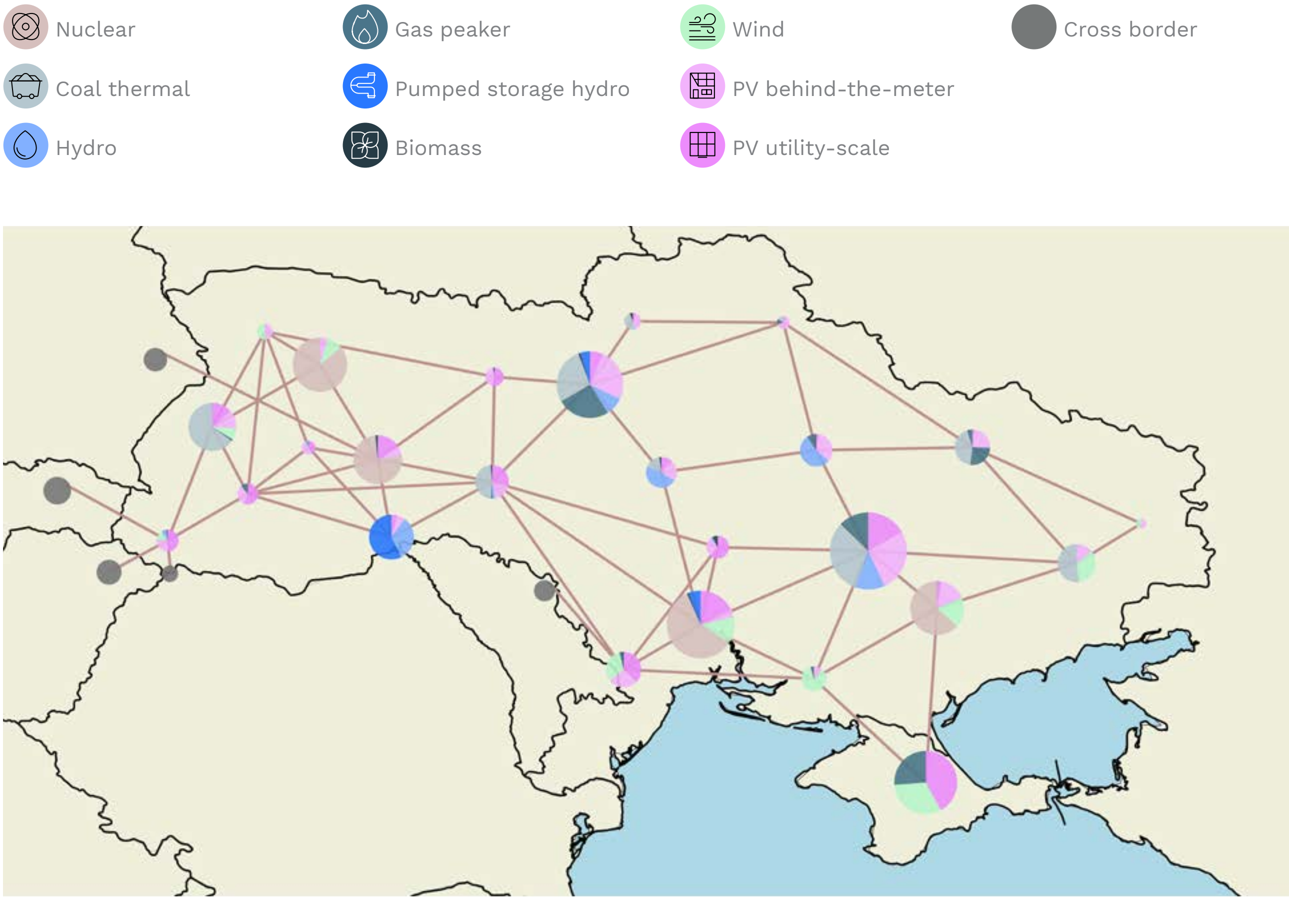
To address this and improve model accuracy, our team developed a customised, bottom-up demand model. This spreadsheet-based model differentiates net demand for commercial/industrial (C&I) and residential users by region, with hourly granularity. It applies demand factors individually to each Distribution System Operator (DSO) region and consumer type, enabling more precise regional demand representation[3]. Enhanced geographic granularity improves the accuracy of power flow and grid load results. For further details, refer to Appendix B. This DSO-level demand is then used as input for the PyPSA-UA model, which simulates transmission and self-consumption losses based on actual power station outputs.

1.3. Key model features

We cover 26 interconnected regions under our modelling, connected by the aggregated high-voltage lines representing Ukraine's system topology in a simplified manner. Additionally, neighbouring countries are represented as potential electricity importers or exporters, to provide a simplified simulation of inter-regional cooperation. Generating capacities are distributed geographically according to their location. Demand centres are modelled as aggregated distribution-level nodes at low-voltage, with BtM generation connected directly to low-voltage demand, decreasing the amount of energy supplied from the transmission grid to respective nodes.

3 Key challenge amid geopolitical considerations on the future demand from the regions under occupation.

FIGURE 2. Map of the Ukrainian power system representation in PyPSA-UA model



Source: OET based on Instrat & CEL

We allow commercially available technologies as candidates for investment optimisation: onshore wind, utility-scale PV, gas peakers (representing gas ICE and OCGTs), battery storage systems. Gas-fired technologies are represented as one aggregated in this study due to a) comparable costs and efficiencies and b) similar ramping constraints within an hourly resolution of the model. ICE and OCGTs are different in start-up costs and down times, but the current iteration of the model cannot capture these factors. We model combined heat and power (CHP) units based on their historic availability profiles and set their capacities exogenously. We do not optimise or expand CHP capacity since we do not model changes in the heat demand which could drive the investment decision. Integrating heat demand into PyPSA-UA is considered for future studies.

As BtM generation, we model typical rooftop PV with slightly lower capacity factors than ground-mounted one. We acknowledge that some Ukrainian consumers will be installing gas-fired cogeneration engines for self-consumption in response to frequent power shortages during the wartime. However, we do not model them due to the limitations of this version of the PyPSA-UA. We cannot reliably model the output profile of such an installation and allocate it geographically, and decided not to install them on the system level as one responding to market signals.

BtM generation affects the system by reducing the grid electricity demand, resulting in a so-called “duck curve”. BtM PV generation is non-curtailable upon the system operator’s commands as it is too small and is not required to report the production level in real time. We model the installed BtM PV generation as such cannot be curtailed and that reduces the demand on the distribution level.

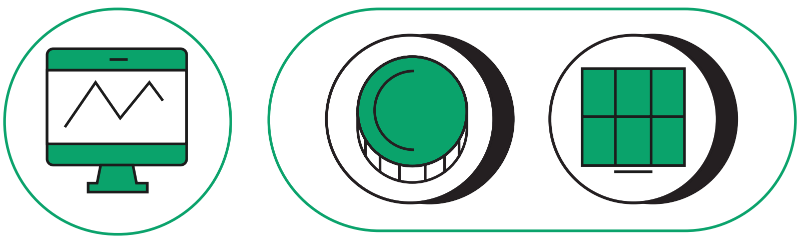
1.4. Limitations of the modelling

For the purposes of this research, we focus on immediate actions required in terms of new capacities. We do not model the system beyond 2030 due to high uncertainty. The outcomes of this study may not be cost-optimal in the long term; however, given the uncertainty of the war outcome, reliable long-term planning is hardly possible. Our results represent potential developments grounded in reality for the next 5 years, focusing on commercially available technologies to address immediate needs.

There are several simplifications in the current version of PyPSA-UA, which may overestimate the overall flexibility of the system:

- Demand for ancillary services such as frequency regulation (power reserve) is not modelled.
- Unit commitment is not implemented. This means that power stations are modelled on aggregated levels per node, not down to individual generating units. Only ramping constraints are introduced for thermal generators, while minimum stable load and start-up costs are not.

Cross-border electricity trade is simplified with neighbouring countries representing an unlimited importer or exporter. We don’t model the respective hourly prices of neighbours but fixed prices across all hours (50 EUR/MWh for export and 150 EUR/MWh for imports). This assumes that excess PV energy – up to the interconnectors’ capacity – can almost always be exported instead of being curtailed.



2. What are the scenarios?

2.1. Scenarios

Given the current uncertainty regarding the military and geopolitical situation, we believe that Ukraine may benefit from assessing two critical outcomes of the ongoing Russian invasion. That is why in our study we look into immediate future and two key pathways for 2030:

- **The 2026 scenario** describes the immediate response the Ukrainian power system needs
- **The Frontline pathway** assumes a prolonged conflict that will lock control over territories along today's frontline in 2030.
- **The Victory pathway** envisages Ukraine regaining control over all of its territory including the Crimean peninsula by 2030.

The 2026 scenario represents conservative estimates of the power demand within the current line of control over territories and limited repairs to damaged power plants, assuming war continues until throughout 2025-2026. The 2030 pathways represent two situations in which the Ukrainian power system can find itself: one with lower demand and strained generation capacities, and another representing a rapid increase of demand from returning residents and industrial ramp-up with more room for repaired stations but still a fraction of pre-2022 levels. We assume the full-scale hostilities to end in 2027 under the Victory scenario.

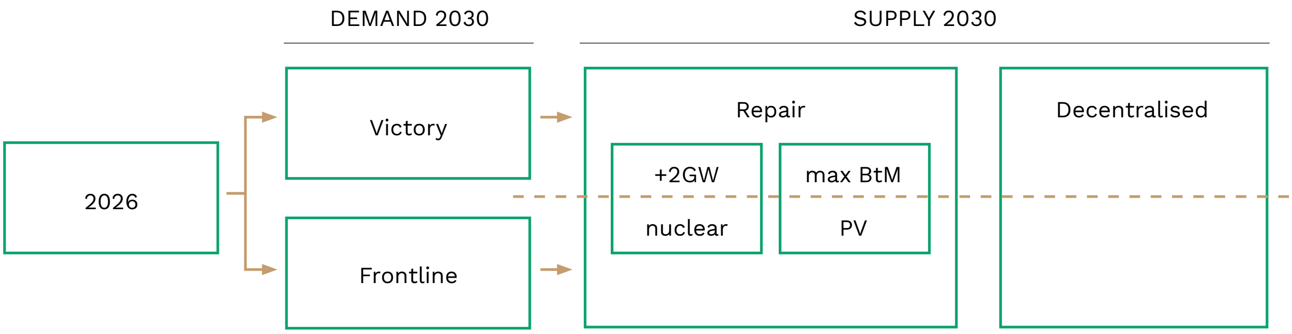
On top of key pathways, we model two scenarios each representing a vision for availability of generating assets:

- **The Repair scenario** (baseline scenario) assumes that damaged power plants will be restored rather than built from scratch. This is a reactive, conservative scenario representing a baseline reliance on the legacy of "centralised" stations vulnerable to further attacks.
- **The Decentralised scenario** investigates the power system in which all coal assets are either destroyed beyond repair or the decision is made not to repair them due to their vulnerability to attacks. The model suggests a mix of commercially available technologies that enables a decentralised power system.

For sensitivity analysis investigating detailed research questions, we also studied two specific sub-scenarios based on Repair assumptions:

- **+2 GW nuclear baseload sub-scenario** suggesting 2 GW of nuclear baseload is added representing an announced plan to expand Khmelnytska Nuclear power station by 2030, and
- **Maximisation of BtM PV sub-scenario,** investigating a potential limit of Ukraine's power system to absorb prosumer-based generation without reducing the nuclear baseload.

FIGURE 3. Graphical representation of modelling scenarios



2.2. Key assumptions

Demand

The 2026 Scenario stands at the beginning of two pathways with estimated annual gross electricity demand at 110 TWh (the pre-war demand was around 150 TWh). Under the Victory scenario, the modelled gross demand almost reach pre-war demand level by 2030, but with more territories under control. Under the Frontline scenario, Ukraine's economy remains crippled and electricity demand reaches only 121 TWh, a 20% reduction compared to 2021. For reference, the National Energy and Climate Plan (NECP) scenarios until 2030 are based on 146-152 TWh total generation assumptions, meaning the government is not considering an alternative scenario with lower demand.

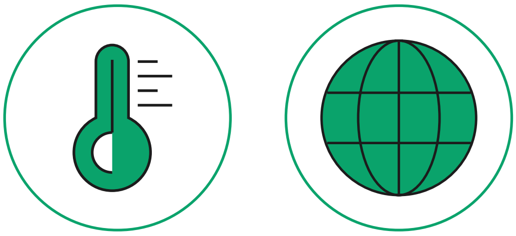
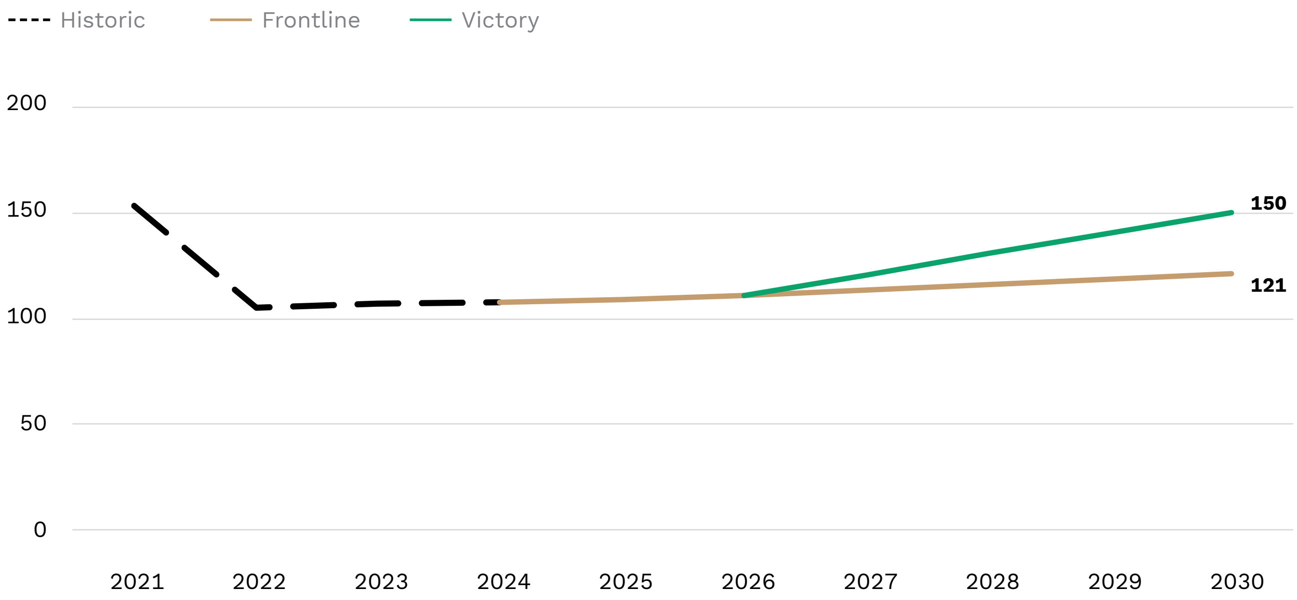


FIGURE 4. Gross electricity demand under modelling scenarios [TWh]



Source: Instrat & CEL calculation, Ukrenergo

Note: Gross demand means net consumer demand plus grid losses and self-consumption of power stations. Gross demand is a result of the PyPSA-UA model, based on net demand model input.

Supply

The access to public data on the scale of damages to the generating capacities is limited for security reasons. Our estimates of the scale of damages and capacities repaired until 2026 and 2030 are based on publicly available statements and newsletters of the Ukrainian energy companies as well as on interviews conducted with experts. For the 2026 scenario, we assume that 900 MW market-participating distributed gas-fired engines and turbines will be installed. This is based on our understanding and analysis of the publicly announced pipeline in Ukraine.

For 2030 pathways, we assume all power plants that are currently on the temporarily occupied territories will be looted and inoperational. The Repair scenario under Frontline pathway assumes damaged power plants are partially repaired, and Zaporizhzhya nuclear power plant remains unavailable. The Victory pathway allows more extensive repair of coal and hydropower plants due to reduced risks, and assumes regained control over Crimean power plants and limited availability of ZNPP. We set these restored capacities as model inputs in the Repair scenario.

All costs and technology prices are the same for all scenarios. We do not assume additional carbon taxation to be imposed or an emission trading scheme implemented until 2030. Please see Appendix D for a detailed breakdown and description.

Behind-the-meter photovoltaics growth assumptions

The Polish experience is a success story for boosting BtM PV generation. Driven by route-to-market policies for prosumers (net metering introduced in 2016 and replaced by net billing in 2022) and the "My Electricity" subsidy program for the PV equipment purchase (2-10 kW capacity), Poland has reached 1.4 mln residential PV installations (or 8.6% of all households) in 2023, adding 1.25 mln in only 5 years (ARE, 2024). Notably, out of total 11.5 GW of residential PV only 3.2 GW were subsidised under the program – the rest 72% of installations were financed by households solely (NFOSiGW, 2024).

We believe that Ukraine stands on the verge of a similar wave, with all factors converging and government policies in place. And it's the BtM PV, not utility-scale merchant projects, that will represent the majority of added solar capacity in the next 5 years. Ukraine's BtM PV growth will be driven by the following four factors:

- **A** "Cost parity" of BtM PV against the retail electricity tariffs
- **B** Introduction of net-billing for prosumers
- **C** Subsidised loans
- **D** Emergency supply source

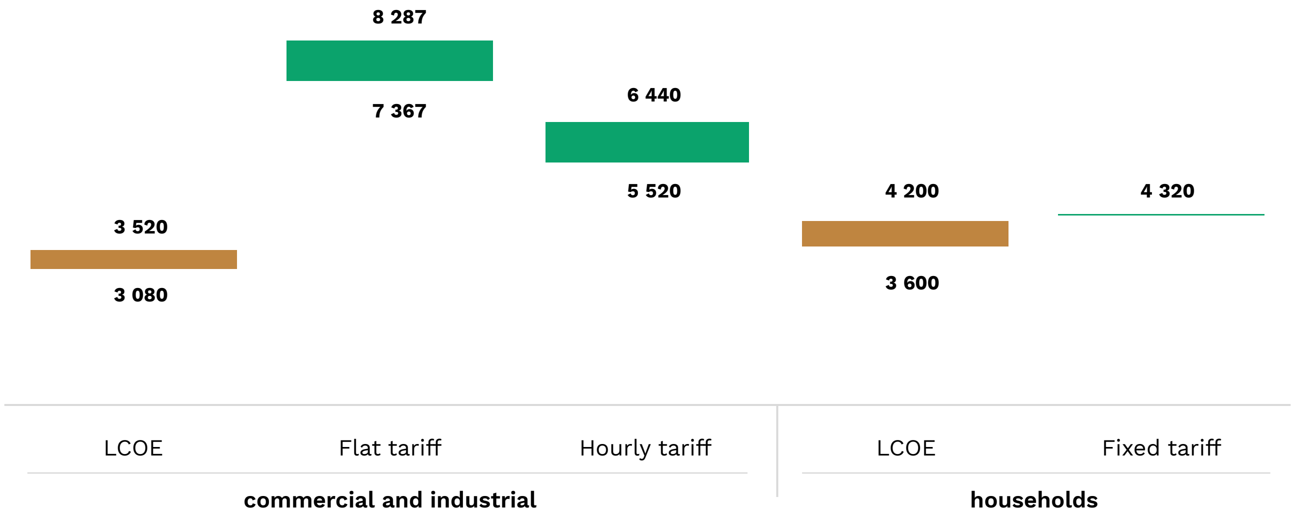
A "Cost parity" of BtM PV against the retail electricity tariffs

Prosumers are making investment decisions not based on wholesale market electricity price but on their final tariffs. The cost of on-site PV consumption is already competitive against the cost of electricity from the grid in Ukraine. While capture prices on the wholesale market barely cover LCOE[4] of utility-scale projects, avoiding the grid charges makes BtM PV a strong investment case. For commercial and industrial (C&I) consumers, the payback period is around 4-6 years depending on the region[5]. Household (HH) consumers have historically enjoyed the subsidised tariff which was way below PV costs. This is the reason why HH BtM PV was driven solely by a feed-in tariff support scheme. In June 2024, the HH tariffs were increased by 64% compared to 2023 and for the first time have crossed the boundary of PV LCOE. The Ukrainian government is likely to revisit the regulated HH tariff yet again in future as a response to damages to the infrastructure and a source of financing for the energy sector.

4 The Levelised Cost of Electricity (LCOE) is the discounted lifetime cost of building and operating a generation asset, expressed as a cost per unit of electricity generated.

5 Distribution grid tariffs in Ukraine vary between DSOs serving different administrative regions.

FIGURE 5. Estimated Levelised Cost of Electricity of Behind-the-meter PV installations and consumer tariffs in 2024 [UAH’2024/MWh]



Source: Instrat & CEL calculation, Market Operator

Note: hourly tariff represents the capture price of PV for consumers exposed to hourly pricing. Data representative of September 2024.

B Introduction of net-billing for prosumers

Net billing is a policy that provides an easy route-to-market for prosumer-generated electricity. It guarantees that prosumers can export excess generation to the grid at wholesale market prices bought out by their suppliers, with no licensing or additional permitting. The account of electricity sold is settled every month, either against the respective supplier’s bill or in monetary form. This policy can drive interest in deploying behind-the-meter generation to both reduce their bills and ensure a certain level of energy security. Additionally, those prosumers who were sizing their PV on a lower end in order to minimise power exporting to the grid now can add more capacity. The policy has been enacted in Ukraine only recently in 2024, and is expected to become a main driver for unlocking the potential of small-scale generation.

C Subsidised loans

In response to the energy crisis in the middle of 2024, the government of Ukraine has introduced a set of subsidised loan programs. These loans are provided at below-market rates and under less strict guarantee and collateral requirements. This significantly simplifies access to finance for prosumers and reduces barriers for financing energy projects as well as costs of produced electricity. Three programs are in place now covering several groups of prosumers:

- "5-7-9%" loan program (CMU 2024), providing loans up to
  - EUR 3.3 mln at 5-7% for 10 years for C&I applicants,
  - EUR 110k at 7% for 5 years for homeowners associations (de-facto collective prosumers),
  - EUR 10.5k at 0% for 10 years for households (but only for up to 10 kW PV/wind installations combined with storage);
- Loans from the State Fund for Decarbonization and Energy Efficient Transformation, up to EUR 560k at 7-9% for up to 10 years – for C&I entities introducing energy efficiency measures including self-consumption of electricity (CMU 2024);
- GreenHouse program by the Energy Efficiency Fund which covers up to EUR 22.5 of energy equipment cost for residential building association (EEF 2024).

D Emergency supply source

Blackout risks and challenges are prompting consumers to take energy supply into their own hands. BtM PV systems already offer bill savings, with optional government-backed financing available. Demand for self-supply is expected to grow as the risk of prolonged supply interruptions persists.

As of today, there is no reliable open-source information on the installed behind-the-meter energy assets. BtM generation can be installed by both C&I and HH prosumers, either under legacy Feed-in Tariff (FiT) mechanism, under new net billing mechanism or as fully "merchant" without selling excess electricity to the grid. While the data on FiT capacities is available in Ukraine (1.5 GW solar by HH as of end 2023), there is no reliable source on installations for self-consumption that were never reported to authorities and grid operators.

The recent reports indicate a massive demand for subsidised loans programs. In the first 4 months, 2484 applications from legal entities were submitted to banks, 1081 approved and 220 loans issued (NBU 2024). This translated into around 200 MW of new BtM generating capacity with 96 MW of gas cogeneration engines, 51 MW diesel/petrol emergency generators and 49 MW of solar PV.

At the same time, 1 100 thousand households received energy loans in one month only. There is no indication of installed capacities by households. If the total loan volume of UAH 204 mln is assumed to be 10 MW PV + 5 MWh storage systems, it would amount to 10 MW financed in two months.

To investigate the issue further, we've analysed the Ukrainian customs data on PV panel imports during 2010 – H1 2024. We identified approximately 500 MW of PV capacity that was not covered by any support scheme as of the end of 2023, along with around 400 MW of panels imported in just the first half of 2024. We estimate that half of the 500 MW was imported by operators to restore damaged and liberated PV stations, while the other half likely represents BtM PV systems installed for self-consumption without injecting excess power to the grid.

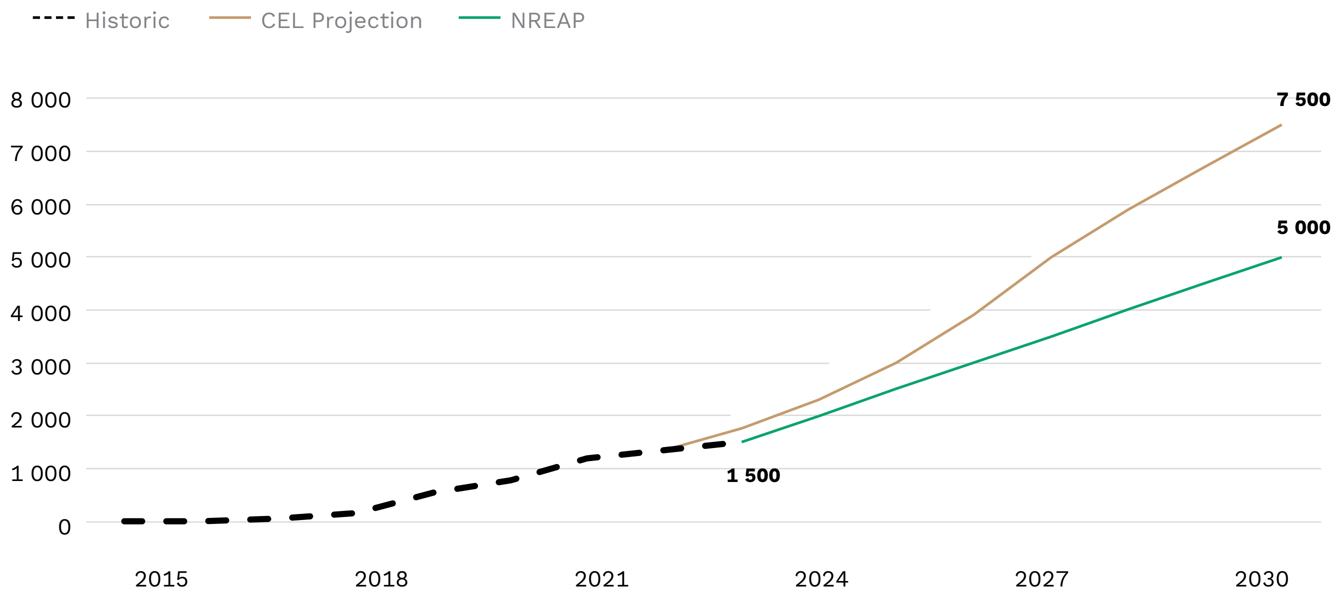
Our modelled assumptions converge from the following projections:

- start with 1 750 MW BtM PV as of 2023 (1 500 MW under FiT + 250 MW imported in 2022-2023), and annual average additions of 800 MW (based on the first half of 2024 imports).

- projections based on Poland's experience: number of C&I and HH consumers installing PV adjusted to 25% for the Ukrainian case.

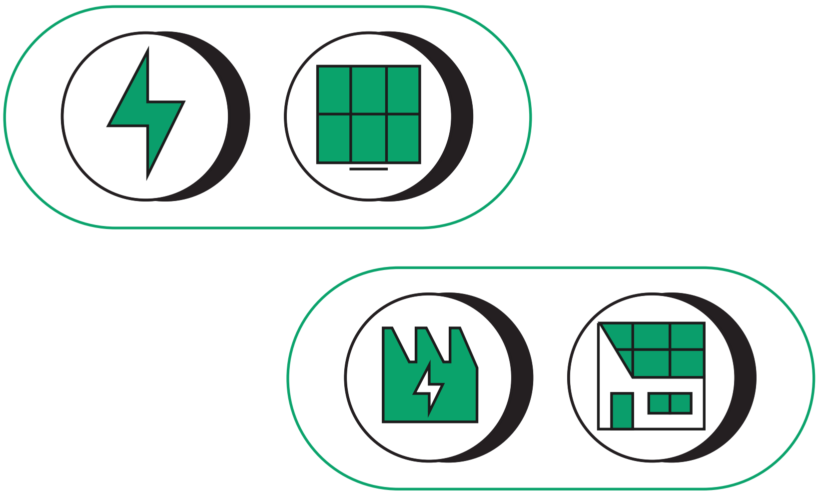
The NREAP 2030 envisages 5 000 MW of household BtM PV to be installed by 2030. We estimate the similar figure and suggest an additional 2 500 MW installed by C&I consumers by 2030. For details of calculations please refer to Appendix C. We estimate that 500 000 households will have PV installed for self-consumption by 2030, representing 3% of all households (or 10% of rural households), and around 35 000 businesses.

FIGURE 6. Projected assumptions on installed behind-the-meter photovoltaics in Ukraine [MW]



Source: NREAP 2030, Instrat & CEL estimates

Our BtM PV assumptions are exogenous[6] inputs to the model due to challenges typical for such installations in the power system optimisation models[7]. Eventually, it will represent a share of total PV suggested to be cost-optimal by the model and may as well be treated as another type of PV installed in the system. The aim of our research is not to "forecast" how much BtM is to be expected by 2030 but rather investigate whether the Ukrainian power system can manage the assumed BtM PV capacity. The results of our key scenarios provide a view on the optimal amount of both utility-scale and BtM PV, and their shares eventually could be interchangeable.



6 Pre-determined rather than defined by the model

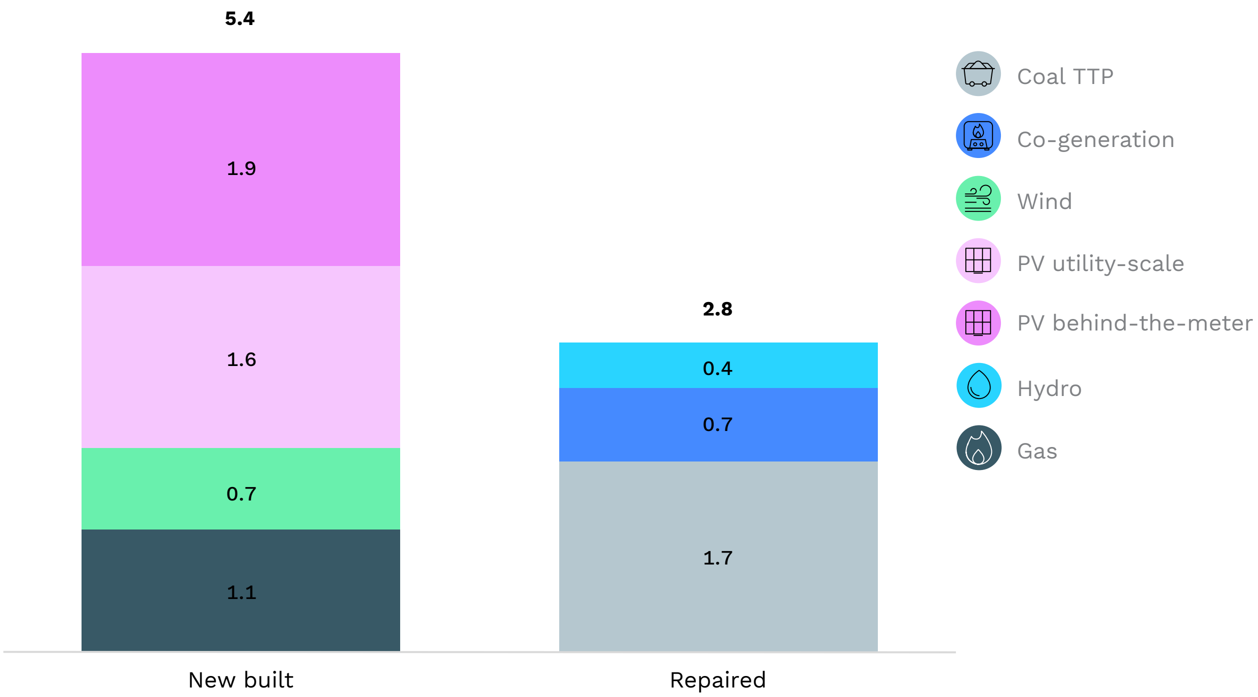
7 BtM PV can be cost-optimal for the customers, but utility-scale PV is typically more cost-efficient for the system and as such preferred by optimisation models

3. What are our findings?

3.1. Ukraine needs 5.4 GW of new capacities by 2026

Ukraine is facing a power deficit during periods of seasonal peak consumption and remains under constant threat of further attacks on its energy system. To address its immediate energy needs, Ukraine urgently requires new 4.3 GW RES by 2026, 1.1 GW new fast-start gas supported with 2.8 GW of repaired thermal power, CHP, and hydropower plants as well as ensured additional 0.6 GW of cross-border capacity. PV can play a decisive role with 3.5 GW, of which the majority could be behind-the-meter. This effort requires mobilisation of a major investment of at least EUR 4.3bn in the next 2 years. Unlocking investments and deploying such capacity in a record timeframe calls for decisive policy actions. The best way is to leverage the existing pipeline of utility-scale project developers and tap into the potential of small and medium prosumers.

FIGURE 7. Additional capacities required by 2026 [GW]



Source: Instrat & CEL calculations based on PyPSA-UA modelling.

3.2. PV and wind can become the backbone of Ukraine's power system by 2030, supported by flexible capacities

Under our **baseline scenario** which assumes repairs of damaged capacities, the Frontline pathway requires 9.4 GW of new RES and 1.1 GW of new gas capacities, together with 3.8 GW of repaired legacy capacities by 2030. The Victory pathway requires 12.8 GW of RES and 0.9 GW of new gas in addition to 7.4 GW repaired and 3 GW unoccupied capacities.

The Decentralised scenario, which assumes no repairs of coal power stations are possible or they are abandoned in favour of new decentralised generation, requires a more extensive buildout. The Frontline pathway requires additional 11.3 GW of renewables and 3.5 GW of gas, and the Victory pathway 15.6 GW of RES and 5.3 GW of gas.

The role of new gas generation would differ under two scenarios. Under Repair, gas-fired plants would play a role of peakers running during 12-18%[8] of all hours in a year, which means that an ICE technology is likely preferable for investment. Under the Decentralised scenario, gas partially replaces a sub-peak coal profile operating during 67-74% of the time. This requires more investments in OCGT/CCGT technologies capable of maintaining longer continuous loads during winter seasons.

The model does not suggest additional capacities of biomass or battery energy storage due to their relative high costs which makes them uncompetitive[9]. These technologies may provide additional flexibility and diversify the mix, but would rely on support schemes and result in slightly higher total system cost.

3.3. The behind-the-meter PV can be the key element of a new decentralised generation

Our model demonstrates that Ukraine's power system is capable of absorbing the electricity generated by 7.5 GW of BtM prosumer PV without cannibalising other renewables sources and with no changes to nuclear baseload generation. It also decreases the distribution losses by 6%, potentially reducing distribution tariffs by 2-3%. However, with the expected BtM PV deployment rate, there is less room left for utility-scale renewables or no room at all under the Frontline pathway.

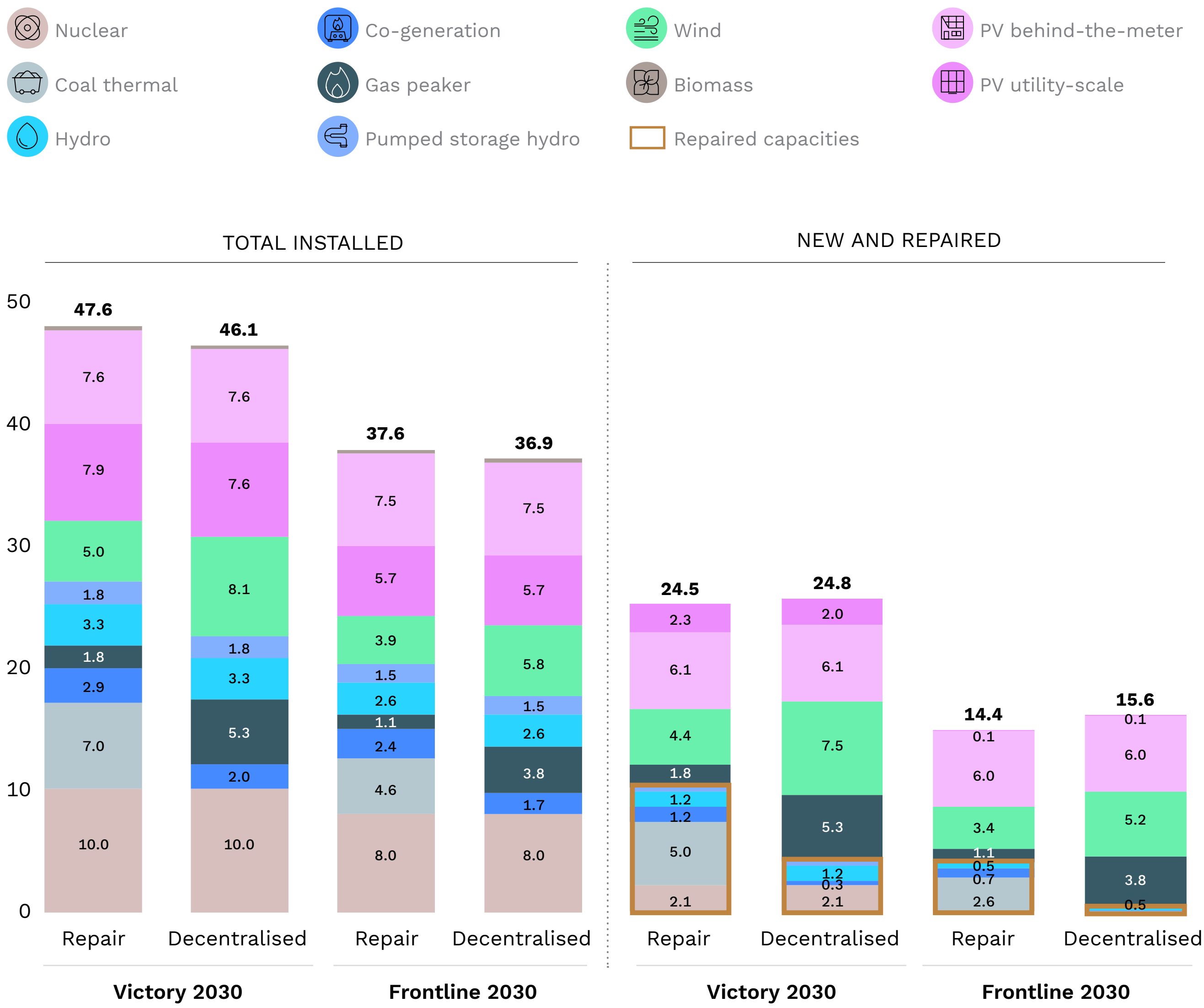
We also investigated a hypothetical "limit" of how much BtM PV the Ukrainian power system can absorb without reducing the typical load of its nuclear fleet. We found this to be 15.8 GW of BtM PV until 2030. How-

8 Frontline/Victory pathway data

9 PyPSA-UA does not model the balancing market, which could be the main revenue source for battery storage and flexible biomass generation.

ever, under this hypothetical scenario such capacity pushes the boundaries of system's flexibility and cannibalises utility-scale PV and wind. Generation-wise, such mix requires coal plants to stay idle during 17% of hours and lead to a 20% curtailment of utility-scale PV and wind plants' output. The resulting power mix is not drastically different to a system with half of that BtM capacity, resulting in a mere 1 percentage point increase of RES share compared to the optimal Victory scenario. Such a system requires 27% more investments, however results in roughly the same annual system cost due to savings on fuel expenses, which suggests a balance between short-term capital expenditures and long-term operational expenditures.

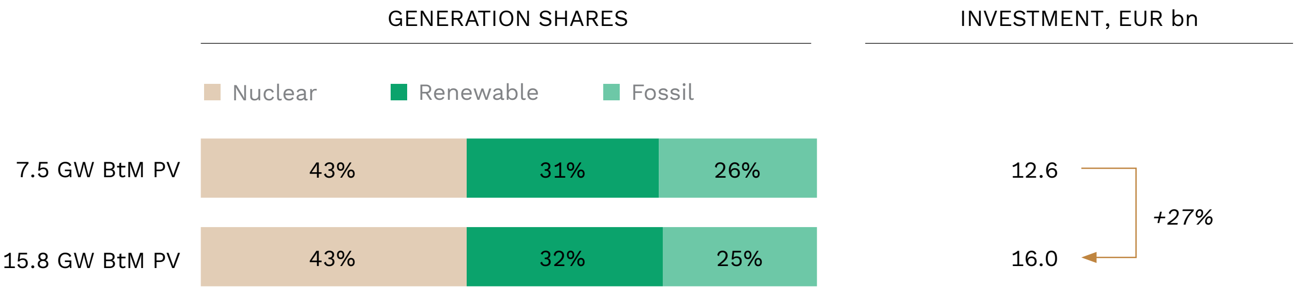
FIGURE 8. Power plant capacities in 2030 scenarios [GW]



Source: Instrat & CEL calculation based on PyPSA-UA modelling.

Note: Gas capacities of 1.8 GW in the Victory 2030 pathway represent a combination of new-built and a Crimean gas generation fleet of 0.9 GW.

FIGURE 9. Generation mix share under different behind-the-meter PV levels, Victory pathway & Repair scenario 2030

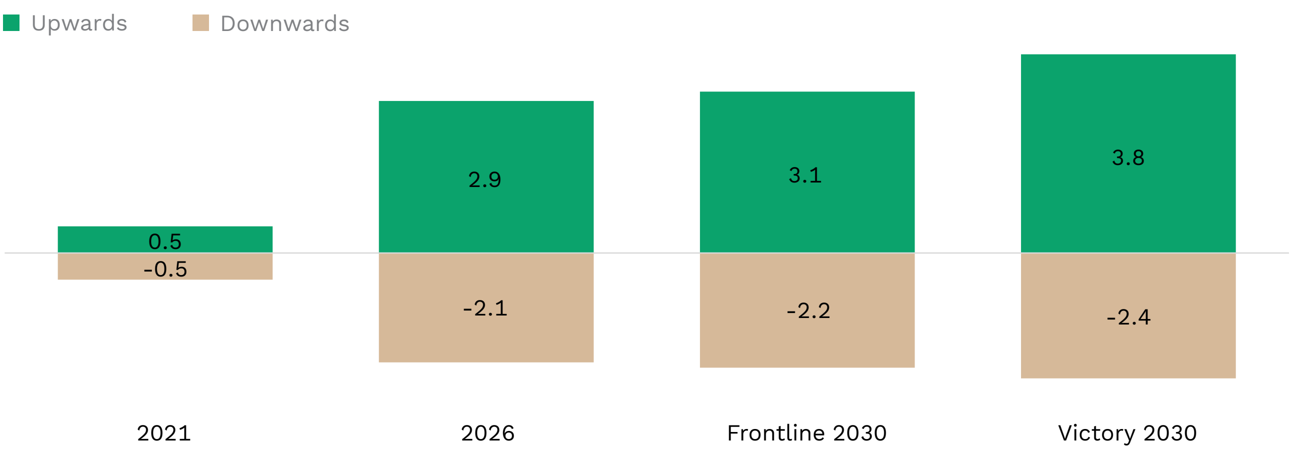


Source: Instrat & CEL calculation based on PyPSA-UA modelling.

3.4. Demand for flexibility will increase, and export will play a crucial role in the medium-term

The increase of renewable energy share requires more flexibility in both upward and downward directions. Flexibility can be measured in two terms: its "power" and "volume". The flexibility "power" requirement can be measured as system ramping – a change in residual load[10] between hours. This means how fast the generation other than variable renewable energy must ramp up and down between hours to match the demand which was not met by wind and solar PV. Compared to 2021, the maximum requirements increase 5.8 times for ramping up and 4.2 times for ramping down already in 2026 under our modelled optimal mix. Even further increase is expected in 2030 pathways which puts the flexibility of conventional generation to its limits.

FIGURE 10. System maximum ramping no comma afterwards, [GW/hour]



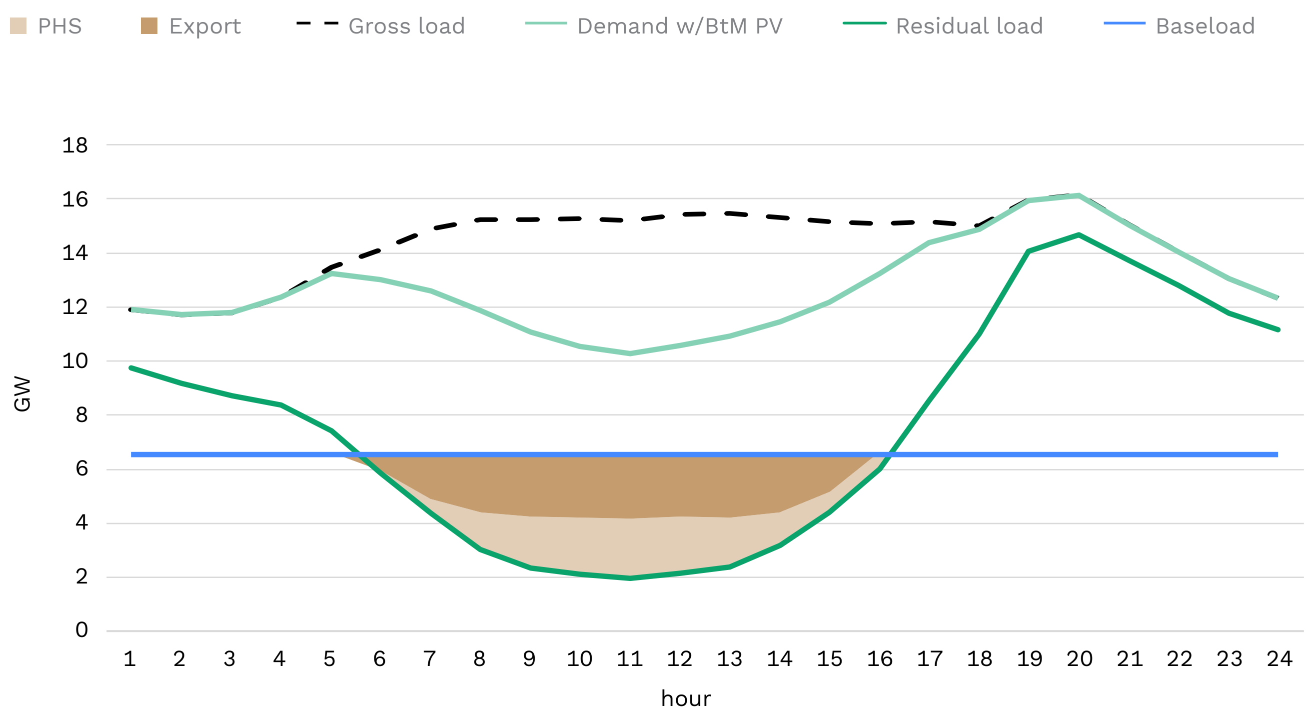
Source: Instrat & CEL analysis based on PyPSA-UA modelling (2026 and 2030) and on Ukrenergo (2021).

10 Residual load (demand) = Gross consumption (incl. losses and self-consumption of power plants) – variable RES generation. It represents how much of demand is "left" to be satisfied by technologies other than PV & Wind.

The BtM generation is not reported in real-time directly to the system operator but rather is reflected as a reduced load curve. With the increase of prosumer solar generation, the curve bends towards the bottom during noon, resembling the duck hence the name “duck curve”. The power system can absorb PV generation which pushes the residual load below the level of its baseload by employing its downward flexibility options within their “volume” limit. Energy storage is limited by its technical volumes, and demand-side response by consumers’ readiness to self-curtail. Export potential is dictated by other countries’ generation mix and baseload generation, e.g. countries with lots of PV will be less likely to import energy during solar peak production. In our research, we assume export is not constrained and demand-side response is not present.

To achieve our modelled 2030 power mix, Ukraine will rely on its existing pumped hydro capacities and projected cross-border capacity for export. At its maximum, the daily PV “volume” needed to be absorbed will reach up to 30 GWh, while the existing PSH water reservoir in Ukraine are capable of absorbing only 13.8 GWh. The remaining share will fall onto export, should it be available for up to 2.3 GW capacity during solar peaks as our modelling results require. In practice, it is not guaranteed that the European countries interconnected with Ukraine will be able to absorb this electricity all the time, as they will also experience solar generation peaks, albeit with some time-shift. The inability to export due to any reason (technical or price) will result in 3 GW less of a “PV absorption”.

FIGURE 11. Snapshot of a “duck curve”, Victory pathway & Repair scenario on 11/05/2030 [GW]



Source: Instrat & CEL calculations based on PyPSA-UA modelling.

Note: Residual load = Gross consumption (incl. losses and self-consumption of power plants) – variable RES generation

3.5. Security premium – a transition to a decentralised gas & renewable system costs more but is more resilient

Repair baseline scenarios require the least investment: EUR 12.5 bn in the Victory pathway and EUR 9.3 bn in the Frontline pathway over the next 5 years. These baseline scenarios however leave the repaired coal power stations vulnerable to attacks. The Decentralised scenarios suggest slightly higher investments of EUR 18.8 bn for the Victory and EUR 13.6 bn for the Frontline pathways. The 46-50% capital cost increase when comparing Repair and Decentralised scenarios is essentially a security premium for a generation fleet less susceptible to military attacks.

FIGURE 12. Total financing needs required during 2025-2030 [EUR bn]

Source: Instrat & CEL calculations based on PyPSA-UA modelling.

Note: the total sum may decrease for Victory 2030 scenarios for up to EUR 1.5 bn if wind turbines on the temporary occupied territories remain intact.

3.6. New nuclear generation plans will impact renewable energy deployment and may lead to less investment in renewables and higher risks of power shortage

We examined the potential impact of deploying an additional 2 GW of nuclear capacity as part of a sub-scenario of 2030 Repair. This expansion would significantly influence power system dispatch and the energy mix:

- **Renewables Substitution:** The added nuclear capacity would substitute 1.8 GW of solar and 1.4 GW of wind in the Victory pathway and 0.6 GW of wind in the Frontline demand level, compared to the Repair (baseline) scenario.

- **Increased Curtailment:** Renewables would face curtailment of 7.4% in the Victory pathway and 15% in the Frontline pathway, compared to cost-optimal scenarios with no curtailment. This would drive up energy costs.

- **Lower Fossil Fuel Utilization:** Conventional generation would see reduced utilization, lowering the share of fossil fuels in the energy mix. However, the added nuclear capacity would also reduce the share of renewables—from 31% to 25% in the Victory pathway and from 33% to 30% in the Frontline pathway.

While expanding nuclear power could accelerate decarbonization, it would compete directly with renewable energy targets, creating a trade-off between these objectives. To be economically viable, the additional 2 GW of nuclear capacity would need to cost less than EUR 1.6 billion under the Victory pathway and EUR 0.6 billion under the Frontline pathway. These cost thresholds are not feasible for new nuclear projects and could only be realistic for restoring the existing Zaporizhzhia Nuclear Power Plant (ZNPP).

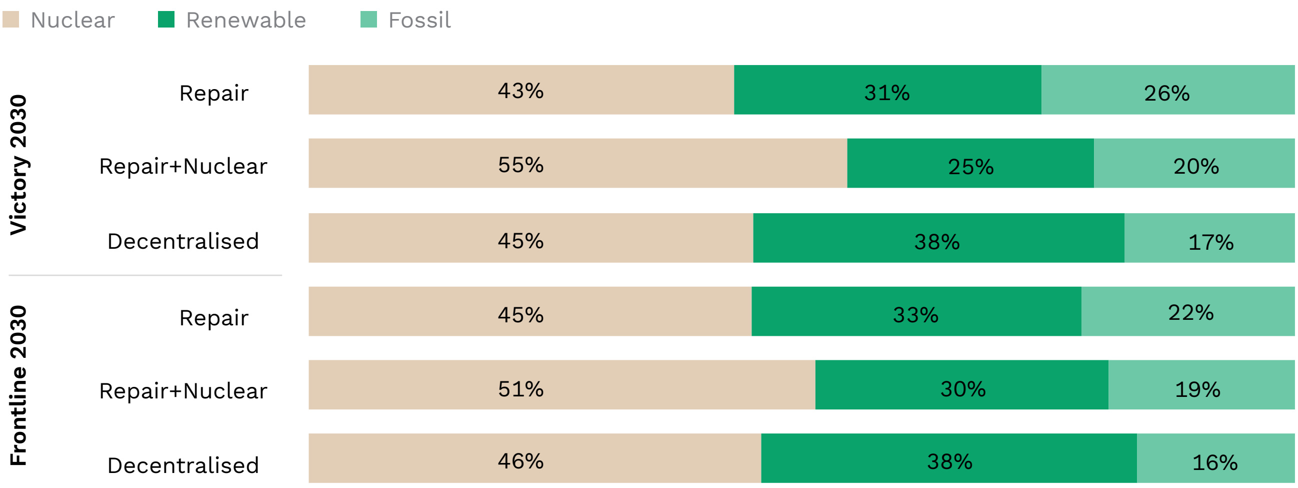
The construction of two new nuclear blocks will also bear some risks:

- Nuclear generation represents a rather big centralised generation asset which will be susceptible to potential attacks.

- Nuclear projects are prone to overruns in budgets and timelines. Construction of such a massive infrastructure project requires years of preparation and mobilisation of the economy, supply chain and equipment manufacturing. It is very unlikely to finish a project before 2030 in a country that commissioned its last infrastructure project of such scale in 2004.

- Ambiguity of the government's plans will shake the investors' confidence. If the government doubles down on its plan to deploy new nuclear power by 2030, it may send a signal to investors that less investment into other types of generation is required. Nuclear plans can potentially reduce the RES auction quotas.

FIGURE 13. Sensitivity analysis of the effect of additional nuclear in 2030 scenarios



Source: Instrat & CEL calculations based on PyPSA-UA modelling.

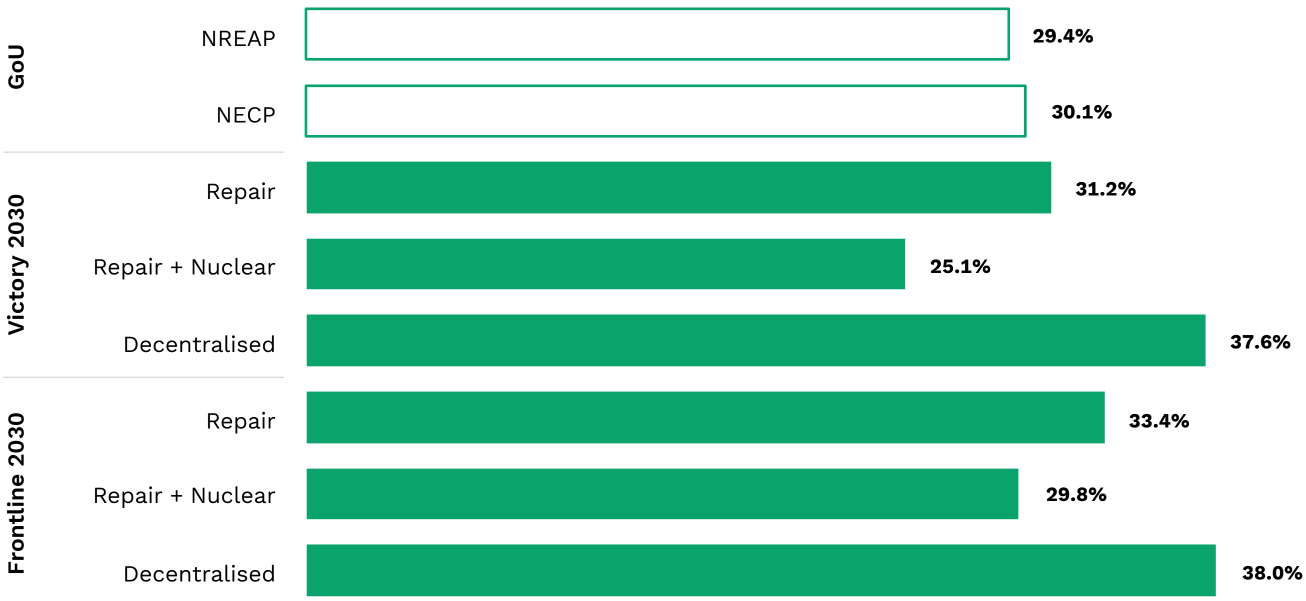
3.7. Government's renewable electricity targets are achievable yet conservative and can be jeopardised by additional nuclear capacity

The Ukrainian government has set a renewable energy target of 29.4% of total electricity generation by 2030, as outlined in its National Renewable Energy Action Plan (NREAP 2030) and National Energy and Climate Plan (NECP 2030). The NREAP targets 5 GW of BtM PV by 2030 driven solely by households. Our modelling confirms this estimate and acknowledges additional contribution of C&I prosumers of 2.5 GW, reaching a total of 7.5 of BtM PV. Our Repair scenario, consistent with NREAP's renewable capacity goals, projects a slightly more ambitious RES share of 31.2% under the Victory pathway and an even higher 33.4% under the Frontline pathway.

However, if the government proceeds with plans to add 2 GW of nuclear capacity by 2030, meeting the RES target under the Victory pathway could become challenging. Our Decentralised scenarios, which most closely aligns with the NECP's WAM[11] 2030 projections, shows that a 37.6-38% RES share is achievable with reduced nuclear availability and increased gas capacity. While additional nuclear power may hinder the RES goals, investing in a decentralised energy system can help exceed them.

11 with additional measures

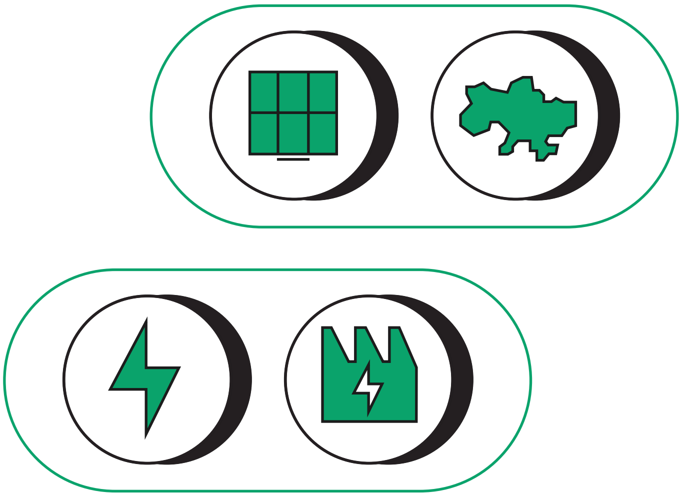
FIGURE 14. Renewables share in total electricity generation under the Ukrainian government's plans and Instrat & CEL scenarios.



Source: Instrat & CEL calculations based on PyPSA-UA modelling and Government of Ukraine.

Note: RES share from total electricity generation.

NREAP – National Renewable Energy Action Plan. NECP – National Energy and Climate Plan.



4. What are the policy implications?

Ukraine faces an unprecedented challenge, requiring the installation of 10.5 to 14.6 GW of new capacity by 2030 according to Instrat & CEL modelling, depending on the future electricity demand scenario. Critically, 5.4 GW of this capacity must be deployed within the next two years. A deployment pace of this magnitude was last achieved in 2019-2020, spurred by the Feed-in Tariff (FiT) mechanism. Today, however, investors need even stronger, more reliable policy support to meet these ambitious goals.

Decisive government actions are essential to unlocking the necessary investment and accelerating deployment. The question is, what steps can Ukraine take to meet this pressing need?

4.1. Renewable energy auctions to provide certainty to investors and unlock the existing pipeline of RE projects

The Government of Ukraine first introduced renewable energy support auctions in 2019, yet only held its initial pilot sessions in October-November 2024. A total of 111 MW was auctioned – 88 MW for wind, 11 MW for solar PV, and 11 MW for bioenergy and small hydro combined. Unfortunately, the auctions failed to attract any participants. The government has not yet released a 5-year renewable energy auction quota.

Currently, Ukraine's wind energy pipeline includes 4.8 GW of projects primed for deployment over the next five years, of which an estimated 1.2 GW could realistically be installed by the end of 2026 (data courtesy of the Ukrainian Wind Energy Association). This pipeline, already at intermediate or advanced stages of development, is sufficient to meet Ukraine's 2030 renewable energy targets. Renewable energy auctions have the potential to activate this pipeline, offering guaranteed offtake and pricing, which can help secure essential financing.

Given the support scheme's commissioning deadlines – 1.5 years for PV and 3 years for wind – our model suggests that procurement over the next five years should align with the annual capacity targets detailed in Table 1. This would facilitate timely deployment and help Ukraine achieve its renewable energy objectives.

TABLE 1. Suggested RE auctions maximum quota to reach 2030 targets [MW]

Scenario	Technology	2025	2026	2027	2028	2029
Victory	PV utility	-	550	550	550	550
	Wind (2-y development)	670	1 220	1 220	1 220	
	Wind (3-y development)	670	1 830	1 830		
Frontline	PV utility	-	-	-	-	-
	Wind (2-y development)	670	870	870	870	
	Wind (3-y development)	670	1 300	1 300		

Source: Instrat & CEL estimates.

Note: Wind (2-y development) represents theoretical projects in late stage of development, Wind (3-y development) represents projects at earlier stage. Typical full development cycle time for wind projects is 4-8 years.

A significant barrier to successful renewable energy (RE) auctions in Ukraine is the lack of investor confidence in government support payments. Both the legacy Feed-in Tariff (FiT) scheme and the new auction-based Contracts for Difference (CfD) rely on the same funding source – a transmission tariff distributed among all consumers. However, FiT payments have historically faced underfunding, partly due to government limits on energy price increases and compounded by market shocks from the ongoing conflict. As of October 2024, the debt to existing renewable energy projects has accumulated to UAH 32.2 billion (EUR 0.74 billion) (GB 2024).

To instil investor confidence and ensure the success of RE auctions, the government must send a clear signal of its commitment to honouring these contracts. This would include establishing a robust procurement pipeline and providing a transparent forecast of transmission tariffs for the next five years, ensuring adequate support payments. Such measures are essential to build trust in the government's ability to finance newly signed contracts and attract the investment needed to reach Ukraine's renewable energy targets.

4.2. Enabling an efficient balancing market is paramount to ensure deployment of new flexible capacities

To address Ukraine's urgent need for 1.1 GW of new flexible gas capacity over the next two years, substantial improvements are needed in the balancing market. Flexible assets derive the majority of their revenue from the balancing market rather than from direct energy sales to consumers, making a robust and well-regulated balancing segment essential. Despite clear demand for flexible capacity, private investment has been absent due to regulatory barriers.

Two primary issues deter investors in Ukraine's balancing market

First, price caps restrict profitability; the cap is set at 10 000 UAH/MWh (~222 EUR/MWh) for peak hours (17:00–23:00) and even lower during off-peak hours. For gas assets, revenue heavily depends on the number of hours they can operate. For instance, based on 2024 pricing and our 2030 model, a 1-MW gas unit could earn around EUR 130 000 at a 10% load or EUR 275 000 at a 22% load as projected for 2026. However, gas plants will likely need to provide more stable loads during winter, and under current pricing, projected payback times range from 7–13 years – less attractive for investors facing high market risk. Additionally, the low price caps render battery storage and bioenergy projects financially unfeasible within the balancing market.

Second, the market suffers from accumulated debts and delayed payments to balancing energy suppliers. Ukrenergo, the system operator, recently reported UAH 34 billion (EUR 0.75 billion) in unpaid imbalance debts and UAH 16 billion (EUR 0.35 billion) owed to balancing energy suppliers. Currently, suppliers often face 6-12 month delays for payments, and the risk of partial or non-payment grows over time. Even if price caps are adjusted, payment risks will likely continue to dissuade investors from entering this market.

In situations where market revenue is insufficient, a government subsidy — volume-based (e.g., contracts for difference) or capacity-based (e.g., capacity markets) — could provide necessary support. Such mechanisms address market inefficiencies and encourage private investment. Ukrainian law allows for tenders to support new generation capacity and provide subsidies, yet this has not been implemented to date. This support could be crucial for mitigating investment risks during wartime.

Recently, the Ukrainian government announced plans for auctions to secure up to 700 MW of new flexible capacity, though an auction date has not yet been set (CMU). Given the urgency and lead time required for project development and equipment procurement, these auctions should be announced as soon as possible. Cost-efficiency, however, must be a priority; the maximum auction price of EUR 855 000 per MW per year nearly covers the entire project CAPEX within a single year, even though contracts are expected to last at least a decade. While competition could drive prices lower, we recommend reassessing the starting price to enhance value for consumers.

Key steps to bolster investment in the balancing market include:

- Identifying and eliminating the sources of debt accumulation
- Ensuring timely, full payments to balancing energy suppliers
- Raising price caps to allow greater price flexibility, attracting investors
- Offering early entrants risk-reduction mechanisms like capacity payments at competitive rates to support maximum capacity deployment at reasonable costs

4.3. Actively support behind-the-meter photovoltaics development

Behind-the-meter PV systems offer a powerful pathway toward grid decarbonization, driven by consumers' concerns over energy security and rising costs. BtM generation can complement utility-scale projects, providing a decentralised, resilient energy source. These assets are generally faster to deploy, with significantly reduced development times and minimal permitting requirements, enhancing the grid's resilience against disruptions. In Ukraine's urgent energy landscape, empowering consumers as "prosumers" could enable rapid deployment of new capacity, leveraging the resources and savings of businesses and households.

By supporting BtM development, the government can attract private financing and household investment, mobilising a valuable source of funding. For banks, financing numerous small-scale projects rather than a few large ones reduces risk and creates a diversified client portfolio backed by a low-risk business model. This diversified approach can accelerate the path to a more sustainable, resilient energy system.

Ensure stable financing for recently introduced subsidised loan programs

The Government should earmark the financing from the state budget sufficient for deployment of 900-1000 MW BtM PV annually in the next 5 years. At 13% market loan rate and 7% subsidised at 30% of equity, total subsidy spending will amount to EUR 543, or UAH 24 bn mln by 2030.

TABLE 2. Estimated annual subsidy to cover difference between market and subsidised interest rate for behind-the-meter PV [nominal 2024 currency]

Currency	2025	2026	2027	2028	2029	2030	Total
EUR mln	28	54	80	104	128	150	543
UAH mln	1 220	2 391	3 513	4 586	5 611	6 586	23 906

Source: Instrat & CEL estimates.

Support behind-the-meter deployment in public sector

State and municipal companies and institutions may also benefit from BtM PV and reduce public spending on energy bills. In November 2023, The Ministry of Energy of Ukraine presented a draft program for distributed energy promotion until 2030 (MEU 2023). This program envisaged state support for BtM generation for state and municipal institutions, with focus on critical infrastructure companies in 2024-2026 and other entities afterwards. Unfortunately, this draft has not been adopted.

ESCO[12] contracts can alleviate the financing requirements. Currently there are more than 700 ESCO contracts signed in Ukraine , with only 60 signed in 8 months 2024 (UA energy 2024). There is a significant potential for budget-constrained state institutions to install decentralised generation under ESCO contracts. However, at times such institutions may lack internal capacity to conduct tenders efficiently or may be unaware of such opportunities. A centralised procurement for BtM PV under ESCO contracts or other types of financing could be more efficient and faster.

Consider introduction of grants to reduce up-front costs

At current market prices, batteries may remain economically viable only for emergency supply. Grants for batteries can reduce the upfront costs and reduce the cost of shifting energy per cycle thus enhancing the motivation to utilise the asset more frequently rather than keep it as an emergency.

A promotional campaign to popularise BtM PV and inform public about the opportunities

A targeted promotional campaign highlighting the advantages of installing BtM systems is essential for raising awareness, enhancing understanding, and driving the adoption of solar power among households and businesses. This campaign should deliver clear and comprehensive information on the latest policies, potential applications, and available financing options, making adoption both accessible and appealing.

To effectively reach a wide audience, the campaign should establish a strong presence across television, online media, and social networks. This should be complemented by a dedicated website that offers detailed information and step-by-step guidance on installing BtM solar PV systems. Additionally, the initiative should actively engage the community by inviting citizens to participate in the movement, thereby contributing to Ukraine's energy security and sustainability. Collaboration with industry associations and NGOs are essential, with the government providing funding for presence in media platforms.

4.4. Tracking the installed capacity of behind-the-meter photovoltaics is crucial for both system planning and investment decision-making

For effective forecasting and long-term system planning, the system operator requires comprehensive data on the installed capacities of BtM generation sources. Enhanced visibility into these distributed assets would enable more accurate demand forecasting, optimization of system flows, and

12 Energy service contracts, where the service company uses its own finance to introduce energy efficiency measures including BtM generation and recovers costs from the savings on costumer's bills.

reduced balancing requirements. BtM PV installations have the potential to significantly improve grid flexibility and determine the level of nuclear baseload the system can accommodate. Therefore, the visibility of both the number and capacity of BtM installations is essential. To address this, the government should:

- establish a regular data collection process and through distribution system operators, alongside self-reporting requirements for prosumers, whether or not they are formally registered as „active consumers",
- provide Incentives for self-reporting, for example guarantees of origin granted only to registered installations, disregarding whether they are feeding to the grid or not,
- require installation companies to report new installations as part of the service, ensuring timely data updates when new systems come online.

4.5. The role of aggregation

An energy aggregator is a company that pools together energy assets or customers to participate collectively in energy markets. By combining smaller assets of diverse technologies, which would otherwise face barriers due to size and administrative costs, aggregators enable these assets to access wholesale market opportunities. Acting as a virtual power plant, an aggregator manages the outputs of all combined assets, capturing additional value for asset owners.

Aggregators can be instrumental in facilitating the smoother integration of BtM applications. First, they can link BtM solar to energy markets, enabling these assets to participate in paid curtailment through the balancing market. Second, aggregators can incorporate BtM cogeneration gas engines, which are increasingly being installed by district heating, water supply companies, and heat-intensive industries across Ukraine. By the end of 2024, at least 50-100 MW of BtM gas engines with small individual capacities are expected to be installed, with industry projections suggesting another 300-500 MW by 2026. If these engines operate solely based on onsite demand, they would miss opportunities to contribute to the balancing market and provide system flexibility.

A framework for energy aggregation was introduced in Ukrainian legislation in mid-2023, with secondary regulations anticipated by 2025 to enable its full application. This model has the potential to significantly reduce system operator uncertainties, enhance demand forecasting, and reduce government expenditure on new generation capacity. To expedite the benefits of aggregation, the government should support the development of aggregators in Ukraine. Ukraine can more effectively harness the potential of BtM and other distributed energy resources, optimising grid performance and reducing the cost of grid integration by promoting aggregators through the following measures:

- **Fund research on energy aggregation:** Provide grants to support research on energy aggregation in Ukraine, encouraging knowledge-sharing on technical solutions and aiding in the development of industry standards.
- **Create a technical standards task force:** Assemble a task force to establish and update technical requirements for aggregators and their connected assets, ensuring alignment with grid needs and market protocols.
- **Offer incentives:** Promote new entrants in the aggregation sector through targeted subsidies, low-interest loans, and grants, enabling a competitive market for aggregators.
- **Establish pilot programs:** Create pilot projects in collaboration with the system operator to test aggregator participation, focusing on BtM solar and cogeneration assets to build confidence in the model.
- **Raise awareness among BtM asset owners:** Conduct outreach programs to educate owners of BtM assets about the value aggregation can bring, including market participation options and flexibility services.

4.6. Baseload vs renewables and sending the right signals to investors

The government must be mindful of the signals it sends to the market, as unclear or ambiguous plans can lead to risks of underinvestment and supply shortages. While power systems with surplus installed capacities can afford delays in commissioning new generation, Ukraine's current energy deficit means that any delays could result in energy shortages and economic disruptions, with insufficient generation capacity to fill the gap. If the government moves forward with both new nuclear projects and expanding other technologies, the eventual integration of nuclear power could lead to reduced returns for investors—particularly if overall demand growth remains low.

Furthermore, the existing inflexible baseload capacity, primarily from Soviet-era nuclear plants, combined with limited storage capacity and modest demand growth, will impose a ceiling on renewable energy integration beyond a 33% share of total generation within the 2030 horizon. Any new non-renewable technologies added to the grid should be designed to follow load fluctuations in order to accommodate peak demand. If nuclear power is to play a role in the future energy mix, it must utilise modern, flexible designs capable of supporting the integration of renewable energy sources.

Explanations and abbreviations

ARE	Energy Market Agency (Agencja Rynku Energii) in Poland
BtM	Behind-the-meter
C&I	Commercial & Industrial
CAPEX	Capital expenditure (i.e. investment costs)
CfD	Contract for difference
CMU	Cabinet of Ministers fo Ukraine
CHP	Combined heat and power generation
DSO	Distribution system operator
DSR	Demand-side response
ESU	Energy Strategy of Ukraine
FiT	Feed-in tariff
GB	Guaranteed Buyer (an off-taker of renewable energy under support schemes in Ukraine)
GoU	The Government of Ukraine
HH	Households
ICE	Internal combustion engine
MEU	Ministry of Energy of Ukraine
NECP	National Energy and Climate Plan until 2030
NEURC	National Energy and Utility Regulatory Committee (in Ukraine)
NREAP	National Renewable Energy Action Plan until 2030
NPP	Nuclear Power Plant
OCGT	Open-cycle gas turbine
OPEX	Operating costs
PSH	Pumped storage hydropower
PyPSA-UA	An optimisation model of the Ukrainian energy system created based on the PyPSA framework (Python for Power System Analysis)
PV	Photovoltaics
RES	Renewable energy sources
SAEE	State Agency for Energy Efficiency (in Ukraine)
TPP	Thermal power station
TSO	Transmission system operator (in Ukraine: Ukrenergo – UE)
ZNPP	Zaporizhzhya Nuclear Power Plant

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Appendix A – Selected methodological details

General scenario assumption on generation

- Seriously damaged power plants are not repaired. We made assumptions on power plants that can be repaired based on the best knowledge and interviews with industry experts. We don't disclose these detailed assumptions due to security concerns.
- Currently occupied power stations are looted and destroyed beyond repair by the russian army upon withdrawal except for Crimean generation fleet.
- Crimean power plants are considered to be operational in the Victory scenario and comprise 966 MW of gas-fired OCGT, 213 MW of gas-fired CHPs and 375 MW of PV.
- All power plants' capacities are aggregated on a regional level.
- The model uses data based on the 2018 weather year. We didn't model sensitivity scenarios to accommodate weather variability.
- In our calculations we consider only investment into generating assets, cost of grid repairs are not considered. Grid expansion is not envisaged by the model, the suggested capacities can be deployed within the pre-2022 grid topology and transmission capacity.

Nuclear

Maintenance schedules for PypSA-UA are calculated based on historical data and adjusted for availability of ZNPP, with total availability around 79% (compared to 66%-77% during 2018-2021). The installed available capacity of nuclear power in our model may differ from figures reported in comparable studies (NECP 2024, REKK 2024, Greenpeace 2024). We assume that the currently occupied Zaporizhzhia nuclear power plant will remain unavailable under Frontline and only partially available on Victory scenarios. Most studies assume ZNPP as full operational by 2030. Our approach stems from our view on the limited availability of water for cooling (since the Kakhovsky water reservoir is destroyed) and years of inspection, restoration and demining activities (retreating russian army will likely loot and mine the power plant), leading to only 2 out 6 blocks available by 2030 under Victory pathway. Nuclear ramping constraints are set based on our analysis of historic performance at 5% change of capacity per hour both upwards and downwards.

Coal

Coal-fired power plants represent thermal power-only stations which is predominant technology in Ukraine as of today. Ramping constraints are determined as % of capacity change per hour and are set based on historic performance: from 4.9% to 10% upwards and 6.4% and 14.5% downwards. Maintenance schedule from 2018 is assumed for modelling. Cost of repair the damaged coal units is based on public statements of DTEK (Interfax, 2024).

Co-generation

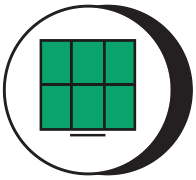
Co-generation comprises both gas – and coal-fired plants as per typical grouping used in Ukraine and represents the legacy fleet. Co-generation capacity is neither set for optimisation by the model nor expanded exogenously beyond the existing capacity as no announcement were made regarding new CHP plants. The generation profiles for CHPs are derived based on historical data of majority of power plants and adjusted according to their availability due to attacks. The profiles are exogenously determined as minimum "must-run" obligations, meaning minimum CHP output is pre-determined. CHP load can respond to demand above the minimum must-run profile up to its maximum capacity. In PyPSA-UA, CHP load changes from winter to summer mode on April 15th, and from summer to winter on November 1st.

Gas

Gas-fired power station represent a combination of ICE and OCGT technologies. The gas capacities are determined by the model except for Victory pathway, where 1 GW of gas OCGT stations considered to be operational in unoccupied Crimea. Ramping constraints for gas units are set at 100% of capacity per hour both upwards and downwards.

Hydro and pumped storage hydro

Hydro generation is modeled based on river water inflows based on 2018 satellite data. We didn't assume expansion of neither hydro or pumphed storage hydro before 2030. The three Ukrainian PSH reservoir volume is calibrated according to their project capacity. Dnistrovska PSH assumed to have the maximum reservoir volume despite only 4 of 7 planned generating units deployed. This means that additional units to Dnistrovska PSH will not increase the volume of flexibility but it's maximum hourly power / depth of peaks that the power system could absorb.

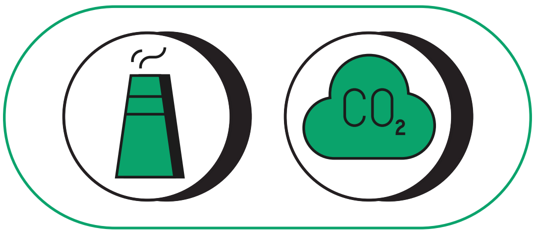


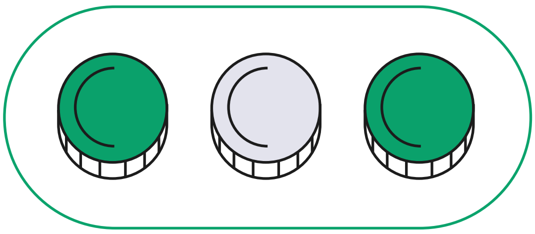
Photovoltaics

Solar irradiance is differentiated regionally in PyPSA-UA based on satellite data meaning PV generation per MW will be higher in regions with higher irradiance. Key differences between utility-scale and behind-the-meter PV is PyPSA-UA are:

- BtM PV has lower capacity factor compared to utility-scale PV in the same region, representing a typical installation on rooftops with sub-opimal inclination angles.

- BtM PV is assumed to not have operational marginal costs, so that it is always generates power and is not curtailed by the model. This is designed to simulate non-dispatchable nature of BtM PV.





Appendix B – Demand modelling

Our demand model estimates the total net residential demand based on the number of population in each region and an annual growth rate, and total net C&I demand based on annual growth rate and adjusted demand by sectors. We calibrated the dataset with various publicly available data (Energy Map, UNDP 2024, NEURC 2024)

TABLE 3. Assumptions on population in administrative districts of Ukraine [mn people]

Region	2023	2026	Frontline pathway 2030	Victory pathway 2030
Cherkasy	1 164	1 169	1 118	1 118
Chernihiv	932	946	1 059	1 059
Chernivtsi	900	877	695	695
Crimea	–	-	-	2 021
Dnipro	3 228	3 252	3 240	3 240
Donetsk	650	700	301	750
Ivano-Frankivsk	1 406	1 300	1 071	1 071
Kharkiv	1 967	1 917	1 866	1 866
Kherson	250	353	264	456
Khmenlytskyi	1 200	1 219	1 017	1 017
Kirovohrad	928	929	913	913
Kyiv city	2 300	2 500	3 284	3 284
Kyiv region	1 700	1 750	1 948	1 948
Luhansk	-	-	–	523
Lviv	2 624	2 566	2 263	2 263
Mykolayiv	860	840	820	820
Odesa	1 846	2 044	2 243	2 243
Poltava	1 355	1 466	1 311	1 311
Rivne	1 206	1 127	940	940
Sumy	951	1 026	916	916
Ternopil	1 000	953	733	733
Vinnytsia	1 438	1 376	1 315	1 315
Volyn	1 100	1 039	879	879
Zakarpattia	1 300	1 139	870	870
Zaporizhzhia	850	1 051	714	1 251
Zhytomyr	1 196	1 119	1 167	1 167
Total	**32 351**	**32 659**	**30 948**	**34 670**

Source: Ptuha research institute, Instrat & CEL calculations

TABLE 4. Modelled net regional demand per type of consumer [GWh]

Region	2026			Frontline pathway 2030			Victory pathway 2030		
	HH	C&I	Total	HH	C&I	Total	HH	C&I	Total
Cherkasy	1 059	1 902	2 961	1 179	1 980	3 159	1 179	2 039	3 218
Chernihiv	764	799	1 564	1 008	832	1 839	1 008	857	1 864
Chernivtsi	765	629	1 394	684	654	1 339	684	674	1 358
Crimea	-	-	-	-	-	-	2 448	4 753	7 201
Dnipro	3 620	14 541	18 161	4 213	15 309	19 522	4 213	25 137	29 350
Donetsk	603	2 255	2 859	324	2 347	2 671	807	2 905	3 711
Ivano-Frankivsk	1 077	1 232	2 309	952	1 282	2 234	952	1 320	2 272
Kharkiv	1 914	2 685	4 599	2 104	2 794	4 898	2 104	2 877	4 982
Kherson	268	230	497	327	239	566	566	246	812
Khmenlytskyi	978	1 510	2 489	961	1 572	2 533	961	1 619	2 580
Kirovohrad	914	1 060	1 975	1 042	1 178	2 220	1 042	1 477	2 519
Kyiv city	2 829	5 466	8 296	4 683	5 688	10 372	4 683	5 859	10 542
Kyiv region	2 936	3 058	5 994	3 900	3 183	7 082	3 900	3 278	7 178
Luhansk	-	-	-	-	-	-	464	435	899
Lviv	1 966	2 920	4 886	1 966	3 039	5 005	1 966	3 130	5 096
Mykolayiv	915	1 273	2 188	1 011	1 422	2 433	1 011	1 763	2 775
Odesa	2 491	1 652	4 143	3 509	1 720	5 229	3 509	1 771	5 280
Poltava	1 143	3 239	4 382	1 282	3 442	4 724	1 282	4 678	5 960
Rivne	978	1 027	2 005	883	1 069	1 952	883	1 101	1 984
Sumy	712	935	1 647	795	973	1 768	795	1 002	1 798
Ternopil	671	694	1 365	570	722	1 293	570	744	1 314
Vinnytsia	1 307	1 657	2 964	1 386	1 724	3 110	1 386	1 776	3 162
Volyn	876	848	1 724	812	883	1 694	812	909	1 721
Zakarpattia	1 229	790	2 018	953	822	1 775	953	846	1 800
Zaporizhzhia	924	3 786	4 710	900	4 346	5 246	1 577	6 161	7 738
Zhytomyr	954	1 264	2 218	1 079	1 315	2 394	1 079	1 354	2 433
Total	**31 895**	**55 453**	**87 348**	**36 526**	**58 532**	**95 058**	**40 837**	**78 711**	**119 548**

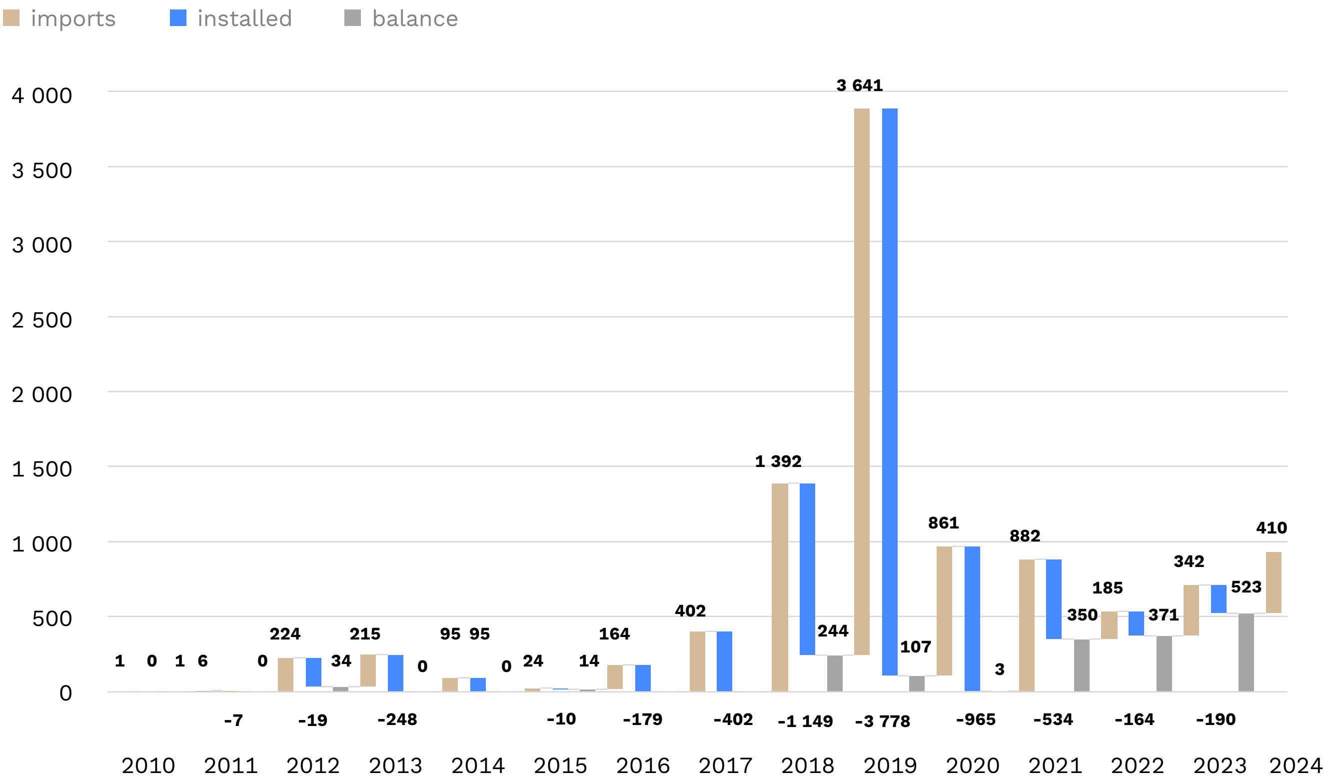
Source: Instrat & CEL calculations

Appendix C – Behind-the-meter photovoltaics assumptions and modelling

We analysed the PV panels imports for 2010 – 1H 2024 and compared it to publicly available figures on new PV installations in each year under the FiT support scheme. The import data for energy was obtained by an official parliamentary request for disclosure and will not be published here due to security limitations. The source data on imports of PV panels is provided in dollars and kg. We used open source data to assume the average weight of panels typical for each year and cross-referenced the historic PV module prices.

The difference between imported and installed each year is shown as green bars “balance” in the graph below. Out of 523 MW “balance” as of end 2023, we assume 250 MW to represent BtM PV and the rest is imported for repowering and repair of damaged and unoccupied stations.

FIGURE C. 1. Estimated imports and deployment of PV panels in Ukraine [MW]



Source: Instrat & CEL calculations based on the Ukrainian customs office data and NEURC

The final input on BtM PV capacity additions for the model is estimated as average between the following two approaches:

1. a simplified one based on imports data – 400 MW during the first half of 2024 projected as 800 MW in 2024 and in all years until 2030.

2. We used Polish statistics to estimate how many C&I and HH consumers have added PV between 2016 and 2023. Ukraine and Poland have a very similar number and distribution of HH consumers (Poland 2022: total 16.2 mln, rural 5.4 mln, Ukraine 2024 estimated: total 14.6 mln, rural 4.9 mln). We scaled down both the number of new installations by 0.25 representing the difference in GDP per capita between Ukraine and Poland in 2023 (World Bank 2024).

Average capacities for new additions are 9 kW for households (compared to 27 kW historically under FiT) and 60 kW for C&I.

TABLE C. 1. Historic data on distributed PV generation additions on Poland

Poland case		2015	2016	2017	2018	2019	2020	2021	2022	2023
PV HH, additions	ths	–	12	13	25	100	303	397	356	190
	MW	–	72	81	160	649	2 015	3 064	3 183	1 953
PV C&I, additions	ths	–	–	–	–	–	–	20	31	24
	MW	–	–	–	–	–	–	860	1 547	2 959

Source: ARE, Instrat & CEL calculations

TABLE C. 2. Historic data and projections on distributed PV generation additions in Ukraine

Ukraine projection		2022	2023	2024	2025	2026	2027	2028	2029	2030
PV HH, additions	ths	7	4	6	25	76	99	89	47	50
	MW	206	82	57	225	682	892	802	427	450
PV C&I, additions	ths	n/a	n/a	4	5	8	6	6	6	5
	MW	125	125	253	296	470	365	346	360	300
NREAP 2030	MW	-	1 500	2 000	2 500	3 000	3 500	4 000	4 500	5 000
Estimate, bottom-up	MW	-	1 750	2 060	2 581	3 733	4 990	6 138	6 925	7 675
Estimate, average growth	MW	-	1 750	2 550	3 350	4 150	4 950	5 750	6 550	7 350
Final model, input	MW	-	1 750	2 300	3 000	3 900	5 000	5 900	6 700	7 500

Source: NEURC, SAEE, Instrat & CEL calculations

Note: NREAP 2030 provides only 2030 figure, 2024-2029 is estimated as annual average addition

Appendix D – Detailed scenario assumption

TABLE D. 1. Assumptions for the installed capacity of generation and storage technologies in the scenarios considered (before optimisation by the model) [MW]

Capacities	2026	Victory 2030			Frontline 2030		
		Repair	Repair+	Decentral-ised	Repair	Repair+	Decentral-ised
Nuclear	7 980	10 040	12 040	10 040	7 980	9 980	7 980
Coal power-only	3 660	7 935	7 935	-	4 570	4 570	-
CHP (gas & coal)	2 327	2 882	2 882	2 210	2 397	2 397	1 725
Gas peaker	900	1 840	1 840	1 840	900	900	900
Big Hydro	2 405	3 197	3 197	3 197	2 473	2 473	2 473
PSH	1 515	1 839	1 839	1 839	1 515	1 515	1 515
Wind	1 319	3 190	3 190	3 190	1 860	1 860	1 860
PV utility	5 652	6 027	6 027	6 027	5 652	5 652	5 652
PV BtM	3 000	7 500	7 500	7 500	7 500	7 500	7 500
Bioenergy	304	304	304	304	304	304	304
Small hydro	122	122	122	122	122	122	122
Total generation	**29 184**	**44 876**	**46 876**	**36 269**	**35 274**	**37 274**	**30 032**
Imports	2 300	3 000	3 000	3 000	3 000	3 000	3 000
Export	800	3 000	3 000	3 000	3 000	3 000	3 000

TABLE D. 2. Assumption on currency rate and fuel costs shared across all scenarios

Parameter	Metric	2023	2026	2030
EUR/UAH x-rate	-	1 500	2 000	2 500
Natural gas	EUR/MWh	40.2	30.0	22.3
	UAH/ths m3	15 242	13 649	13 739
Coal (6000 kcal/kg)	EUR/t	123.3	100	60
	UAH/t	4 932	4 800	3 900
Carbon tax	EUR/t CO_2	0.8	0.8	10
	UAH/t CO_2	32	38	650

TABLE D. 3. Assumption on costs of new generation capacities

Technology	CAPEX 2026, EUR/ kW	CAPEX 2030, EUR kW	Varia-ble costs (excl. fuel), EUR/MWh	Fixed costs, EUR/kW/y	Efficiency, %	Lifetime, y
Gas open cycle (OCGT & engines)	1 000	1 000	5	20	0.41	25
Biomass CHP	3 100	3 000	4.8	158	0.32	25
Onshore wind	1 100	1 000	2	17		20
PV (utility scale)	550	400		7.6	‘	25
PV (rooftop C&I)	619	450		9.2	`	25
PV (residential)	660	480		10		25
Utility-scale Li-Ion energy storage 2h	366	277	3	20	0.9	25
Utility-scale Li-Ion energy storage 4h	695	522	3	30	0.9	25
C&I Li-ion energy storage 2h	730	550	10	40	0.9	20
C&I Li-ion energy storage 4h	1 390	1 040	10	50	0.9	20
Residential Li-ion energy storage 2h	1 100	830	20	100	0.85	20
Residential Li-ion energy storage 4h	2 090	1 570	20	100	0.85	20

Note: Efficiencies for batteries represent round-trip efficiency, for other technologies – net electrical efficiency

TABLE D. 4. Other assumptions used in the report

Parameter	Value
Discount rate	12%
Repair cost of coal plants (Interfax 2024)	EUR 50 mln / GW
Nuclear power station CAPEX - new-build	6 000 EUR/kW
Nuclear power station CAPEX - repair	1 000 EUR/kW

Appendix E - Detailed modelling results

TABLE E. 1. The installed capacity of generation and storage technologies determined by the model [GW]

Technology	2026	Frontline pathway 2030				Victory pathway 2030			
		Repair	Decen-tralised	Repair + 2 GW nuclear	Repair + max BtM PV	Repair	Decen-tralised	Repair + 2 GW nuclear	Repair + max BtM PV
Nuclear	8.0	8.0	8.0	10.0	8.0	10.0	10.0	12.0	10.0
Coal power-only	3.7	4.6	-	4.6	4.6	7.0	-	7.0	7.0
CHPs	2.3	2.4	1.7	2.4	2.4	2.9	2.0	2.9	2.9
Gas peaker	1.1	0.9	3.8	0.9	0.9	1.8	5.3	1.8	1.8
Biomass	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Hydro	2.5	2.6	2.6	2.6	2.6	3.3	3.3	3.3	3.3
Wind	1.3	3.9	5.8	3.4	3.1	5.0	8.1	3.5	4.4
PV utility-scale	7.2	5.7	5.7	5.7	5.7	7.9	7.6	6.0	6.0
PV behind-the-meter	3.4	7.5	7.5	7.5	15.7	7.6	7.6	7.6	15.8
PSH generation	1.5	1.5	1.5	1.5	1.5	1.8	1.8	1.8	1.8
Total generation	**31.4**	**37.4**	**36.9**	**38.9**	**44.6**	**47.6**	**46.1**	**46.4**	**53.5**
Import	2.3	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Export	0.8	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

Source: Instrat & CEL calculations based on PyPSA-UA modelling

TABLE E. 2. Generation mix determined by the model [TWh]

Technology	2026	Frontline pathway 2030				Victory pathway 2030			
		Repair	Decen-tralised	Repair + 2 GW nuclear	Repair + max BtM PV	Repair	Decen-tralised	Repair + 2 GW nuclear	Repair + max BtM PV
Nuclear	53.7	53.7	53.7	61.0	53.7	64.2	65.7	81.1	64.2
Coal power-only	15.3	16.6	-	13.0	15.5	27.2	-	20.8	26.0
CHPs	8.8	8.2	5.3	7.7	8.2	9.4	6.5	8.2	9.2
Gas peakers	2.1	1.0	13.4	1.7	1.5	1.6	18.7	1.1	1.9
Biomass	2.7	2.4	2.2	1.8	2.0	2.7	2.3	2.3	2.3
Hydro	9.2	9.1	8.5	8.5	8.6	9.3	8.8	9.1	9.1
Wind	3.3	12.2	17.5	9.5	7.9	14.4	24.0	8.9	11.3
PV utility-scale	11.0	8.4	8.4	7.8	5.5	12.1	11.8	9.0	8.3
PV behind-the-meter	3.5	7.8	7.8	7.8	16.2	7.9	8.0	7.9	16.4
PSH generation	1.3	1.6	1.2	2.0	2.4	1.6	1.2	1.4	2.6
Total generation	**110.9**	**121.0**	**118.0**	**120.7**	**121.4**	**150.4**	**146.9**	**149.9**	**151.4**
DSO-level demand	98.1	107.0	107.0	107.0	107.0	133.6	133.6	133.6	133.6
Losses	10.8	11.2	9.1	10.4	10.7	14.0	11.6	13.8	13.6
PSH consumption	1.7	2.1	1.6	2.6	3.2	2.2	1.6	1.9	3.5
Total gross demand	**111.3**	**0.9**	**118.5**	**120.8**	**121.7**	**150.5**	**147.7**	**149.9**	**151.4**
Export	0.7	121.2	0.8	0.8	0.8	0.7	0.8	0.7	0.7
Import	0.4	0.2	0.5	0.2	0.2	0.0	1.2	-	0.0

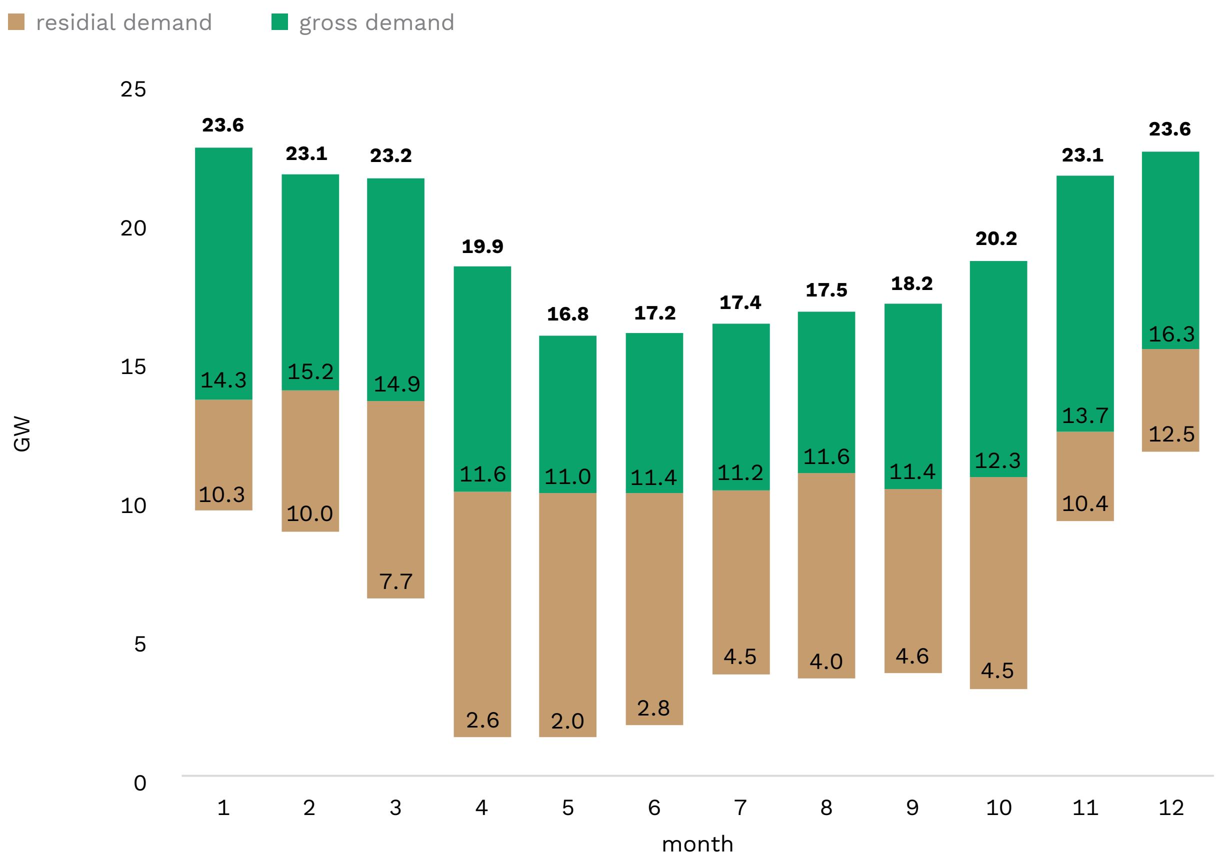
Source: Instrat & CEL calculations based on PyPSA-UA modelling

Note: Total gross demand = DSO level demand (net demand incl distribution losses) + losses (transmission grid + self-consumption of power plants) + pumped storage hydro consumption

Appendix F - Insights into ramping and flexibility

The peak system load can reach 23.6 GW during winter 2030, and the residual load could go down to 2 GW in May. This difference does not directly mean the power plants will have to ramp their productions for over 21 GW in an hour but rather gives a perspective of increased pressure on the system's balancing capabilities.

FIGURE F. 1. Monthly min & max load, Victory pathway 2030 [GW]

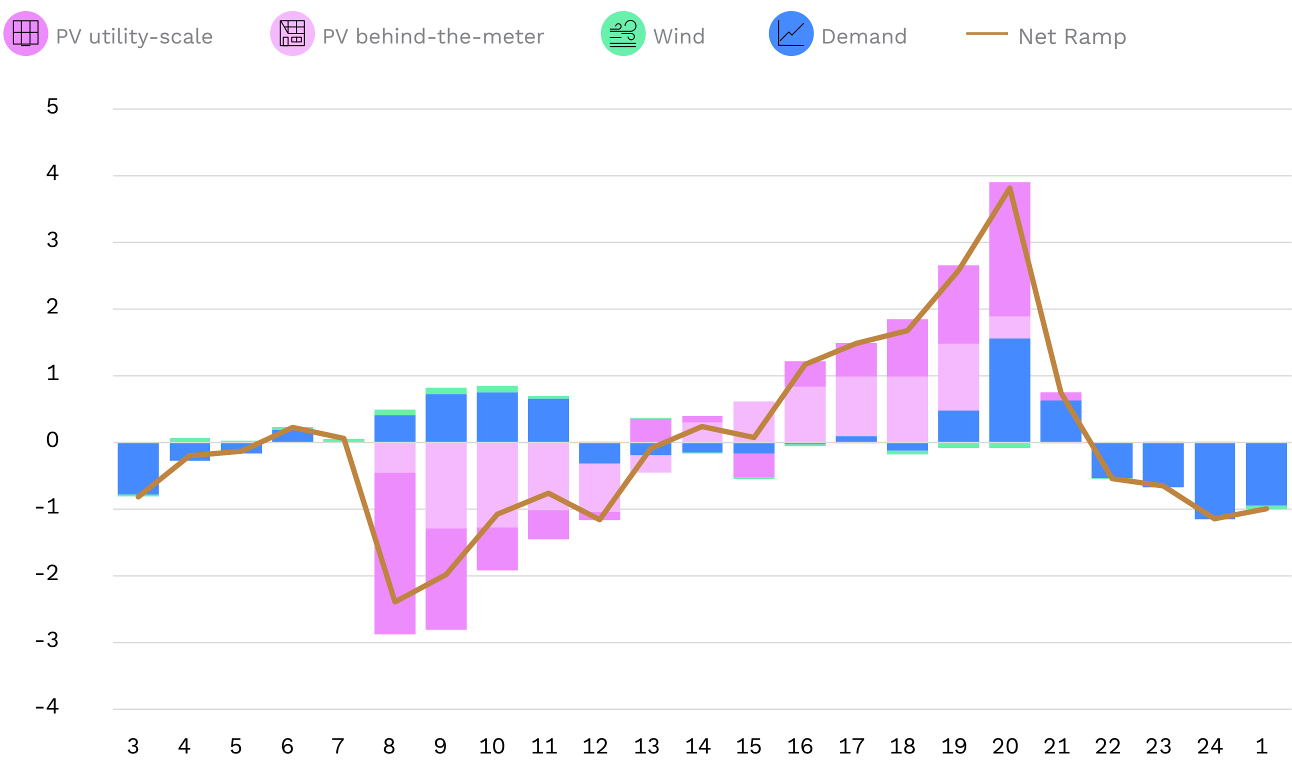


Source: Instrat & CEL calculations based on PyPSA-UA modelling

Note: Residual demand = Gross consumption (incl. losses and self-consumption of power plants) – intermittent RES generation

The demand for flexibility will increase twofold on average, with max. hourly ramps reaching 3.8 GW in the upward and 2.4 GW in the downward directions, compared to 1.7 GW in both directions in a system with no intermittent renewables. Solar generation contributes the most to increased ramping demands, creating more demand to reduce dispatchable generation in the morning and rapidly increase in the evenings. Non-curtailable BtM PV will push the limits of downward flexibility.

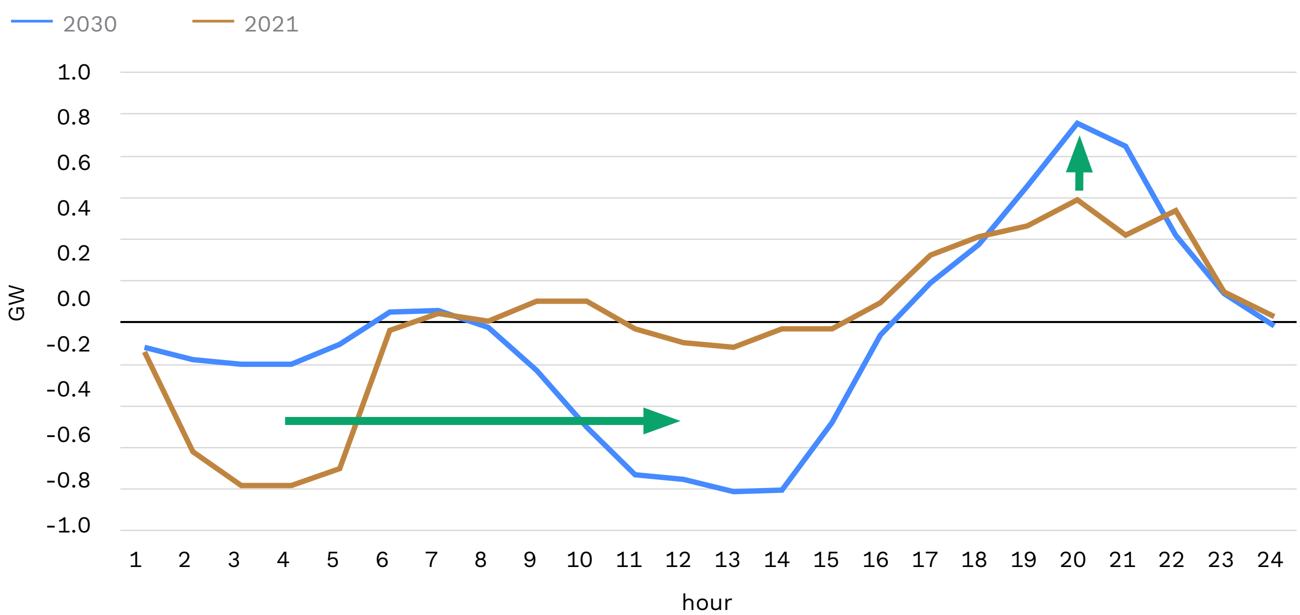
FIGURE F. 2. Hourly ramps and its contributors in the Ukrainian power system, Victory Pathway, 25/03/2030 [GW/h]



Source: Instrat & CEL calculations based on PyPSA-UA modelling

The role of PSH will shift from storing the excess baseload generation during nights to capturing solar peaks and shifting them to evenings. In the medium term, pumped hydro storage will be crucial to integrating solar energy.

FIGURE F. 3. Change in average pumped hydro storage profile, Victory pathway 2030 [GW]



Source: Instrat & CEL calculations based on PyPSA-UA modelling (2030) and Ukrenergo (2021)