Empowering Ukraine Through a Decentralised Electricity System

A roadmap for Ukraine's increased use of distributed energy resources towards 2030

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Abstract

This roadmap from the IEA, *Empowering Ukraine through a Decentralised Energy System,* outlines a pathway to rebuild and modernise Ukraine's power sector amid ongoing attacks on its energy infrastructure.

Since Russia's full-scale invasion of Ukraine in February 2022, nearly two-thirds of Ukraine's dispatchable power capacity has been occupied, damaged, or destroyed. The report highlights distributed energy resources (DERs) as a vital solution to address their power deficit while enhancing Ukraine's energy security, resilience, and flexibility. DERs – such as solar PV, wind, batteries, and small modular gas turbines – enable local power generation while also reducing vulnerability to targeted attacks. IEA analysis shows that a diverse mix of DERs offers a cost-effective and resilient path for Ukraine's power system recovery.

Urgent actions include deploying small gas turbines and DERs such as solar PV and batteries to address a projected 6 GW winter power deficit in 2024/2025. The move towards a greater level of decentralisation in power generation can also support Ukraine in meeting its long-term decarbonisation goals, as set out in the 2030 National Energy and Climate Plan and the 2050 Energy Strategy. The roadmap also lays out seven key policy recommendations for Ukraine to build a more resilient and modern power system by establishing a vision for decentralisation and by strengthening regulatory frameworks, coordination mechanisms, electricity markets and relevant technical requirements.

Acknowledgements, contributors and credits

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Note: because of the ongoing invasion, a significant portion of Ukraine's energy data has been restricted and is not accessible to the public. All data and other information in this report is based on publicly available sources.

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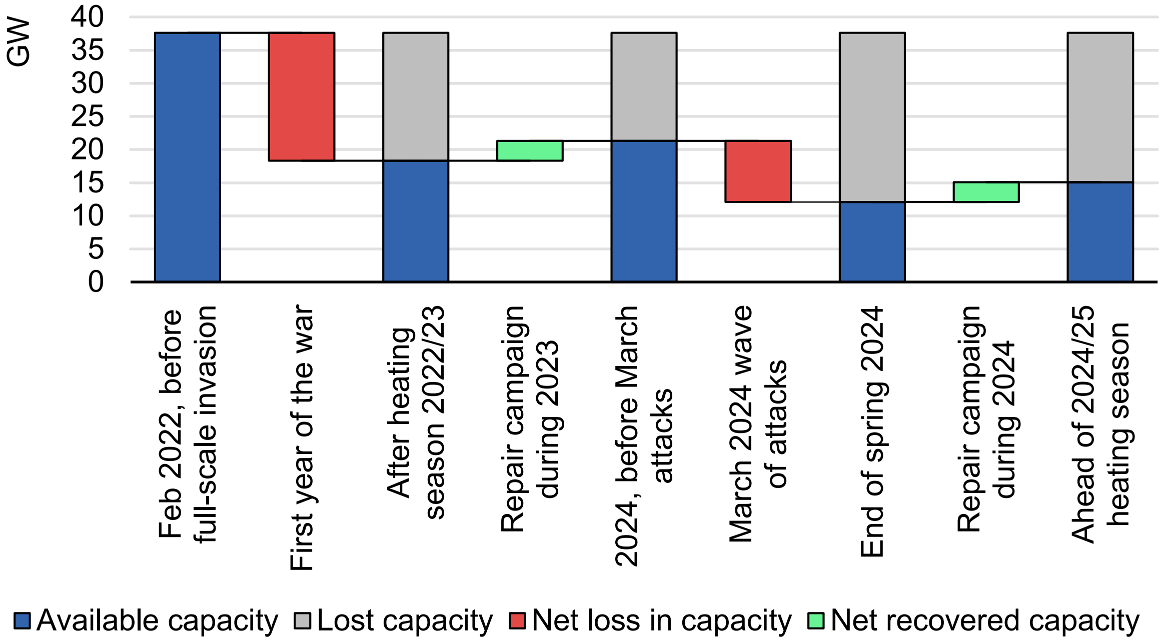
Executive summary

Systematic targeting of Ukraine's power system threatens to destroy reliable access to electricity

The systematic targeting of Ukraine's energy infrastructure since February 2022 has resulted in unprecedented damage to the country's power system. Following intensified attacks in the spring of 2024, nearly two-thirds of the country's dispatchable power generation capacity was occupied, damaged or destroyed. While Ukraine works to repair and reconstruct after each attack, Russia continues to target the country's power generation facilities and transmission infrastructure. Air defence and passive protection measures have repelled the bulk of the attacks but remain unable to prevent extensive damage.

Available installed capacity of dispatchable power generation in Ukraine



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Sources: IEA analysis based on exchanges with ENTSO-E, the European Commission, Green Deal Ukraina, the Kyiv School of Economics; UNDP (2023), Update on the Energy Damage Assessment June 2023, Towards a green transition of the energy sector in Ukraine; Ukrainska Pravda (2024), Russia has destroyed 9.2 GW of Ukrainian power generation, EU ambassador says; EnergoReforma (2024), Енергетикам на початок ОЗП вдалося відновити приблизно 3 ГВт пошкодженої РФ генерації – радник прем'єра.

These attacks have had a devastating impact on the daily lives of citizens across Ukraine, affecting access to electricity, heating and water. Ukrainians across the country are living with the effects of rolling blackouts as well as unscheduled power outages. Most citizens have faced these daily power cuts with resolve, but the limited availability of electricity has affected services ranging from education to health services, making daily life difficult. With peak demand this winter likely to reach 18.5 gigawatts (GW), the supply deficit could increase to as much as 6 GW, which would result in longer and more widespread power cuts. While managing this immediate crisis, Ukraine must also plan for the years ahead. Without urgent investment, the country faces power shortages not only during winter peak demand, but also in the summer months when maintenance of the nuclear fleet and the unavailability of combined heat and power (CHP) plants constrain available supply.

Power sector reconstruction presents an opportunity to modernise Ukraine's energy system

Decisions about rebuilding Ukraine's power sector should address both critical generation needs and longer-term modernisation objectives. In the short term, the country needs to rapidly increase power generation capacity, improve energy efficiency and enhance system resilience to withstand and recover from attacks, with urgent action required to ensure security of supply through 2025 and 2026. Looking ahead, Ukraine envisions developing a modern, decarbonised power system that is fully integrated with European markets, a vision that is outlined in key policy documents such as its 2050 Energy Strategy and 2030 National Energy and Climate Plan (NECP). The key challenge is to ensure that today's decisions on power sector reconstruction, market design, and new generation assets immediately bolster the security of energy supply while supporting this longer-term transformation.

As Ukraine rebuilds its power sector, system flexibility emerges as a critical challenge. Prior to the full-scale invasion, Ukraine managed variations in demand and increasing levels of variable renewable energy (VRE) through its coal fleet and hydropower plants. Russia’s ongoing attacks have left Ukraine with insufficient flexible generation capacity. While VRE assets have also been affected, the impact has been smaller, with their share of VRE in the generation mix remaining largely stable at 8.7% in 2024, compared with 9.4% in 2021. As Ukraine reconstructs its power system and increases VRE deployment driven by energy security needs, cost-competitiveness and decarbonisation objectives the need for flexible resources to manage daily demand variations and VRE generation patterns is becoming increasingly important.

Analysis shows why distributed energy resources should be a pillar of rebuilding

Distributed energy resources (DERs) emerge as a key solution that can support Ukraine's immediate needs while advancing its longer-term vision.

DERs comprise a diverse set of technologies – including solar PV, wind, batteries and small, modular gas turbines – that offer multiple strategic advantages. Their geographical distribution across the network enhances system resilience against targeted attacks while enabling power generation closer to demand centres. At the same time, their modular nature enables rapid deployment to address generation shortages where they are needed. The IEA's modelling analysis for this report, examining interconnected scenarios for 2025 and for 2030, demonstrates how DERs can address Ukraine's dual challenges: meeting pressing generation needs and enhancing system resilience while also supporting longer-term decarbonisation goals through the increased deployment of solar PV and wind, supported by flexibility resources for reliable system integration.

DERs can fulfil Ukraine's 2025 power system needs while delivering a cost-optimal solution. IEA modelling shows that rebuilding Ukraine's power system based on small modular gas turbines and gas engines alone would require USD 13.4 billion in upfront investment. A more diverse DER deployment, including variable renewables and batteries, would require between USD 15.5 billion and USD 23 billion upfront investment. However, it represents the most cost-effective solution over time when ongoing fuel costs are factored in. With the appropriate policies and regulations in place, this diverse DER scenario would reduce annual system costs by an estimated 5.6.% through operational savings, particularly in terms of fuel costs and electricity imports. This annual cost reduction could increase to 6.3% with enhanced interconnection with the continental Europe system (adding just 500 MW of additional import capacity), which would also reduce upfront financing needs by almost USD 2 billion. Furthermore, DERs provide significant system-wide resilience, the value of which is not captured in these cost comparisons.

Ukraine's pathway to achieving its 2030 energy targets builds on the immediate deployment of distributed energy resources. Ukraine has set clear objectives in its National Energy and Climate Plan (NECP) for the period through 2030. The IEA's baseline scenario shows that these targets can be met by focusing on an optimal mix of DERs and new gas-fired generation assets, rather than just rebuilding lost thermal capacity. Assuming the extension of Ukraine's current nuclear fleet operation through 2030, achieving the NECP goals would require approximately 24 GW of solar, 11 GW of wind, and 6 GW of energy storage capacity, in addition to existing assets. This deployment pathway aligns with Ukraine's stated goals of integration with the European Union and its decarbonisation objectives.

Seven key recommendations for building a more decentralised and modern power system

Drawing on the analysis of Ukraine's power system needs in 2025 and 2030; this report presents seven key recommendations to support both rapid reconstruction and longer-term transformation. These recommendations are aimed at laying the foundation for scaling up the deployment of DERs and realising Ukraine's vision of a modern, decentralised power system. Some actions would need swift implementation to enable rapid DER deployment and address current shortages, while others require early initiation due to their longer implementation timeframes. The recommendations are structured to reflect both the urgency of addressing immediate power system needs and the complexity of some the institutional and regulatory changes required to maximise DER benefits in the longer term.

Create a vision of a decentralised power system for Ukraine. By developing a holistic DER strategy, Ukraine can align its near-term power system recovery with its future goals prioritising resilience, decarbonisation and affordability. This successful evolution requires coordinated work across sectors and stakeholders, from scaling up supply chains and local manufacturing to upskilling the energy workforce. Regulatory and legislative alignment is key to ensuring that the vision of a modern, decentralised power system can become a reality.

Improve the regulatory framework. While a complex task, particularly during wartime, Ukraine can begin to take steps to enable a rapid post-war regulatory transition. Addressing the regulatory and administrative barriers that disproportionately affect DER deployment can lay important foundations and ensure a diverse set of resources. Tariff reforms can help encourage a more prominent role for consumers, supporting the deployment and operation of consumer-side DERs, as well as better demand management and the uptake of more efficient devices, reducing peak capacity needs.

Reform electricity markets. The design of Ukraine's electricity and ancillary services markets needs to accommodate the volume and variety of DERs necessary for a secure, sustainable and affordable power system. Regulators and system operators need to improve market access for smaller-scale resources while ensuring price signals accurately reflect system requirements. Removing market distortions and introducing temporal and locational granularity can steer investment towards a cost-optimal technology mix. Market design rules should enable DERs and batteries to provide multiple system services at both local and system levels.

Strengthen capacity and coordination at the transmission and distribution levels. As the share of generation on the distribution network increases, distribution utilities will need to play a greater role in the planning, operation and supervision of the power system. This will require capacity building for utilities to be able to fulfil their evolving role in a more decentralised power system. In terms of planning, this would involve Ukrainian energy sector stakeholders shifting from a traditional supply-side approach to one that is more integrated and coordinated, involving actors from across the energy sector as well as across the electricity supply chain. Given the increasingly decentralised nature of the power system, it is essential that the Transmission System Operators (TSO) and the Distribution System Operators (DSOs) work in close collaboration, while policy makers and regulators need to take steps to clearly redefine the roles and responsibilities of DSOs towards a reliable and efficient power system.

Establish clear technical requirements for connection of new assets. As Ukraine's power system accommodates a growing share of DERs, transmission and distribution grid codes require updating to ensure the quality and reliability of supply and accurate information on system operations. Requirements should range from improved forecasting of behind-the-meter resources to minimum technical performance standards for DER behaviour during fault conditions. System operators and the regulator should collaborate with Ukraine's standards body to establish technical standards for original equipment manufacturers (OEMs) that ensure compliance with grid code requirements.

Enhance asset visibility, monitorability and control to ensure system security. A decentralised system requires robust data infrastructure for system planning, operations and supervision. This means not only understanding where new consumer-side assets are located, through measures such as DER registries and advanced metering infrastructure (AMI), but also being able to monitor the low-voltage networks that will host a significant part of this new capacity. An increasingly smart grid will enhance system security and enable consumer participation through price signals and aggregator models like virtual power plants (VPPs). Overall, this requires a strong level of cybersecurity, with collaboration between power sector stakeholders, particularly system operators and regulators.

Set appropriate legislative foundations and financial instruments to scale up DER deployment. Rapid decentralisation requires innovative financing mechanisms, particularly during wartime. Blending public, donor and private funds can help reduce the high cost of capital in Ukraine's energy sector. Legislative and regulatory frameworks for private sector investment must be established now to safeguard financing beyond the war period and enable large-scale DER integration. Supporting regional and municipal-level investment through capacity building and financial assistance is crucial for wider DER adoption.

Introduction

Since the beginning of Russia's full-scale invasion of Ukraine in February 2022, the energy sector has been a major target. As of November 2024, Russia had occupied, damaged or destroyed nearly two-thirds of Ukraine's dispatchable power generation capacity. While attacks on energy assets have occurred on an almost daily basis since the war began, 2024 saw attacks on Ukraine's power system intensify to unprecedented levels. Parts of the country, including the capital of Kyiv, have experienced power outages throughout the year, often lasting more than 12 hours per day. The country's grid infrastructure has sustained extensive damage, and major repair efforts have only managed to slow further deterioration. Ukraine faces a future of harsh winters and looming humanitarian crises, with every attack threatening the population's access not only to power and heating, but also water, sewage and sanitation. Without a significant structural shift in the power sector, Ukraine remains caught in a costly cycle of repairs and further attacks.

By shifting to a more decentralised system that relies on distributed energy resources (DERs), Ukraine can better address its most pressing system needs – such as its power deficit – while paving the way toward a power system that is more secure, sustainable, affordable and equitable. Ukraine's government has already made it clear that rapidly decentralising the energy system and increasing system resilience are essential to achieving these objectives. In the medium term this will result in a hybrid system, with centralised legacy power plants operating alongside a range of decentralised technologies. As time goes on, however, it is clear that increasing the share of distributed energy resources – combined with effective demand-side management and energy efficiency policies – will enhance Ukraine's overall economic and political stability.

The following roadmap builds upon the IEA's most recent analysis of Ukraine's energy system heading into the 2024/2025 winter, Ukraine's Energy Security and the Coming Winter. The IEA has developed a tailored power system model to explore the potential for DERs to drive the recovery and reconstruction of Ukraine's power system. It provides actionable recommendations to help Ukraine address urgent needs for the coming year while also bridging the gap between its immediate needs and the government's medium-term vision for 2030.

Chapter 1. Ukraine's power needs and how distributed energy resources can help address them

Distributed Energy Resources (DERs) are generally small-scale[1], modular energy resources that are located close to where electricity is consumed, including rooftop solar photovoltaic (PV) and energy storage. To meet Ukraine's urgent need for dispatchable capacity, this can also include technologies such as diesel or gas-fired combustion engines, small modular gas turbines and small-scale hydropower. Depending on fuel availability, thermal assets can also run on biofuels. DERs are not limited to generation and storage assets, however. They also encompass smart, controllable and more efficient consumer devices such as heat pumps or electric vehicles – solutions that can help shift demand and optimise energy consumption as new end-uses become electrified.

This means that DERs are often consumer-side assets (behind-the-meter), though they can also be installed on the distribution network, situated on the utility-side (front-of-meter). So, while DERs offer great value to the Ukrainian power system, their small scale, modular and distributed nature presents unique challenges for both planners and system operators. Resources on the consumer side of the meter, in particular, require dedicated infrastructure and frameworks to properly incentivise their deployment and maximise their value at both the system and local levels.

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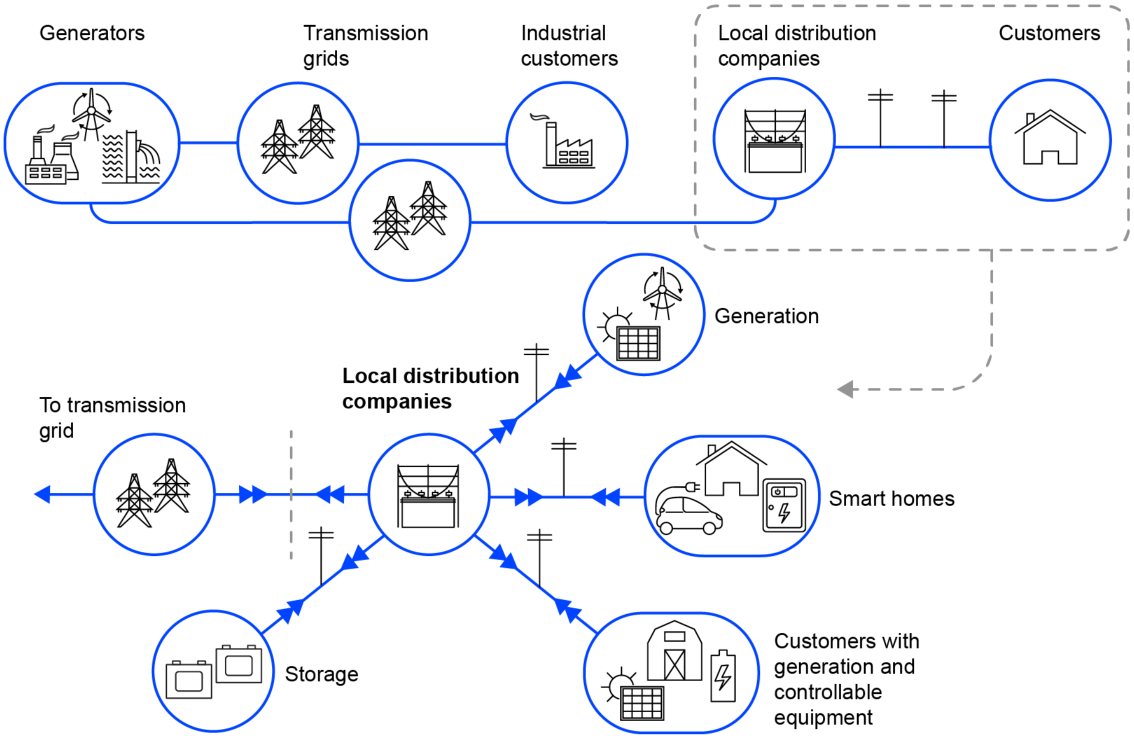
[1] Small-scale is a relative term, but is typically considered to be less than 10 MW.

Consumer-side resources are changing the topology of power systems



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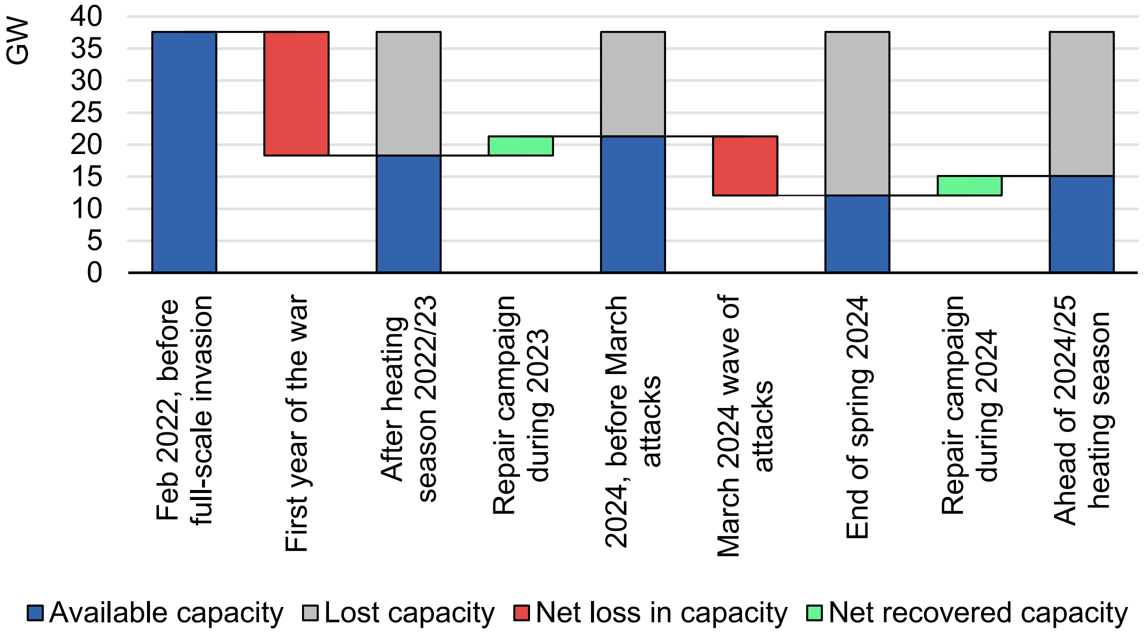
Source: IEA (2022), Unlocking the Potential of Distributed Energy Resources.

Ukraine is in urgent need of new generation capacity

Since the start of its full-scale invasion, Russia has targeted the whole of Ukraine's energy sector, with the power system being especially hard-hit. Generation capacity across Ukraine's regions (oblasts), along with transmission and distribution infrastructure, has been severely damaged, particularly in the east and south – areas closest to the front line. As of autumn 2024, all of Ukraine's thermal power plants (TPPs) had been affected by the attacks and almost all hydroelectric capacity had been destroyed. Between March and July 2024 alone, 9.2 GW of generation capacity was damaged or destroyed, resulting in the loss of almost half of the remaining available generation capacity. By the summer of 2024, rolling blackouts and other unscheduled interruptions to the power supply became the norm, limiting electricity in the worst-affected regions to just a few hours per day. The restoration of 3 GW of thermal generation capacity and the end of the nuclear maintenance season increased available capacity for the autumn of 2024. However, winter 2024/2025 demand is expected to reach between 18 and 19 GW depending on the severity of the season. As a result, it is unlikely that Ukraine will be able to avoid load shedding: The IEA estimates a power deficit of nearly 6 GW over the 2024/2025 winter, depending on the prevailing temperatures and the potential impact of further Russian attacks. Moreover, this power deficit is likely to persist through the winter of 2025/2026.

Available installed capacity of dispatchable power generation in Ukraine



Sources: IEA analysis based on exchanges with ENTSO-E, the European Commission, Green Deal Ukraina, the Kyiv School of Economics; UNDP (2023), Update on the Energy Damage Assessment June 2023, Towards a green transition of the energy sector in Ukraine; Ukrainska Pravda (2024), Russia has destroyed 9.2 GW of Ukrainian power generation, EU ambassador says; EnergoReforma (2024), Енергетикам на початок ОЗП вдалося відновити приблизно 3 ГВт пошкодженої РФ генерації – радник прем'єра.

Moreover, transmission infrastructure has been repeatedly targeted, most recently during the large-scale offensive on Nov. 17, 2024. In addition to physical damage, cyberattacks on energy facilities and companies have tripled since the start of the full-scale invasion.

The advantage of distributed energy resources is their ability to be deployed quickly to where they are most needed. Moreover, many DER technologies are scalable, making them adaptable to evolving system needs – not just during the project and installation phases, but also in response to the dynamic situation on the ground and the challenges that this implies. These include the recovery of occupied or damaged generation resources and fuel supply, restoring demand and implementing measures to increase energy efficiency, promote electrification and manage costs.

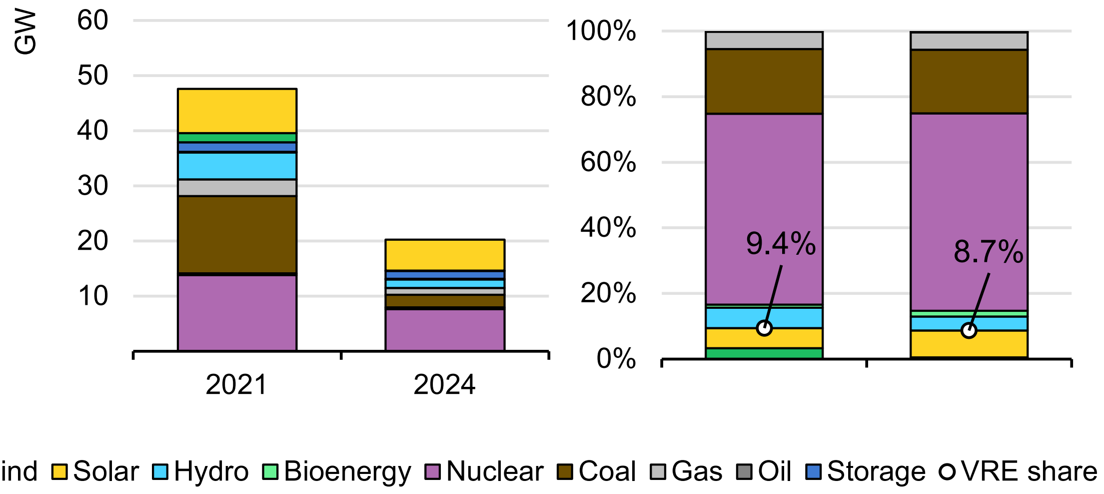
Generation capacity, along with transmission and distribution systems, has been targeted, adding stress and congestion to the grid. Since DERs are often located near demand centres, they are positioned to provide energy where it is most needed, helping to reduce the need for certain grid upgrades and allowing for the prioritisation of other repairs or upgrades. Given that these same DERs are also located at the grid edge, they can also provide important system services for the distribution network, ease congestion and buy time for the deferral of investments in new distribution infrastructure. This, in turn, enhances the flexibility of planning and operations.

Flexibility is a key requirement for Ukraine

Even before the full-scale invasion, Ukraine's power system lacked the flexibility to effectively manage the variability and uncertainty of electricity demand and supply. Before 2022, Ukraine's power system relied on nuclear and coal-fired power plants for baseload power. This was a consequence of a decision to reduce Ukraine's reliance on gas-fired generation after a major dispute with Russia in 2009. Since Ukraine's nuclear fleet is unsuitable for load regulation, its coal fleet – originally designed for baseload generation – was repurposed to balance supply and demand fluctuations. However, coal plants, with their slow ramp rates, high minimum loads and long commitment cycles, are ill-suited to this role. This coal-fired capacity was supplemented with more flexible hydropower capacity – which accounted for 5% of Ukraine's capacity mix before the war, including 1.7 GW of pumped-storage hydro (PSH). Gas-fired capacity represented 9.5% of the pre-war total, though this was in form on inflexible combined heat and power (CHP) plants. Meanwhile, the growth of electricity production from renewable energy sources (RES) in Ukraine occurred without compensatory measures to increase the flexibility of the Ukrainian energy system. The lack of high-flexibility power plants, battery energy storage systems (BESS), semi-peak power plants and other technologies that could enhance grid responsiveness further compounds the challenges

Due to significant losses of dispatchable capacity, particularly in coal and hydropower, Ukraine's power system flexibility has only weakened further since the start of the full-scale invasion. Despite also losing roughly 40% of solar PV and wind capacity, the share of VRE in the generation mix remains similar to 2021 levels due to a 30% decrease in electricity demand. As a result, flexibility needs in the system have remained fairly similar, though the generation capacity to provide this flexibility has decreased significantly.

Change in available installed capacity and estimated share of generation in Ukraine by technology



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As the share of VRE increases, the system needs to be more flexible across multiple time horizons. This includes ramping flexibility for balancing short-term variations and peaking capacity for system adequacy. Currently, balancing depends largely on a shrinking pool of dispatchable generation capacity, increasingly relying on cross-border interconnectors to import power during shortages and export it during surpluses. While interconnectors provide critical flexibility, they are costly and limited, highlighting the need for investments in domestic storage and grid modernisation. The unique characteristics of DERs make them well-suited to provide flexibility at both the local (e.g. for distribution networks) and system level. For example, since distributed resources are located at the grid edge and are often inverter-based, they can adjust their output quickly to provide important local flexibility on weaker, low-voltage networks, such as voltage support. Meanwhile, dispatchable DERs – such as batteries and small gas turbines or engines – can provide vital flexibility across different timeframes, including ramping flexibility and the shifting of demand from periods of low to high demand. Therefore, the challenge is to find the balance of a diverse set of resources that meets both energy and flexibility requirements, when and where they are needed. Importantly, the visibility, predictability and controllability of these resources are essential for providing system flexibility, which in turn requires the right frameworks and infrastructure.

Long-term objectives can be supported by a more decentralised system

Ukraine's decarbonisation efforts are strongly linked to closer integration with Europe, not only through physical interconnection, but also in terms of policy, regulations and legislation. In October 2024, Ukraine adopted a new climate policy law, aligning national targets with those of the European Union, including bringing its net zero target forward to 2050 from 2060. Additionally, Ukraine held its inaugural pilot auctions for renewable energy in the autumn of 2024, supporting its target of increasing renewables to 27% of total energy consumption by 2030. Meanwhile, the government is also streamlining processes for land allocation, permitting, grid connection and environmental impact assessment, putting Ukraine on track to align with key European regulations and legislation.

Ukraine hopes to "build back better" and eventually become a net exporter of clean electricity to Europe, which means that increasing the transfer capacity of the physical interconnection will also be important. Ukraine's synchronisation with the Continental European Network marked a significant milestone, initially allowing 1.2 GW of import capacity for the interconnected systems of Ukraine and Moldova. This has gradually increased over time. This capacity limit was increased to 2.1 GW on 1 December 2024, with the ability to import a further 250 MW for short periods during emergency conditions. Meanwhile, export capacity has also gradually increased, to 550 MW.

DERs, such as solar PV and batteries, offer a great opportunity to reduce Ukraine's reliance on fossil fuels and help the country meet its decarbonisation goals. Electrification of new end-uses, such as heat pumps and electric vehicles, can transform them into smart and controllable loads that function as part of a broader suite of DERs. This not only enhances system flexibility but also supports Ukraine's efforts to decarbonise other sectors such as heating and transport.

Power system reforms and private financing are needed to scale up DER deployment

Ukraine's power sector reflects the structural economic challenges typical of many post-Soviet states, with a largely oligopolistic market dominated by price controls and extensive cross-subsidisation. These issues are compounded by widespread non-payment and customer arrears that burden utilities. Corporate governance and transparency challenges remain, undermining efforts to address Ukraine's needs (e.g. lack of independent oversight or transparent financial management). Electricity tariffs for households remain partially subsidised under the Public Service Obligation (PSO) mechanism to ensure affordability, while non-household consumers procure electricity at market-determined prices. This results in cross-subsidisation, undermining industrial competitiveness and driving up operational costs. It also places financial strain on utilities, limiting their ability to invest in critical infrastructure. The PSO mechanism also distorts price signals for consumers, making it harder to establish a fully competitive electricity market. Tariff reforms are ongoing, including gradual rate increases for households that aim to better reflect the actual cost of supply and reduce reliance on subsidies. However, economic challenges and the ongoing invasion have disrupted or delayed some of these reforms.

Scaling up DERs requires robust financial incentives, while maintaining affordability and equity as core priorities. This involves two key elements: First, market design must enable broader participation of small-scale and distributed resources, such as batteries and small gas turbines, in wholesale electricity and ancillary services markets. Second, consumer tariffs should be structured to incentivise efficient electricity consumption, the deployment of behind-the-meter DERs like rooftop solar and batteries, and the operation of these resources in ways that deliver system-wide benefits.

The development of a sustainable and more decentralised power system in Ukraine hinges on resolving the severe debt and payment crisis plaguing its electricity market. Building new distributed generation capacity, energy storage systems and modernising electrical networks all require substantial capital investment. Ensuring a consistently high level of payment discipline in the market will therefore be crucial.

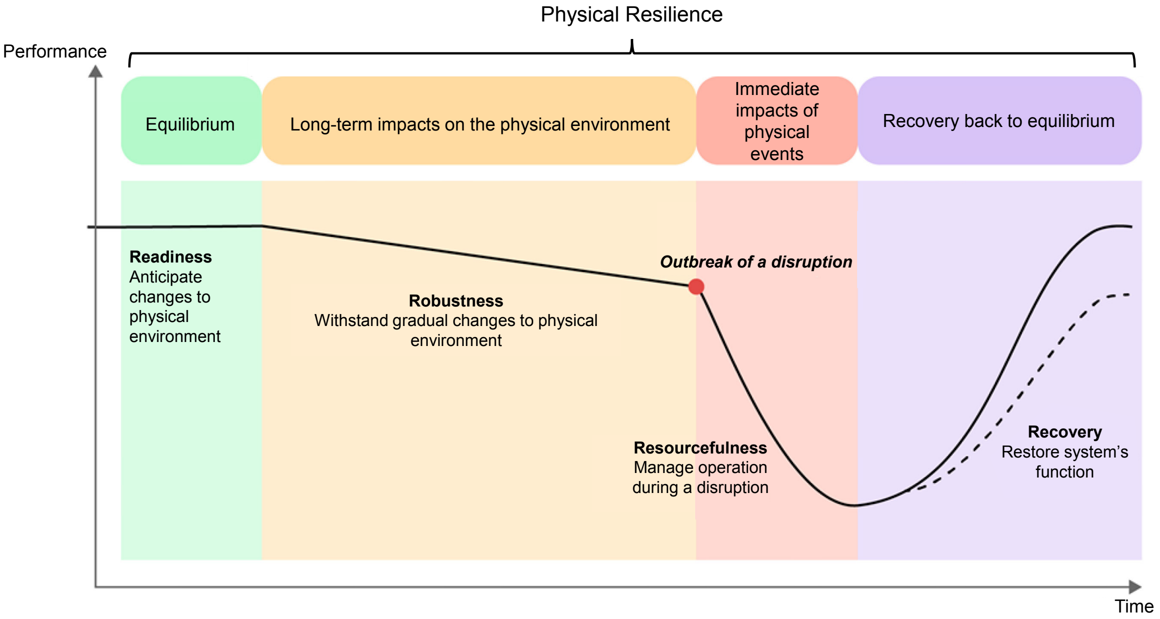
Based on estimates by the Kyiv School of Economics in August 2024, a "building back better" approach to restoring Ukraine's energy sector would require an estimated USD 50.5 billion of new investment. Given the scale of Ukraine's power sector needs, the private sector must serve as the primary source of capital. Foreign aid, through grants and donations, can help mitigate investment risks and lower the high weighted average cost of capital (WACC). Private investment must be unlocked through a secure and transparent investment environment supported by consistent policies. This includes existing concessional loan programmes for both households or communities, as well as risk-sharing mechanisms from international partners. These could involve export credit agencies, such as the Danish Export and Investment Fund or Germany's investment guarantee and export insurance programmes.

Decentralisation can be a key pathway for enhancing system resilience

The resilience of Ukraine's power system will be central to its recovery. The country's centralised grid has proven highly vulnerable to attacks, with large-scale generating units serving as easy targets for Russian missile and drone strikes. Since 2022, Ukraine and its partners have worked to shield its energy infrastructure, using a mix of air defence, critical equipment, passive defence measures and backup systems. A key objective of Ukraine's decentralisation policy is to enhance system resilience – both in the context of the ongoing war and against broader physical risks, including climate hazards. A resilient power system is one that can prepare for disruptive events, adapt to and withstand gradual changes in the physical environment, continue to operate when exposed to shocks such as physical attacks or extreme weather events, and resume operations in the wake of a disruption. A framework for physical resilience defines it through four critical dimensions:

- **Readiness** is the ability to assess, anticipate and prepare for changes in the physical environment in which a power system operates. For example, comprehensive power system planning that fully considers physical resilience in terms of both its value to the system and costs.
- **Robustness** is the ability of a power system to withstand the gradual, long-term changes in a physical environment and continue operation. While more generally related to the climate change, this also applies to the continued operation of a power system despite shifts in energy supply chains caused by geopolitical or market events.
- **Resourcefulness** is the ability to continue operation during immediate shocks, such as physical attacks or extreme weather events. For example, physical hardening of generation assets or the ability for distributed energy resources to remain online during and after a fault.
- **Recovery** refers to the ability to restore operations after disruptions caused by physical attacks or extreme weather. For example, a more resilient electricity system with a well-coordinated contingency plan – covering communications, temporary assets and the system work force – will recover more quickly from interruptions caused by such events.

Conceptual framework of physical resilience of the electricity system



Source: Adapted from IEA (2022), Climate Resilience for Energy Security.

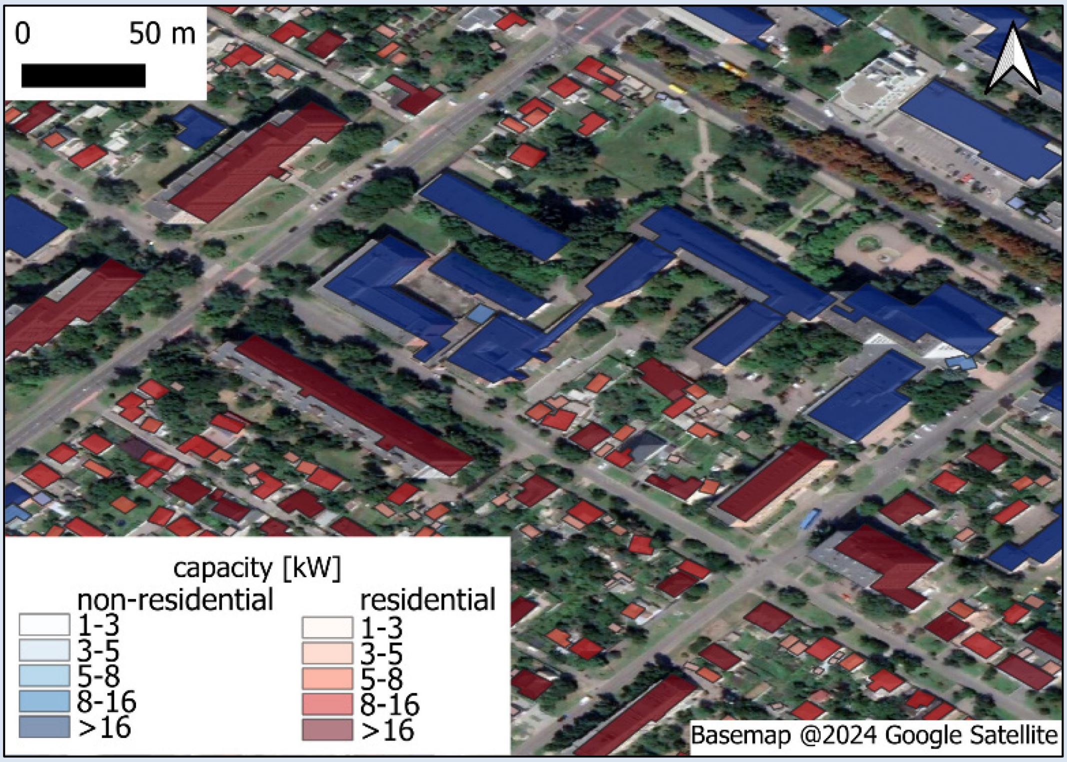
Due to their small, modular and distributed nature, as well as the diversity of their composition, DERs offer several advantages that can enhance the resilience of Ukraine's power system – both during the ongoing invasion and beyond. For example, their small size makes easier to conceal and harder to target. If damaged, the loss of a single unit has less impact on the system compared to the loss of a large, centralised unit. This also has implications for reducing investor risk and lowering the cost of financing such projects.

When power outages do occur, it is also crucial to support the continuity of supply for critical infrastructure. Since the start of the full-scale invasion, Ukraine has endured persistent rolling blackouts, a situation that has worsened considerably since the Russia's renewed targeting of energy infrastructure, which began in March 2024. Conventional backup systems, such as diesel generators, are a type of DER and have proven effective. However, they incur high fuel costs and are of limited value to the larger system under normal conditions. A broader perspective on DERs – one that considers both their long-term benefits in stable conditions and their ability to operate in "island mode" to support critical infrastructure in emergencies – offers a more resilient and cost-efficient alternative. Moreover, the ability of such systems to aid recovery from disruptions – such as the restoration of power after a blackout – further demonstrates how DERs, when designed for resilience, can enhance the overall stability of the system.

Analysis of rooftop potential in Ukraine

Rooftop solar photovoltaics (PV) play an essential role in a decentralised energy system. While there are a few top-down estimates of the potential for rooftop PV in Ukraine, the general approach lacks the level of detail and reliability required for transformation strategies of the energy system.

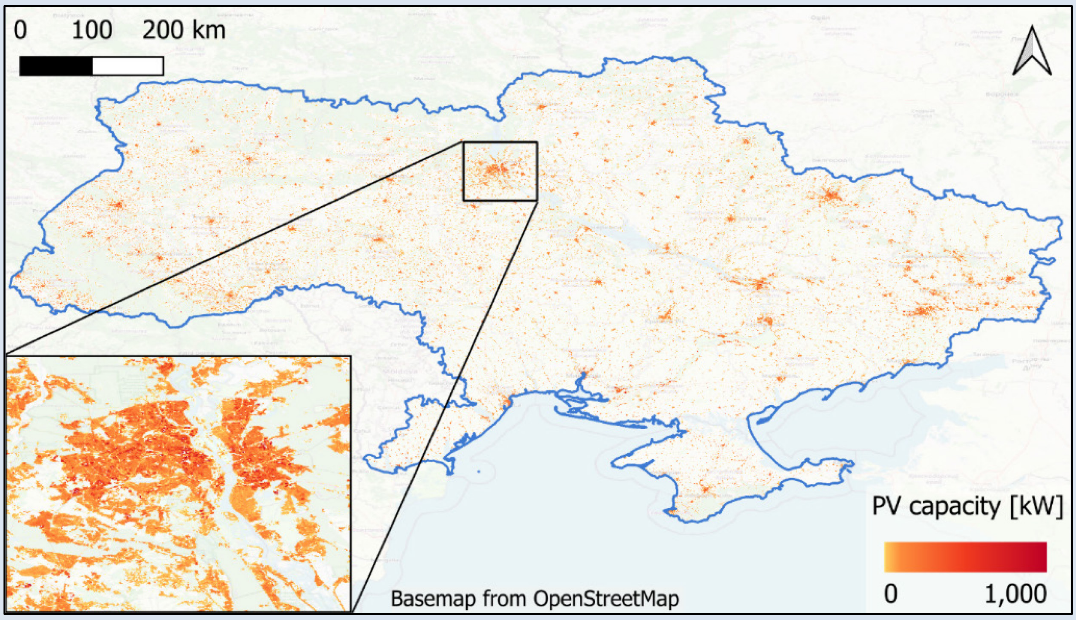
Example of capacity potentials for the City of Cherkasy, at building-level resolution



Source: IEA and Jülich Systems analysis, Forschungszentrum Jülich, High-Resolution Rooftop-PV Potential Assessment for a Resilient Energy System in Ukraine.

A pioneering, detailed, bottom-up approach was developed to create a new high-resolution dataset of capacity and generation potential for Ukraine. This dataset, including hourly timeseries, is also available for download to support further work on rooftop PV in the country. Due to the absence of high-resolution data on Ukraine's building footprints and roof areas at a national scale, 3D building and PV capacity data from Germany was used to train the model, along with two global satellite-based footprint datasets. Data from eastern Germany was selected specifically to increase similarity of the communist-era building structures and the transferability was validated based on small-scale Ukrainian data samples. The satellite-based footprint polygon datasets for Ukraine were scaled to correct building footprint areas using the German training data. Factors for roof area, eligibility and capacity were applied to each building polygon depending on the usage type of the building as well as on the degree of urbanisation of the respective district (raion). The maximum capacities per building are visualised as examples in the figure above. capacity potentials were validated against existing assessments as well as real Ukrainian data and are available per administrative unit or as national raster data at 100m x 100m resolution.39.8 GW, excluding north-facing systems (which potentially account for another 48.2 GW).

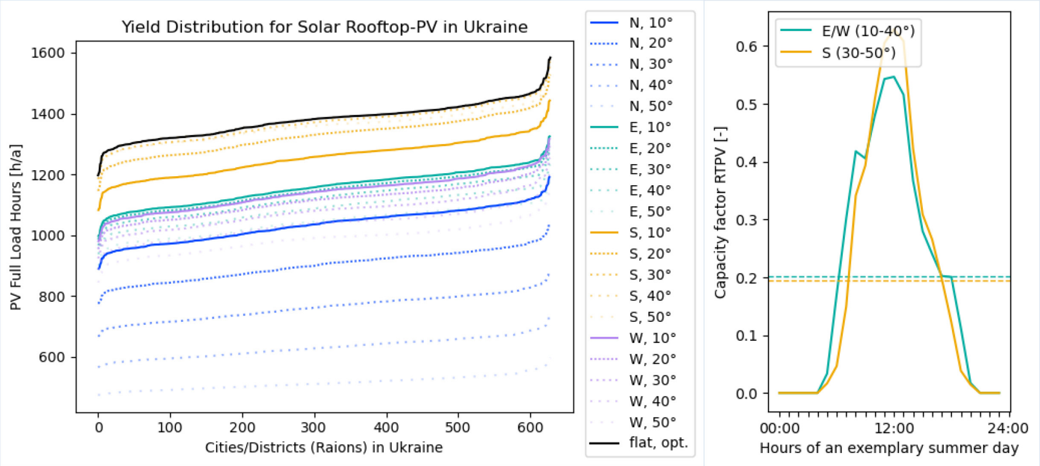
Rasterised rooftop PV capacity potentials in Ukraine



Source: IEA and Jülich Systems analysis, Forschungszentrum Jülich, High-Resolution Rooftop-PV Potential Assessment for a Resilient Energy System in Ukraine.

Using the ETHOS.RESkit tool, energy yield was simulated by district for each azimuthal and tilt configuration to assess the impact of different roof orientations in Ukraine. Annual full-load hours (FLH) of 1239-1457 h/afor an optimal system orientation with increasing trends towards the southeast make Ukraine a promising location for solar. East- and west-facing systems yield considerably less energy annually due to a winter low, but the comparison of hourly time series shows benefits in the morning and evening hours in summer.

Full-load hours per district, azimuth and roof tilt (left) and exemplary summer production timeseries for south- vs. east/west-facing system (right)



Source: IEA and Jülich Systems analysis, Forschungszentrum Jülich, High-Resolution Rooftop-PV Potential Assessment for a Resilient Energy System in Ukraine.

The maximum rooftop PV generation potential in Ukraine (excluding north orientation) amounts to 290.1 TWh. The levelised cost of electricity (LCOE) can be expected to start at USD 6.41 /kWh in 2030.

Chapter 2. A decentralised vision for rebuilding Ukraine's power system

Model overview

The complexity of rebuilding Ukraine's power system while transitioning to a more decentralised future requires sophisticated analytical tools to inform policy and investment decisions. Traditional power system planning approaches, which typically rely on historical patterns and gradual system evolution, are insufficient given Ukraine's unprecedented circumstances. The destruction of major generation assets, the rapid deployment of distributed resources, and the uncertain pace of recovery create a unique planning challenge that demands detailed scenario analysis. Moreover, the interaction between immediate reconstruction needs and longer-term decentralisation objectives requires careful examination of how different technology choices and policy decisions today will impact system development towards 2030. Quantitative modelling can help identify potential synergies and conflicts between short-term solutions and long-term goals, while also evaluating the system-wide impacts of different policy choices.

To explore the potential benefits of decentralisation in rebuilding Ukraine's power system, the IEA developed a comprehensive power system model using the PLEXOS® energy modelling software. The model incorporates both capacity expansion and production cost components, enabling detailed exploration of how such a system could evolve and operate. The capacity expansion component explores least-cost options for addressing Ukraine's power deficit, while the production cost model assesses how the power system operates on an hourly basis to maintain security of supply in an increasingly decentralised energy landscape.

The model represents two main snapshots of Ukraine's power system with the following approach:

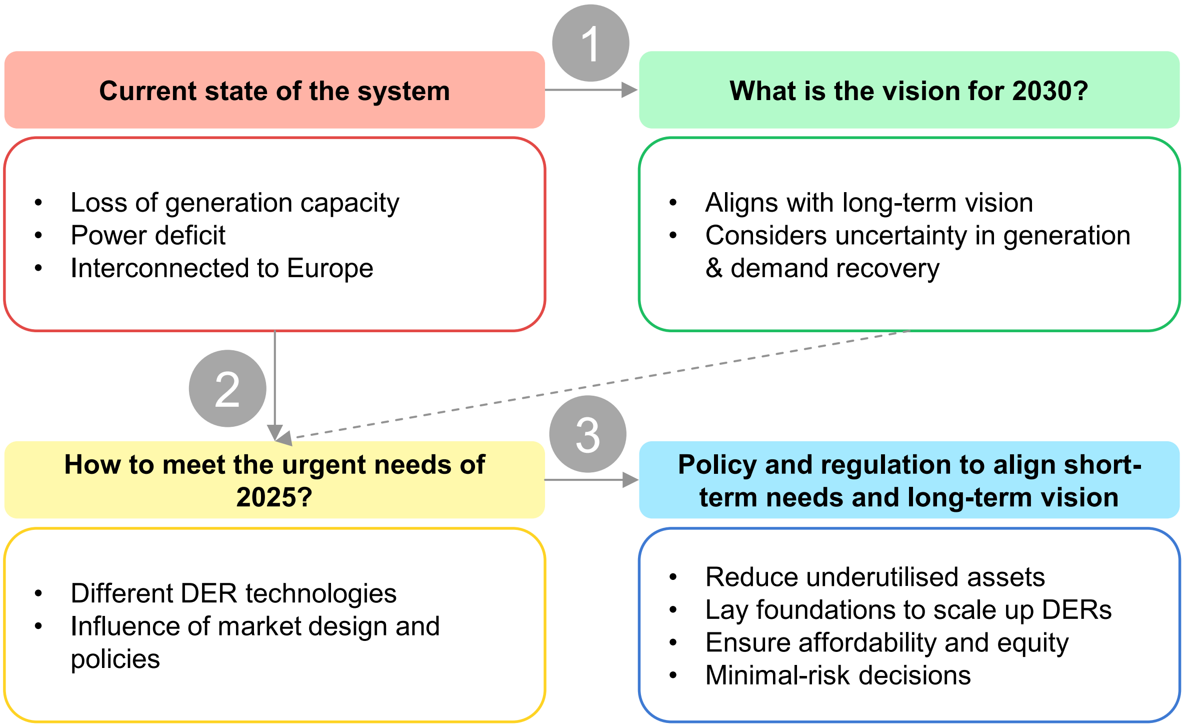
- **2025 (i.e. immediate):** Examining Ukraine's options to address urgent system needs while ensuring affordable, equitable and low-risk solutions for its citizens and economy.

- **2030 (i.e. medium term):** Outlining a vision for a new Ukrainian power system, rebuilt to fully align with its policy goals of decarbonisation, European integration and improved electricity security.

The two analyses are interlinked, since decisions made today to address Ukraine's immediate system needs will have an influence on the pathway taken towards 2030 and beyond. The pathway taken will be shaped by policies, regulations and market design, which will determine not only how new generation capacity is developed, but also how electricity is used and the role played by consumers.

By integrating these two snapshots, the model aims to identify the key actions that Ukraine's power sector stakeholders can take to more closely align the country's immediate needs with its long-term goals.

Overview of the modelling approach to identify key policy and regulatory levers for rebuilding the Ukrainian power system



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The questions addressed in each snapshot differ, as do the main sensitivities explored. In 2025, the focus is on uncertainties surrounding generation capacity and demand amid the ongoing Russian invasion. In 2030, the emphasis shifts to how policies, market design and regulation can influence the future trajectory of Ukraine's power system. Sensitivities modelled in the snapshots of 2025 and 2030, respectively.

2025	**2030**
• Policy influence on the deployment of different technologies • Market design influence on the deployment of front-of-meter batteries • The impact of expanded import capacity with the continental Europe system on generation capacity needs	• How much of the damaged generation fleet can be recovered? • Can the operation of nuclear plants nearing the end of their technical life be extended? • What measures can be taken to promote demand recovery, growth, electrification and improved efficiency?

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The model aims to explore the following key questions:

1. What are the minimum levels of dispatchable capacity required to meet system needs, both in the immediate and longer-term?
2. To what extent can distributed clean energy technologies such as solar photovoltaic (PV), wind and batteries limit the need for new gas-fired capacity to meet immediate capacity needs?
3. What are the immediate and medium-term system requirements, and what regulatory and market conditions are necessary to enable a larger share of clean distributed technologies to meet these needs while ensuring the system remains affordable and equitable?
4. What incentives are needed to enable behind-the-meter assets to meet a greater share of the system requirements in both the immediate and medium term?
5. How are Ukraine's system flexibility requirements evolving, both since the full-scale invasion and across different recovery pathways for the power system? What conditions are needed to ensure this flexibility is met by a growing share of renewables-based DERs?

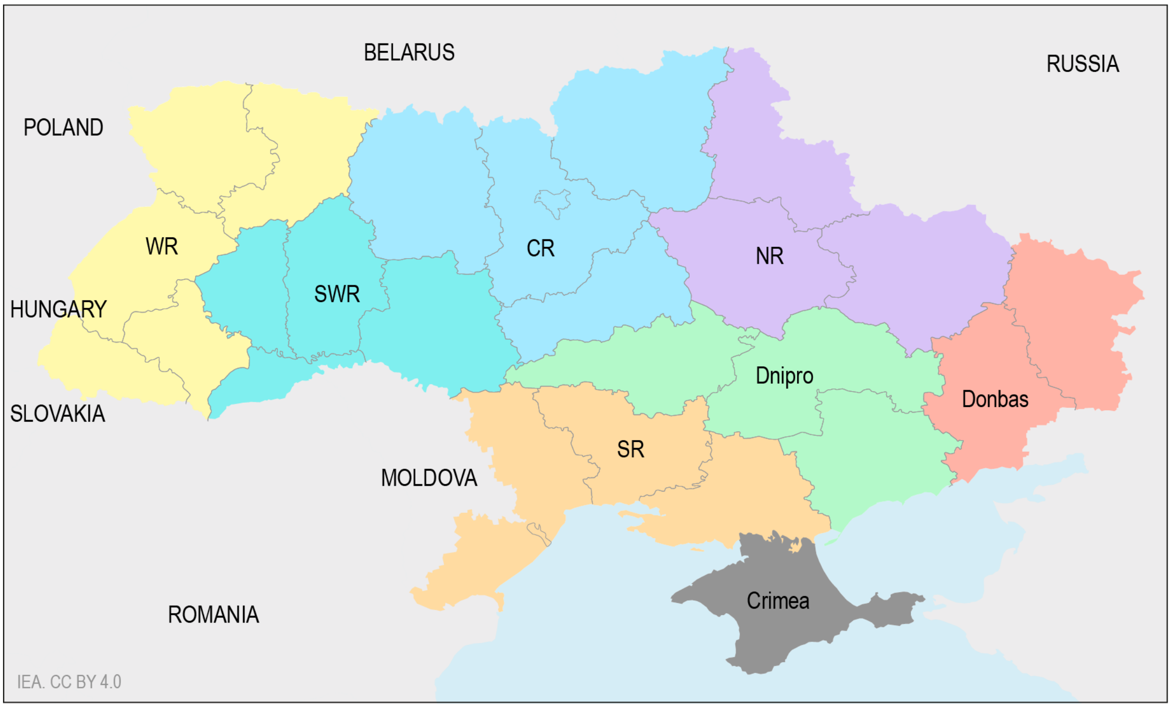
6. How does Ukraine's import and export capacity with the continental European grid influence the reconstruction of its power system?

Importantly, this model serves as a tool to illustrate how policy and regulation are important levers for the reconstruction of the Ukrainian power system. However, it does not possess the level of detail required to replace a full and comprehensive model for capacity expansion planning. Such a model would need to consider, amongst other things, a full planning horizon with a more detailed demand forecast, and be informed by detailed grid studies to ensure that associated grid bottlenecks and costs of reinforcement are accurately included.

Model assumptions

The model is divided into seven regions based on Ukrenergo's own defined power regions, each typically comprising multiple oblasts. While much of Donetsk and Luhansk in the Donbas region are occupied and no longer part of the Ukrainian Independent Power System (IPS), the areas still connected with the IPS are treated as a single node. Crimea is excluded from the model since it is no longer part of the Ukrainian IPS.

Overview of the modelled regions in Ukraine



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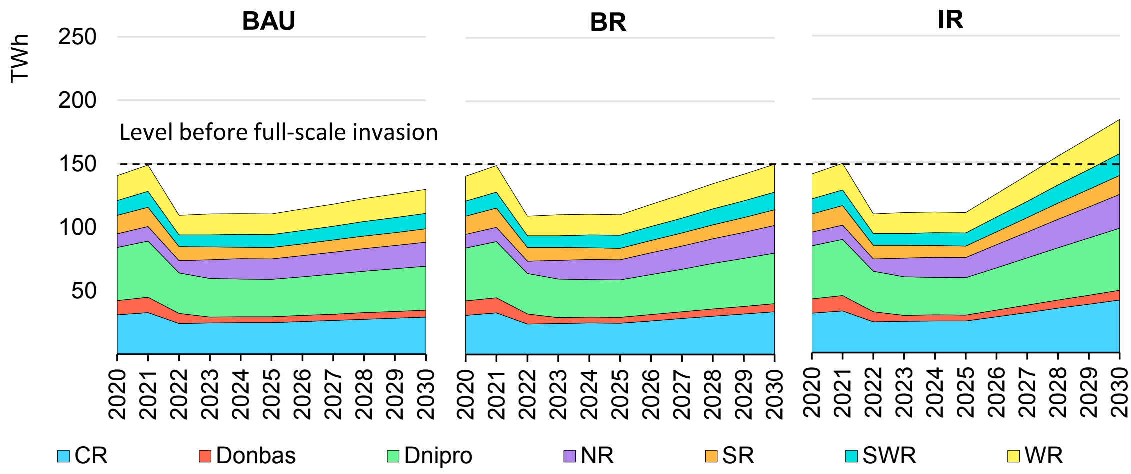
Notes: CR = Central Region; NR = Northern Region; SR = Southern Region; SWR = Southwestern Region; WR = Western Region.

Inter-regional transmission and interconnection capacity to European neighbours (Hungary, Poland, Romania and Slovakia) are assumed based on available information around network infrastructure and transfer capacities between Ukraine and these neighbours. For the purpose of this modelling exercise, Moldova is not explicitly represented to limit the impact of uncertainty around the operation of the 2 520 MW Moldavskaya GRES (MGRES), Moldova's largest power station, which is situated in the breakaway region of Transnistria. However, its network is considered as throughway for power imports and exports to and from Romania.

Electricity demand and reserve requirements

Electricity demand for Ukraine in the model is based on a combination of historical hourly profiles at a national level, regional snapshots of hourly demand on specific days before and after the invasion, and future projections of annual and peak load growth (2025-2030) as per the Net Zero World Initiative's Clean Energy Roadmap for Ukraine. These projections are divided into three scenarios – Business as Usual (BAU), Base Recovery (BR) and Intense Recovery (IR). Each scenario considers different levels of economic recovery, electrification and energy efficiency measures to achieve sectoral emission reductions The resulting annual demand model is shown below, highlighting the drop in demand following the full-scale invasion, the shift in demand to the Northern region, and the recovery (at varying paces) across the different demand scenarios.

Overview of assumed electricity demand growth across three different scenarios



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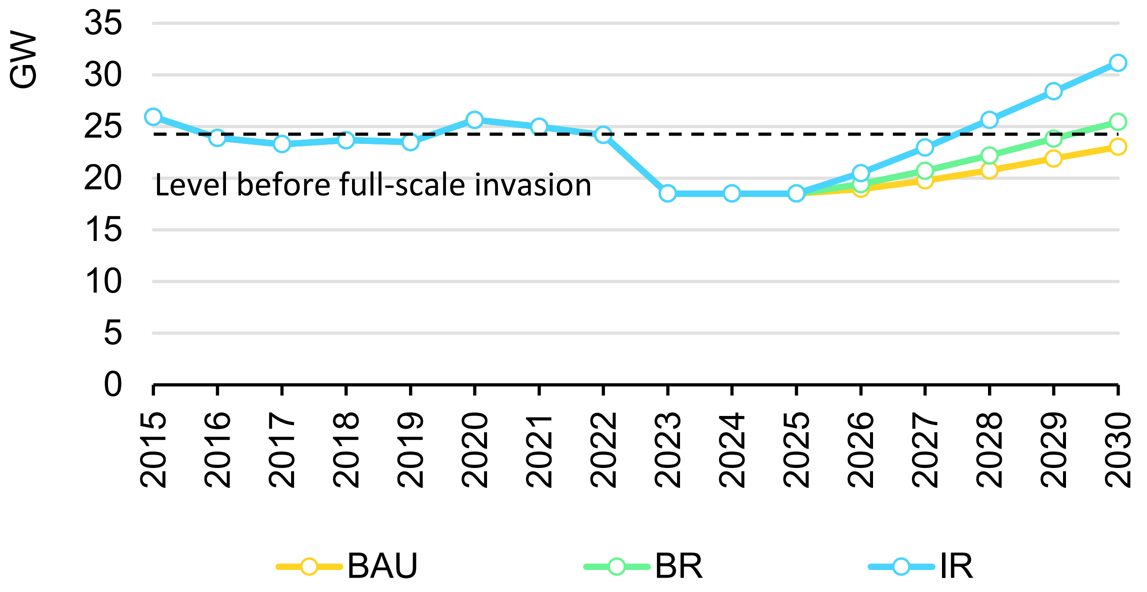
Notes: CR = Central Region; NR = Northern Region; SR = Southern Region; SWR = Southwestern Region; WR = Western Region; BAU = Business as Usual Scenario; BR = Base Recovery Scenario; IR = Intense Recovery Scenario.

Sources: IEA analysis based on Net Zero World Initiative (2023), Clean Energy Roadmap and enriched with information from Green Deal Ukraina (2024), Six options to boost power transfers from Continental Europe to Ukraine, for the next two winters, as well as data from Ukrenergo and the Ukrainian Ministry of Energy.

The primary requirements modelled by the IEA for the Ukrainian power system are based on its energy and capacity needs, which are driven by peak capacity requirements. This is in addition to operating reserve requirements, with spinning reserve based on the largest system contingency – one of the larger units of the nuclear fleet – and a portion of forecasted demand for regulating reserves. Peak demand, both historical and forecasted by scenario, is shown below.

Overview of modelled system requirements in terms of peak demand



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Sources: IEA analysis based on Net Zero World Initiative (2023), Clean Energy Roadmap and enriched with information from Green Deal Ukraina (2024), Six options to boost power transfers from Continental Europe to Ukraine, for the next two winters, as well as data from Ukrenergo and the Ukrainian Ministry of Energy.

Generation capacity

Existing and future generation capacity and its technical characteristics and cost parameters are based on data collected from a range of sources, including public domain information and direct data from utilities and the Ukrainian Ministry of Energy. In the absence of plant-specific data, generic characteristics were assumed based on plant technology and best practice. The status of existing generation capacity is dynamic, influenced by ongoing attacks on the power system on one hand, and repair efforts on the other. Data on installed and available capacities per plant has been validated against damage report assessments and public announcements to reflect the most up-to-date information. This ensures a more accurate representation of available capacity by technology and region, helping to model Ukraine's current and future capacity deficit. Data on generation is captured at plant level for large-scale facilities such as thermal plants, large-scale hydropower and nuclear plants. Smaller plants and variable renewables are aggregated by technology and region.

For more information on the model, please refer to the technical annex.

Value of resilience and speed of deployment

Generation expansion options are represented at a regional level, capturing build costs, technical lifetime and financial assumptions. As the capacity expansion model is based on least-cost optimisation, it naturally favours technologies with larger units that benefit from economies of scale, such as utility-scale wind, solar PV and larger gas turbines. However, the full value of each technology in terms of resilience is not fully captured. For instance, small gas turbines can be easily concealed from potential attacks, while gas engines can be deployed rapidly.

Similarly, distributed solar PV is harder for an adversary to target than utility-scale solar, since it lacks a single point of failure like a substation. Meanwhile, the range of financing options, incentives and deployment speed will also vary significantly by technology. To properly capture **deployment speed** and **resilience** as a consideration in the capacity expansion model, these factors are considered as part of constraints in the feasible expansion plans for 2025 and 2030, based on analysis from the Danish Energy Agency and its Urgency Technology Catalogue.

Overview of different DER technologies to key system requirements

Decentralised generation technology	Wintertime production	Resilience	Deployment speed
Small modular gas turbines	High	Medium-High	Medium-High
Gas / diesel engines	High	High	Medium-High
Distributed PV co-located with battery	Low	High	High
Utility-scale solar PV	Low	Medium	Medium
Onshore wind	Medium	Medium	Low
Utility-scale battery	Medium	Medium-High	Medium-High

Notes: Resilience is assessed based on a combination of fuel supply risk, potential for concealment, reliance on special spare parts and vulnerability to targeting due to size and distribution. Deployment speed considers all processes involved in fully deploying a project including planning and regulatory approval, component acquisition and installation. These attributes are classified as: High (≤ 6 months), Medium-High (≤ 1 year), Medium (≤ 2 years), Low (> 2 years).

Source: IEA analysis based on Danish Energy Agency (2024), Urgent Technology Catalogue for the Ukrainian Power Sector.

The deployment time of different decentralised generation technologies is critical for addressing Ukraine's immediate and urgent capacity deficit. For example, distributed solar PV and behind-the-meter batteries can be deployed within six months, while utility-scale batteries and gas engines can be deployed within a year. Deployment times could be further shortened by reducing regulatory approval times. While small modular gas turbines are would generally be expected to take nearly two years for deployment, this is assumed to be halved due to the ability to cut regulatory approval times and to place at existing locations with grid hosting capacity.

Meanwhile, all considered technologies have been assessed as being at least moderately resilient to physical risks from the ongoing war. However, smaller-scale, more distributed resources – such as gas engines and distributed PV co-located with batteries – offer greater resilience. These technologies have a lower risk profile and more distributed points of failure. They are also well equipped to help the system withstand and recover from disruption due to ongoing hostilities.

To capture the key benefits of distributed resources compared to utility-scale alternatives, constraints are applied to the deployment of different technologies in 2025 and 2030, as detailed in the table below.

Overview of technology ratios in both 2025 and 2030 capacity expansion models

Technology	Expansion constraints – 2025	Expansion constraints – 2030
Gas	60% small gas turbine 40% gas engines	60% small gas turbine 40% gas engines
Wind	Not considered	Restricted to an approximate share of 70:30 of solar PV (utility-scale and DPV) to wind
Solar PV	100% distributed PV	25% utility-scale 75% distributed
Batteries	2 GW max utility-scale	50% utility-scale, 50% BTM

Notes: Based on the ratio of wind to solar PV in the Base Recovery Scenario of Net Zero World Initiative Clean Energy Roadmap: DPV = distributed solar PV.

Modelling the medium-term vision for 2030

Scenarios for a medium-term vision for Ukraine

The medium-term vision of Ukraine is influenced by several factors. First, the government has outlined its longer-term objectives for the energy sector in its National Energy and Climate Plan (NECP) through 2030, and beyond with its 2050 Energy Strategy of Ukraine. Both documents set ambitious goals for decarbonising the country's power sector while ensuring sustainable, affordable and secure energy for its citizens. This goal is further reinforced by the objective of closer integration with the power systems of continental Europe.

Second, the ongoing hostilities have not only devastated Ukraine's energy infrastructure – they have created significant uncertainty about the path to recovery. This uncertainty spans both the recovery of demand – which has fallen by an estimated 30% since February 2022 – and the extent to which generation capacity can be restored or repaired. The demand scenarios are based on the three Net Zero World Initiative (NZWI) scenarios presented in the previous section (BAU, BR and IR),while the generation recovery scenarios are summarised below.

Overview of recovery scenarios generation capacity in 2030

Scenario	Description
Optimistic Recovery	Restoration of all damaged, destroyed or occupied generation. Zaporizhzhia NPP is assumed to be lost.
Pessimistic Recovery	Repair of all damaged generation except for coal-fired assets. Zaporizhzhia NPP is assumed to be lost. Coal generation repaired ahead of the 2024/2025 heating is assumed to be retired.
Optimistic Recovery with Nuclear Extension	Similar to the Optimistic Recovery Scenario, but with the extension of 4.4 GW of nuclear capacity that is currently set to retire before 2030
Pessimistic Recovery with Nuclear Extension (reference)	Similar to the Pessimistic Recovery, but with the extension of 4.4 GW of nuclear capacity that is currently set to retire before 2030.

To illustrate a possible vision for 2030, a capacity expansion model is used to create a snapshot of the year 2030, taking into account the sensitivities mentioned above. It also captures an economic incentive for the decarbonisation of its system based on a carbon price of USD 75 per tonne, roughly equivalent to the current price in Europe. The starting point in the model considers all existing generation capacity as of 2024, accounting for damage and recovery as detailed above. The analysis aims to determine the extent to which DERs could help meet system needs in 2030, considering the economic incentive to decarbonise and the opportunity to trade surplus power with neighbouring European systems.

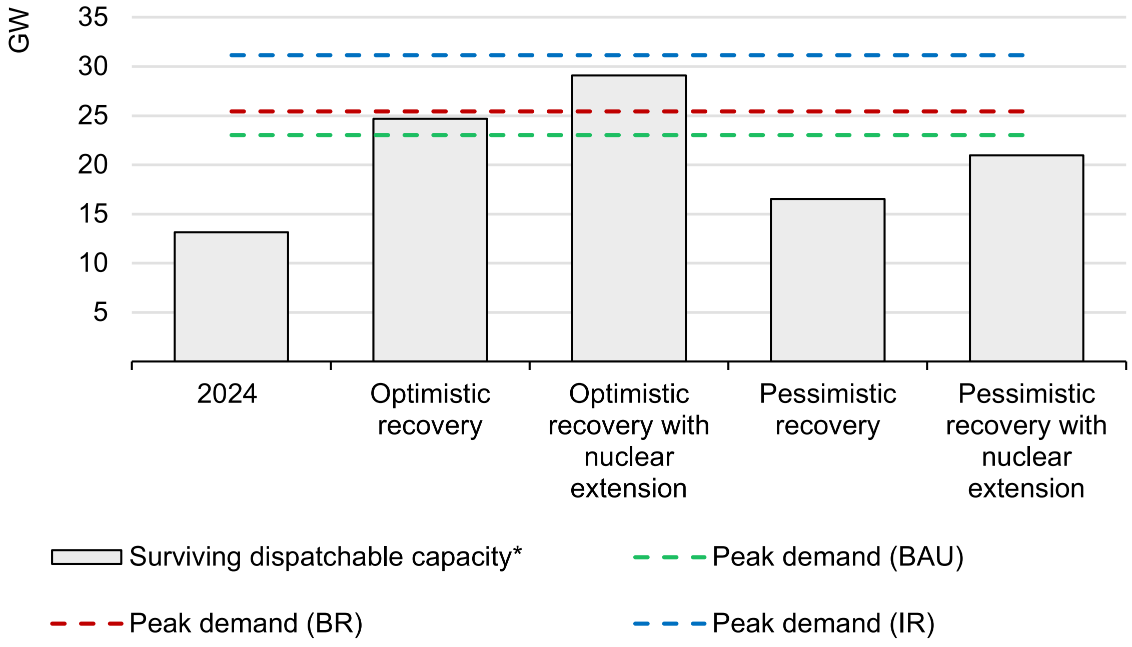
The vision for 2030

These results present a highly varied outlook for the system in 2030, including the levels of dispatchable capacity and storage needed to meet demand while ensuring adequate system security. Importantly, they highlight the range capacities for gas-fired, renewable generation and storage capacity necessary to meet system requirements in a transitioning energy landscape.

For example, the required generation capacity in Ukraine in 2030 will depend on demand levels, which are influenced by the pace of demand recovery and the speed at which measures to achieve emission reduction targets are implemented. The BR Scenario projects a peak demand of around 25 GW, based on demand recovery, the achievement of sectoral emission reduction targets and energy efficiency measures as outlined in the NECP. For this reason, it is considered the reference demand scenario. However, the demand projection ranges from 23 GW to 31 GW, depending on the scenario, resulting in an 8 GW difference in the system's peak capacity requirements.

Similarly, the available capacity from the existing fleet will depend on what can be recovered from the damaged or occupied units, as well as the extension of the operating life of the surviving nuclear fleet. Based on the latest information, this could range from 16.5 GW to 29.1 GW.

Summary of peak capacity requirements in 2030 compared to the surviving capacity of dispatchable generation across different scenarios



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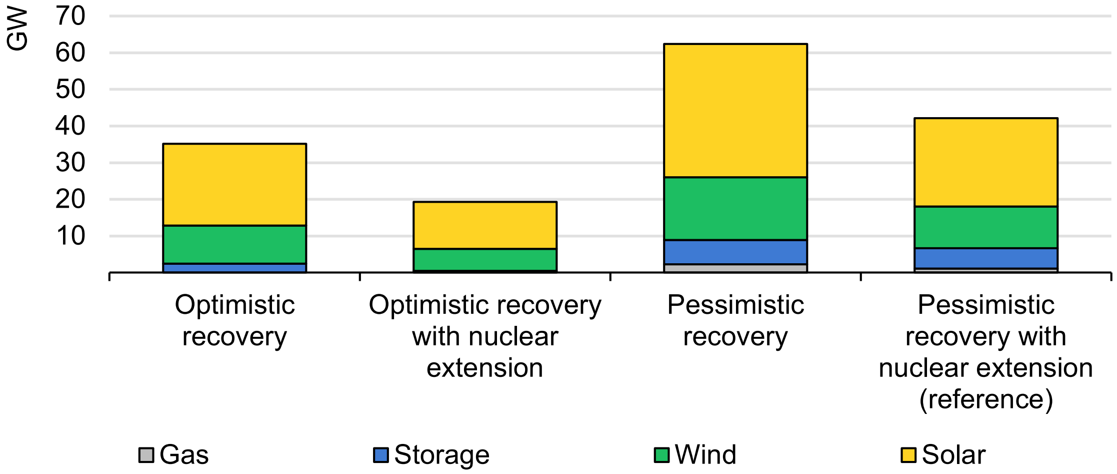
* Surviving dispatchable capacity = dispatchable capacity existing in 2021 which is assumed to be in service under the scenario.

Using the BR Scenario as our reference, the reconstruction of the power system varies significantly depending on the recovery of damaged or occupied generation assets. Indeed, the availability of dispatchable generation capacity could vary by as much as 12.6 GW across all the scenarios. Notably, even under a scenario with sufficient dispatchable capacity to meet peak demand (Optimistic Recovery with Nuclear Extension), the model still invests in 20 GW of wind and solar PV based on the economic incentive to decarbonise the power system. This highlights the combined challenge for Ukraine, which is to simultaneously build back and decarbonise its power system, ensuring that it becomes secure, affordable and sustainable.

Least-cost generation expansion under Base Recovery demand with different combinations of nuclear extension and fleet recovery scenarios



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Considering the scale of damage to the thermal fleet and the difficulty that Ukraine will face in attracting international financing to restore these assets, the pessimistic recovery of generation, where severely damaged or destroyed coal capacity is assumed to be lost, is assumed as the reference case. Additionally, it also assumes that the lifetime of the nuclear plants due to retire before 2030 would be extended beyond their lifespan. Therefore, the Pessimistic Recovery with Nuclear Extension Scenario is used as the reference scenario to represent the vision for 2030 for the purpose of this analysis.

Bridging immediate needs in 2025 with the medium-term vision for 2030

The immediate system needs of Ukraine in 2025

The primary requirements of the Ukrainian power system as modelled for 2025 are defined by three main dimensions: the annual energy, peak electricity demand and operating reserves[1]. Electricity demand varies across the day as well as across the year, with peak electricity demand occurring during the winter months, driven by heating demand.

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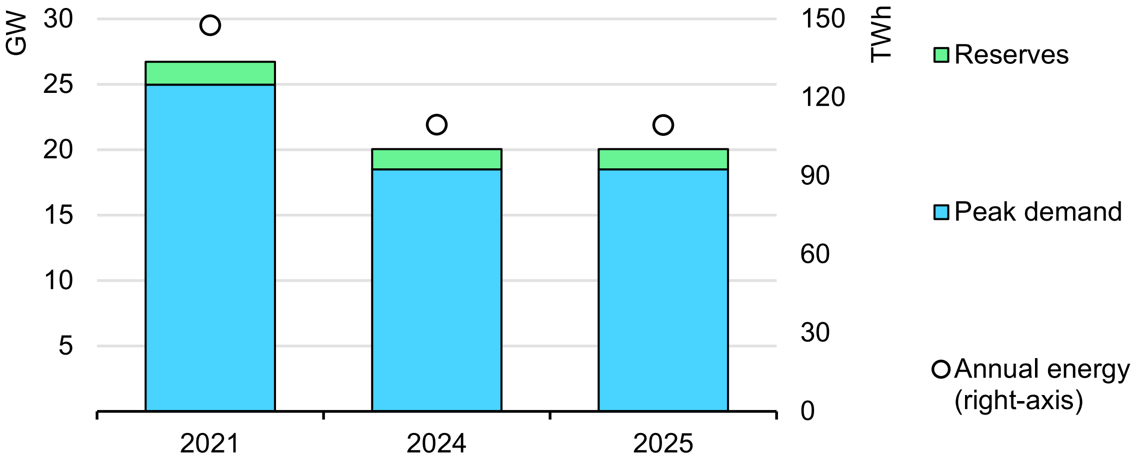
[1] Operating reserves are comprised of 1 GW of frequency containment reserve to cover the largest contingency and balancing reserves which vary across the year, based on 3% load risk.

Primary requirements of the modelled Ukrainian power system



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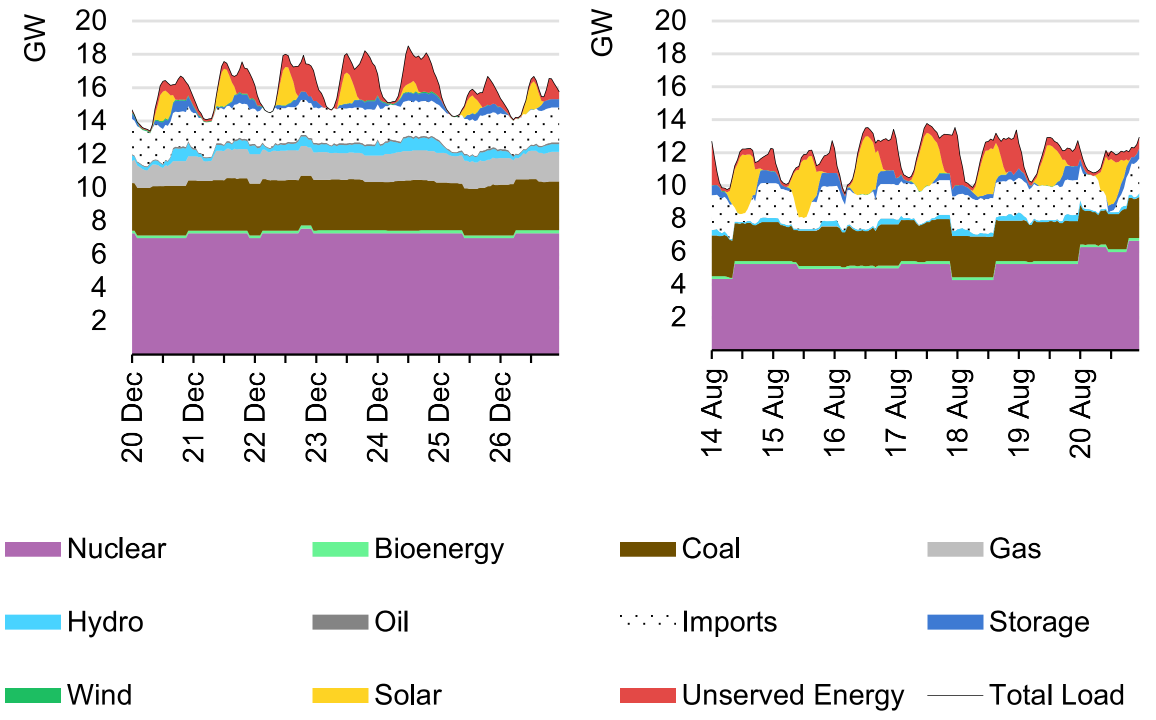
Note: "Reserves" consist of primary (spinning) reserves and regulating reserves. Regulating reserves are estimated based on their value during peak demand.

Furthermore, the available dispatchable capacity in the system to meet this demand also varies across the year, due to a mixture of maintenance, forced outages and the unavailability of combined heat and power (CHP) plants outside of winter months as they are unable to operate in power-only mode

Despite the repair campaign ahead of the 2024/2025 heating season, which was able to repair an estimated 3 GW of thermal capacity, there is still uncertainty around the resilience of the remaining capacity as Russian attacks on energy infrastructure are ongoing. Therefore, it is assumed that only half of the repaired capacity is available at any given moment, leaving approximately 13.6 GW of available dispatchable capacity before maintenance and outages.

Under this scenario, without any new investment the Ukrainian power system falls short of the capacity required to meet both peak demand and energy needs across the year. This occurs not only in the winter months, where the peak demand occurs and the repercussions of shortages can be most severe, but also in the summer months when nuclear and CHP plants are unavailable.

Generation stack during 2025 without any new investments showing unserved energy during (a) winter and (b) summer months



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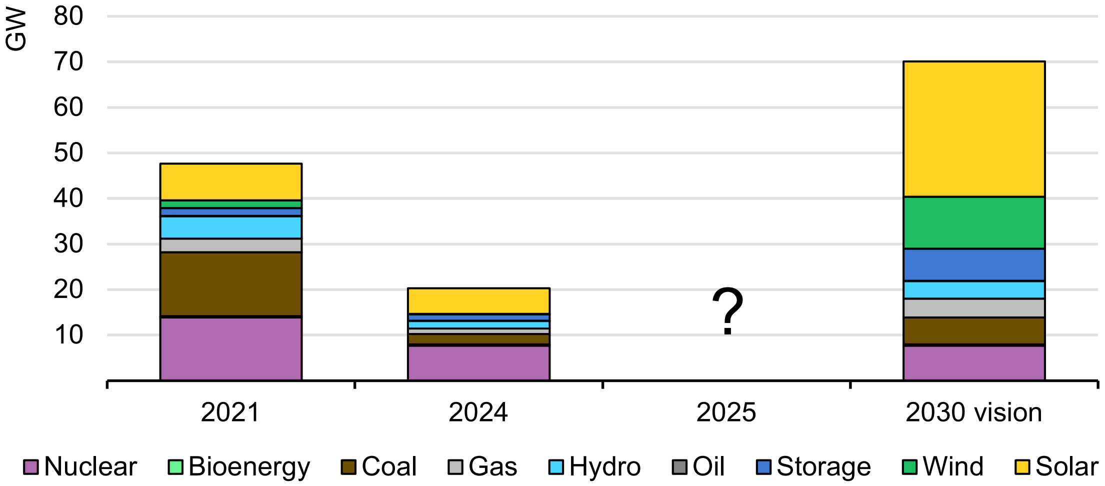
Policy-driven scenarios for meeting the immediate system needs in 2025

Given the immediate needs of Ukraine's power system, many of the policy decisions being made now could shape how these primary needs are addressed. This includes introducing incentives to accelerate the deployment of decentralised resources which can be deployed quickly to contribute to these needs and enhance system resilience. Similarly, decisions made at the broader regional level, such as by the European Network of Transmission System Operators for Electricity (ENTSO-E) can affect how much capacity is available for import and export within the continental European system. Meanwhile, the path to European integration and the alignment of domestic energy policies with the frameworks of the European Union – including the Third Energy Package and Emissions Trading System (ETS) – will significantly influence the optimal approach to rebuilding Ukraine's power system.

The modelling results presented in the previous section establish an aspirational target for Ukraine's power system that aligns with the energy sector's long-term objectives. This section examines how various policy and regulatory mechanisms can be leveraged to direct investments toward both immediate system requirements and enhanced compatibility with this medium-term vision.

What are the immediate needs of Ukraine's power system in light of its 2030 vision?



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To capture the range of possible pathways for addressing Ukraine's energy needs and capacity deficit, multiple scenarios were modelled. These scenarios explore variations in generation mix, flexibility requirements, flexibility providers and trade with the continental European system. They also examine the impact of certain policy and regulatory decisions on the deployment and operation of distributed resources. This includes aspects such as incentives for DER deployment and removing barriers to allow utility-scale batteries to be used as flexible assets for integrating larger shares of solar PV. Additionally, incorporating mechanisms that align with Ukraine's long-term ambitions (and future opportunities for European trade) can significantly influence how the country scales up its renewables sector to address immediate system needs.

Overview of capacity expansion scenarios modelled to address immediate system needs in 2025

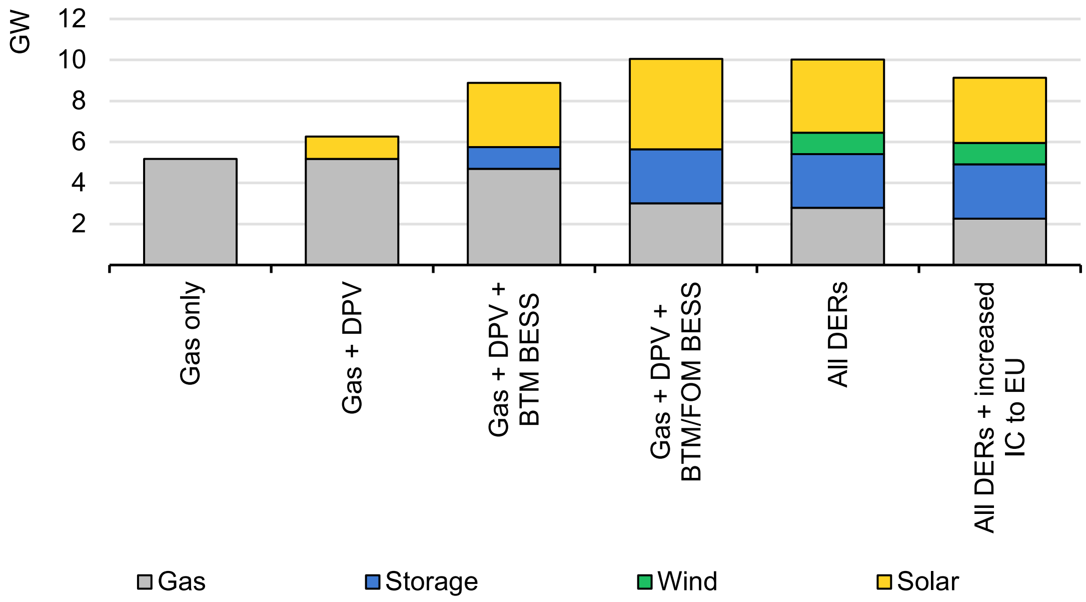
Expansion scenario	DPV	Gas	Wind	FOM BESS	BTM BESS (co-located with DPV)	EU import limit
Gas only	-	Yes	-	-	-	2.1 GW
Gas + DPV	Yes	Yes	-	-	-	2.1 GW
Gas + DPV + BTM BESS	Yes	Yes	-	-	1 GW	2.1 GW
Gas + DPV + BTM/FOM BESS	Yes	Yes		<= 1.5 GW	1 GW	2.1 GW
All DERs	Yes	Yes	<= 1 GW	<= 1.5 GW	1 GW	2.1 GW
All DERs + Increased IC to EU	Yes	Yes	<= 1 GW	<= 1.5 GW	1 GW	2.6 GW

Note: DPV = distributed solar PV; FOM = front-of-meter; BTM = behind-the-meter; BESS = battery energy storage system; IC = interconnection.

Overview of results

The modelling results present the least cost-optimal solutions considering the system requirements and constraints. They confirm that Ukraine urgently needs additional generation capacity to address its power deficit. However, the composition of this capacity depends largely on enabling policy and regulation, which will shape the country's recovery pathway. For example, if generation were to be restored with almost the same capacity as before, relying solely on dispatchable fossil fuels (Gas-Only Scenario), it would require roughly 5.2 GW of gas-fired capacity.

Capacity built to meet Ukraine's immediate system needs under various policy environments



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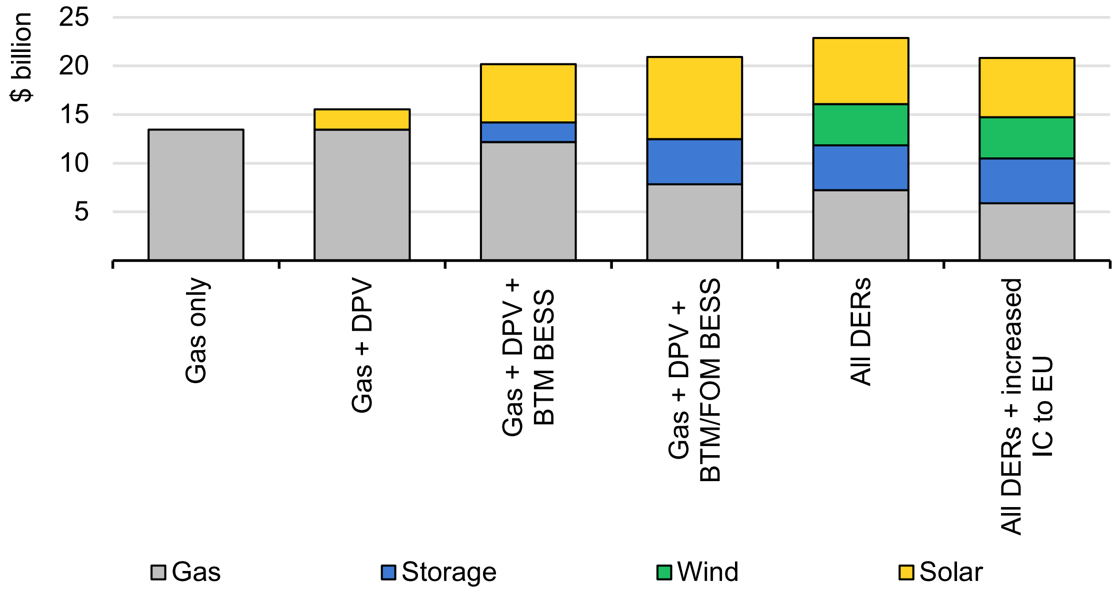
Notes: All DERs = distributed solar PV, a mix of gas engines and small modular turbines and behind-the-meter batteries. BTM = behind-the-meter. FOM = front-of-meter. BESS = battery energy storage system. Increased IC to EU = 2.6 GW of additional interconnection capacity with the continental European system (as opposed to 2.1 GW)

However, by creating the conditions for the deployment of DERs and incentives for their use towards system requirements, the generation mix could diversify away from fossil fuels, laying the foundations to scale up technologies such as solar PV and batteries that are key capacity requirements for the 2030 vision of Ukraine. This would require an additional 23 GW of solar PV, 11 GW of wind and 5.6 GW of BESS relative to 2024.

While new gas-fired capacity will be important for the long-term security of the Ukrainian power system, especially as it provides vital dispatchable production during winter months, it is equally important that this is procured in a cost-effective way that ensures the affordability of the power system. This means procurement should be done in a manner that minimises risk, accounting for uncertainty and avoiding over-investment that may result in assets that are under-utilised (and unprofitable) in the medium term. This is especially true considering the large uncertainty around the recovery of demand and generation capacity, as detailed in the previous section.

By enabling the deployment of a more diverse set of resources, including variable renewables and batteries, the necessary upfront capital costs needed will also increase. Results show that USD 13.4 billion would be necessary to build back Ukraine's power system based on small modular gas turbines and gas engines only. However, by enabling the deployment of a more diverse set of resources, including variable renewables and batteries, the necessary financing required will also increase.

Necessary investment to address the immediate system needs in Ukraine



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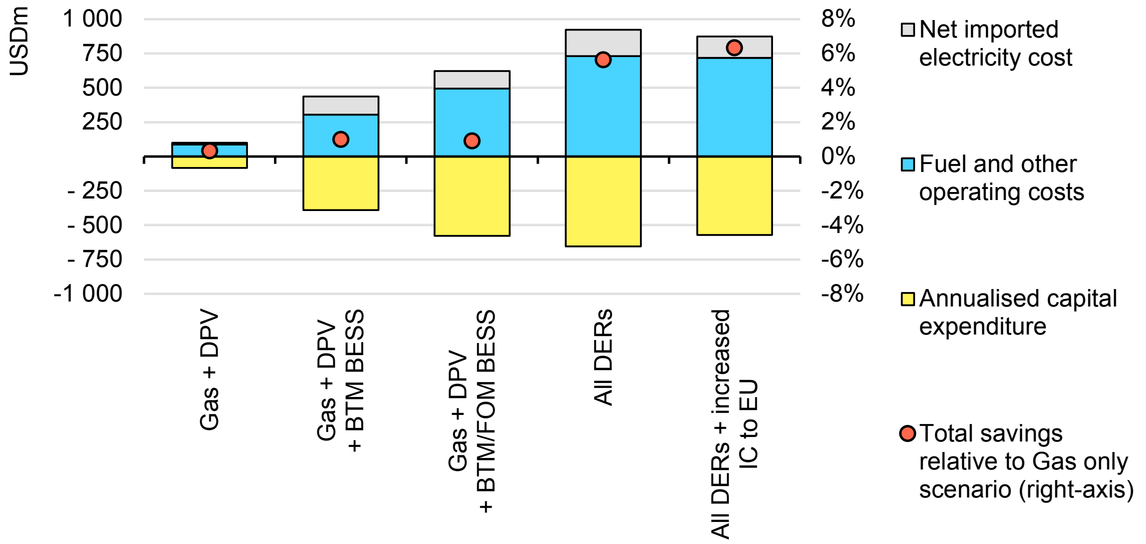
This can range from USD 15.5 billion to 23 billion, but importantly results in the most cost-optimal solution, considering the savings in fuel costs for thermal plants and the net cost for electricity traded with Europe. In this case, total annual savings relative to the Gas only scenario would be 5.6% but would require almost USD 23 billion to finance the build out of DERs that include rooftop solar PV, batteries and wind generation. Meanwhile, the cost of financing can be reduced by almost USD 2 billion with only 500 MW of additional import capacity from Europe and which lead to 6.3% savings on annual operational costs relative to a Gas only scenario.

Total annual system costs and savings relative to a Gas Only scenario in 2025



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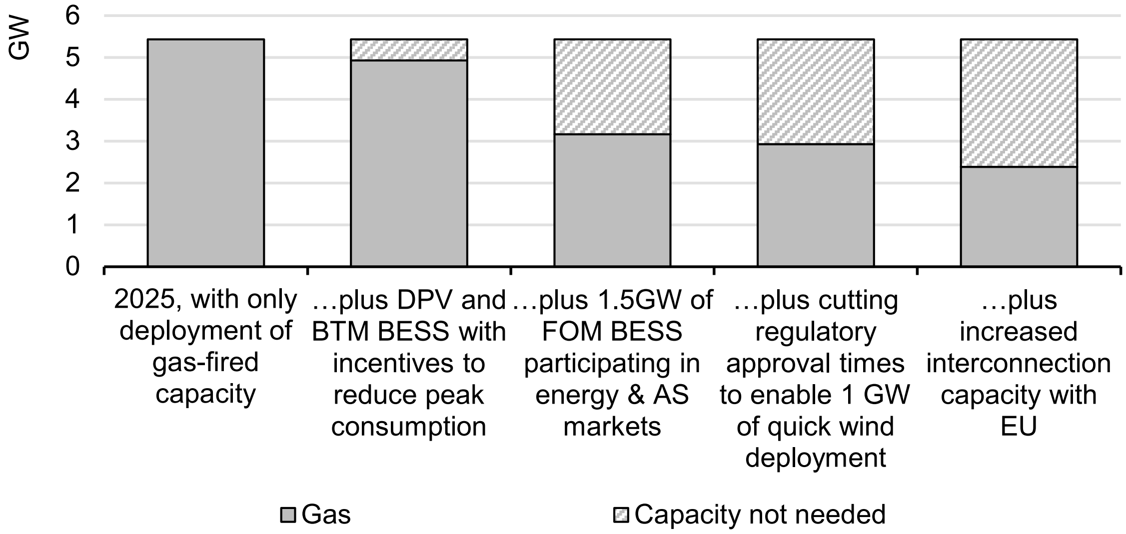
Policy implications

Appropriate incentives for clean technologies are needed to ensure an affordable and equitable system

As the results above show, Ukraine has many options for diversifying its generation mix, reducing its reliance on thermal generation and scaling up its use of DERs to meet its immediate system needs. These include incentives for the deployment of DERs, enabling front-of-meter batteries to provide essential services and flexibility, strengthening market signals for clean energy investment, scaling up supply chains to support this investment, and expanding interconnection capacity with Europe. In this regard, it becomes clear how different policy and regulatory tools can help bridge the gap between Ukraine's immediate system needs and its long-term vision – reducing reliance on fossil fuels while ensuring a secure, affordable and equitable power system.

Impact of different policies on least-cost deployment of gas-fired capacity (relative to a Gas-Only Scenario) to address Ukraine's 2025 power deficit



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Notes: BTM = behind the meter. FOM = front-of-meter. BESS = battery energy storage system.

Network and feed-in tariffs should be structured to encourage consumer engagement

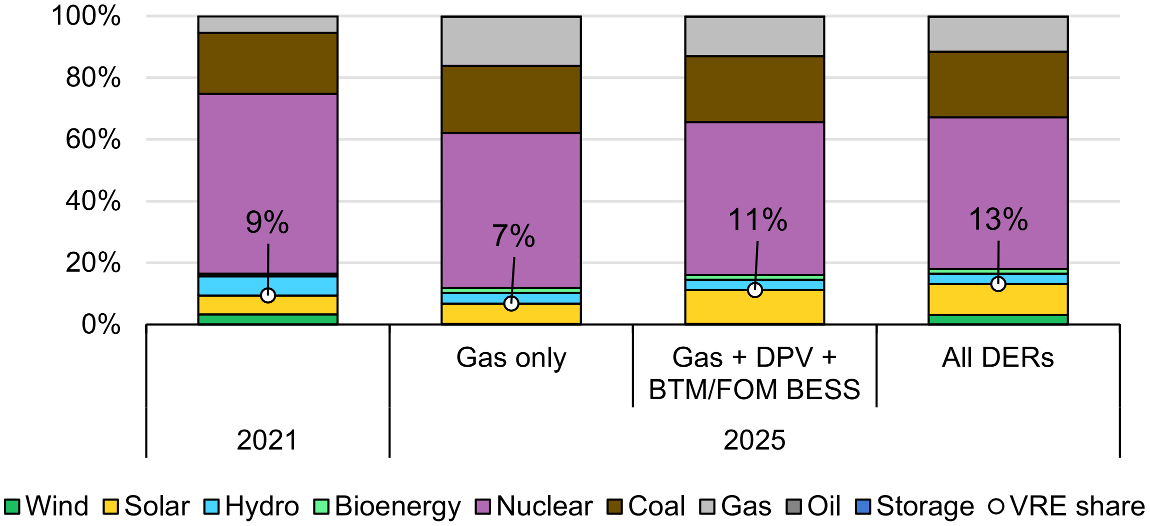
With well-structured incentives for deploying distributed solar PV and behind-the-meter batteries – including incentives for consumers and communities to reduce peak consumption – thermal capacity needs could be reduced by almost around 500 MW. In the case of our model, this is represented by the cost incentive for co-located consumer-side solar PV and batteries to reduce peak demand or provide surplus electricity to the grid during the typical peak time hours of 18h00–22h00.

In the longer term, by moving towards cost-reflective tariffs and providing consumers with appropriate price signals, these DERs could then be further incentivised to provide towards system needs. This would also promote energy-efficient consumption, both through improved devices and changes in consumer behaviour. The challenge for regulators and policymakers is to structure tariffs and incentives in a way that ensures that DERs contribute to immediate system needs while maintaining affordability and equity.

Enabling system-level benefits of batteries is key to ensuring system flexibility

In a system with higher shares of DERs, especially with increasing shares of VRE, there will be a growing need for system flexibility. Across all scenarios, the shares of VRE achieved across are between 7–13 %.

Evolution of generation mix and share of variable renewables in Ukraine according to different model scenarios



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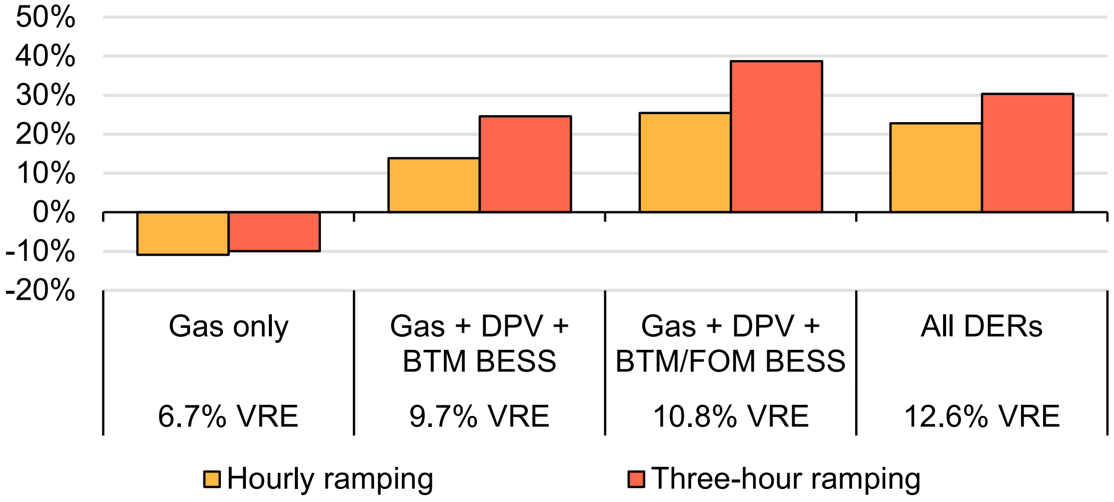
Notes: VRE = variable renewable energy. All DERs = distributed solar PV, a mix of gas engines and small modular turbines and behind-the-meter batteries. BESS = battery energy storage system. BTM = behind-the-meter. FOM = front-of-meter.

As shares in VRE increase, so will the system flexibility needs, including ramping flexibility requirements. However, this equally depends on the VRE generation mix. For example, a system with higher relative shares of solar PV compared to wind will generally experience higher ramping requirements. Therefore, while the All DERs Scenario has the highest share of VRE, the highest ramp requirements are highest in the Gas + DPV + BTM/FOM BESS Scenario.

The change in maximum ramping requirements relative to 2021 in different 2025 scenarios



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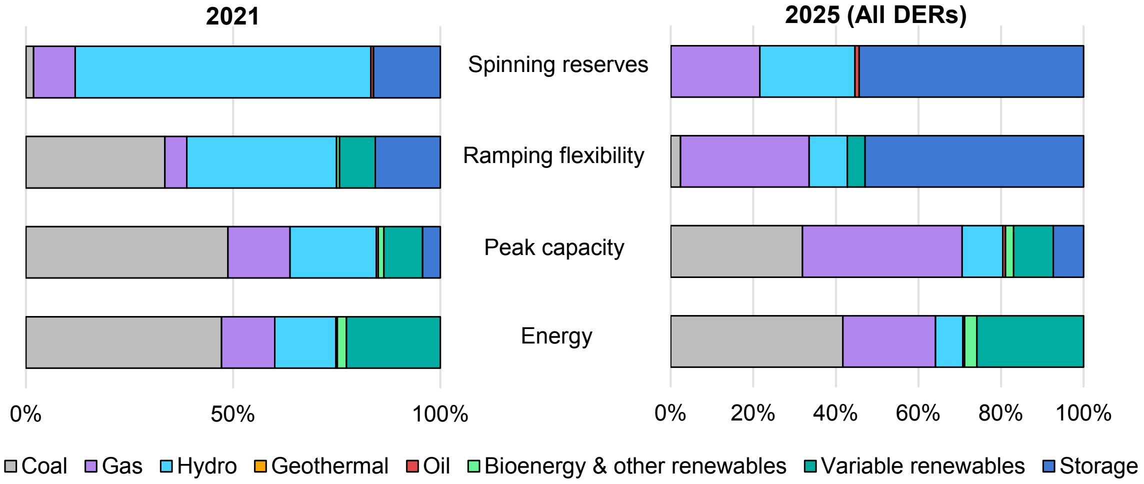
Since Ukraine has suffered huge losses to its thermal and hydro capacity, both of which provided the majority of its flexibility before the full-scale invasion, greater levels of flexibility will be needed to manage the variability and uncertainty in supply and demand, including the ability to manage short-term (e.g. hourly ramping) and intra-daily (e.g. peaking capacity) variations. At the same time, system operators need to maintain operating reserves in order to ensure that the system remains stable in the event of faults and the loss of generation.

While distributed PV combined with behind-the-meter batteries can address some of Ukraine's immediate energy and peaking capacity needs, their system-wide benefits will remain limited without a tariff structure that provides appropriate signals to consumers. Moreover, without a mechanism to enable controllability of demand-side assets (e.g. aggregator) these assets will be unable to provide towards essential system services.

Such measures are important for the long term. But Ukraine's immediate needs can be met by a portion of front-of-meter, utility-scale batteries which can provide a range of services, both at a local and system levels. These would still require appropriate amendments to market design and regulation, including the removal of price caps, enabling revenue stacking and ensuring coordination between transmission system operators (TSOs) and distribution system operators (DSOs) to provide both system-level and local services. These changes would help develop the business case for these resources.

The modelling results indicate that, by enabling the integration of utility-scale batteries in markets – even in a limited way (e.g. 1.5 GW) – Ukraine can gain much-needed system flexibility in the form of peaking capacity, hourly ramping, balancing and spinning reserves. This would allow for increased deployment of variable renewables, including solar PV and wind, which would supply bulk energy to the system reducing the operating cost of the system, while also allowing the faster scaling up DERs to meet the 2030 vision. Importantly, in such a system, a clear distinction emerges between the technologies that provide energy versus those providing critical system services. This underscores the importance of developing market mechanisms that appropriately value the distinct capabilities of technologies such as batteries and DERs in general, ensuring adequate revenue streams for their deployment.

Energy and service contributions of different technologies under different pathways to meet immediate system needs, 2021 vs. 2025

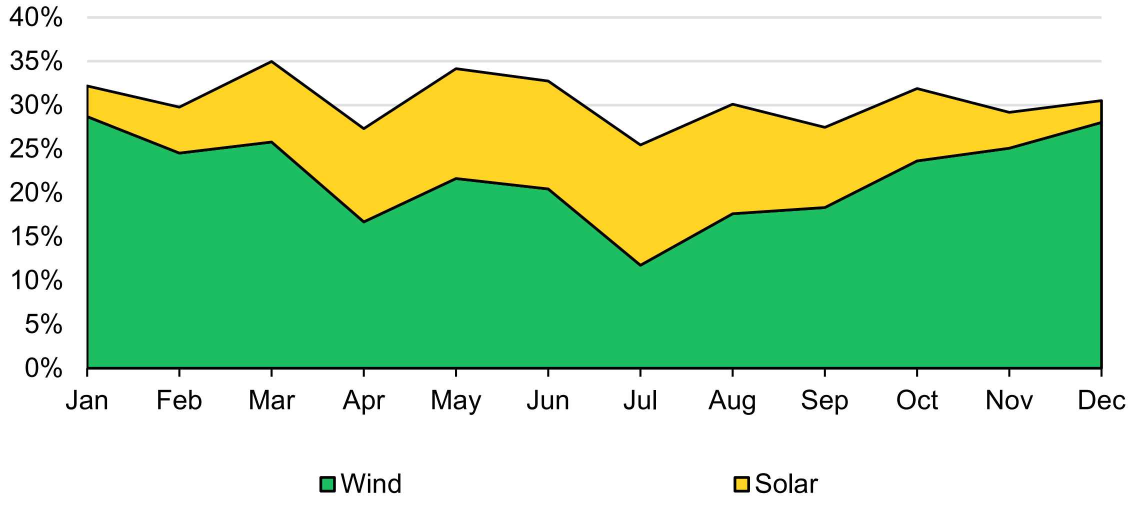


Notes: VRE = variable renewable energy. All DERs = distributed solar PV, a mix of gas engines and small modular turbines and behind-the-meter batteries. FOM = front-of-meter. BESS = battery energy storage system. For calculated contributions, spinning reserves is based on total annual contribution of different technologies to these reserve products. Ramping flexibility is calculated from the contribution to the top 100 hourly ramps. Peak capacity is based on the contribution to capacity needs in the top 100 periods of net demand in the modelled year, with variable renewable contribution based on the difference between net peak and peak load. Full system adequacy assessment requires further study, for example, based on a stochastic adequacy model accounting for interannual variability in demand and supply as well as generator and transmission outages. Energy is the share in annual generation. These measures aim to give an illustration of the diverse aspects of electricity security, but do not encompass all relevant components or potential technology contributions.

Removal of regulatory barriers can enable a diverse set of resources and enhance system security

While distributed solar PV and batteries represent two technologies that can be deployed quickly, have access to concessional financing and increase system resilience, their ability to contribute to winter demand means that gas-fired generation is necessary to ensure system adequacy during the winter peak. However, Ukraine also has a very good wind resource, and indeed, prior to their destruction or occupation by Russia, had almost 2 GW of wind generation. In general, wind and solar resources in Ukraine are complementary to one another, with Ukraine wind production higher during winter months and lower during summer months, thus the inverse of solar production.

Average monthly capacity factors of wind and solar PV in Ukraine based on model inputs



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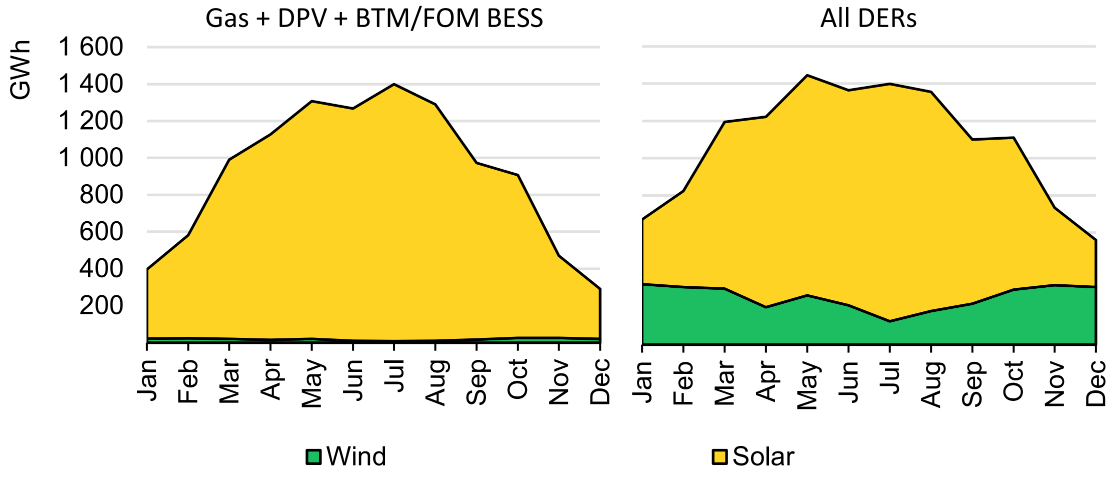
While the deployment time for wind is relatively slow (generally three years), the bulk of this time is spent on planning and regulatory approvals. Therefore, the All DERs Scenario tries to capture a sensitivity where wind projects already in the pipeline are able to be fast-tracked by relaxing some regulatory barriers. In such a scenario, average VRE production during the winter months of November–February increases by 60%, thus reinforcing the benefits of storage to meet winter peak demand. Meanwhile, average VRE production remains fairly similar in both scenarios. While financing for wind projects remains challenging during wartime, some innovative mechanisms are being developed to mitigate political risk, such as the Danish Export and Investment Fund's state guarantees for DTEK's 500 MW Tyligulska wind power plant.

Monthly wind and solar production in 2025 scenarios with and without the limited deployment of 1 GW of wind capacity



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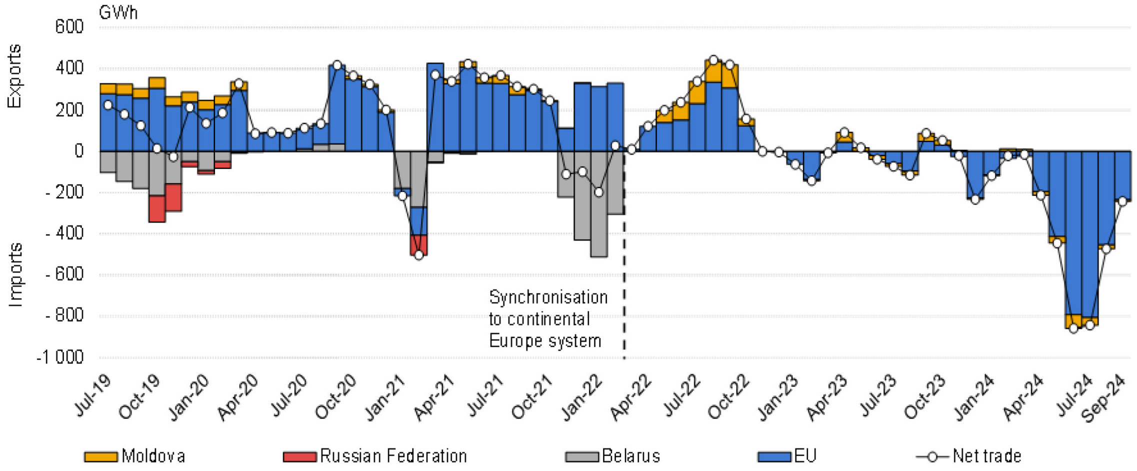
Enhancing trade with continental Europe serves both short-term needs and long-term ambitions

Closer integration with the continental European grid system is a key long-term objective for Ukraine, and it has proved vital to its operation since the onset of the full-scale invasion. Since March 2022, when Ukraine's power system was synchronously connected to the continental European network, this interconnection has provided critical import capacity, support the country during periods of high demand and during severe outages. Indeed, as attacks on and damage to generation capacity have intensified, access to imported power has become increasingly crucial.

Net monthly electricity trade for Ukraine

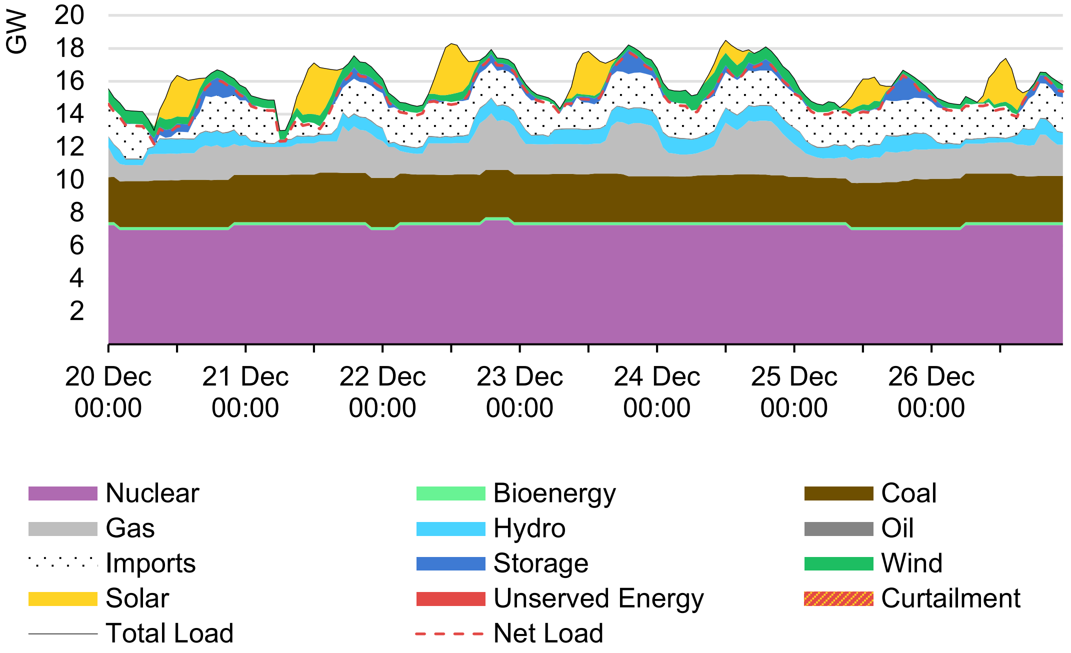


Source: IEA (2024), Ukraine's Energy Security and the Coming Winter.

The ability to increase imports from neighbouring systems can decrease the need for domestic thermal capacity. During periods of peak demand, imports can supply important peaking capacity and supply energy when renewable production is low. During periods of lower demand and higher renewables production, meanwhile, interconnectors can enable the export of the energy that the system cannot absorb (e.g. during midday solar peaks). Interconnectors can still be used for imports during daily peak demand periods. The inflexibility of Ukraine's nuclear and ageing coal fleet means that interconnectors play a crucial role in making the system more flexible to fluctuations and disruptions. The modelling shows that adding 500 MW of import capacity not only boosts system flexibility but also reduces the need for new gas-fired capacity by the same amount. In the longer term, as low-cost renewables scale up, increasing export capacity will become equally important, allowing Ukraine to position itself as a net exporter to Europe. This was already the case when Ukraine was a net exporter of electricity to continental Europe in the early days of synchronisation, before the targeted attacks on its power system began at the end of 2022.

Generation mix modelled for 2025, during peak and minimum net load periods with all DERs and an additional 500 MW of import capacity

Peak net demand



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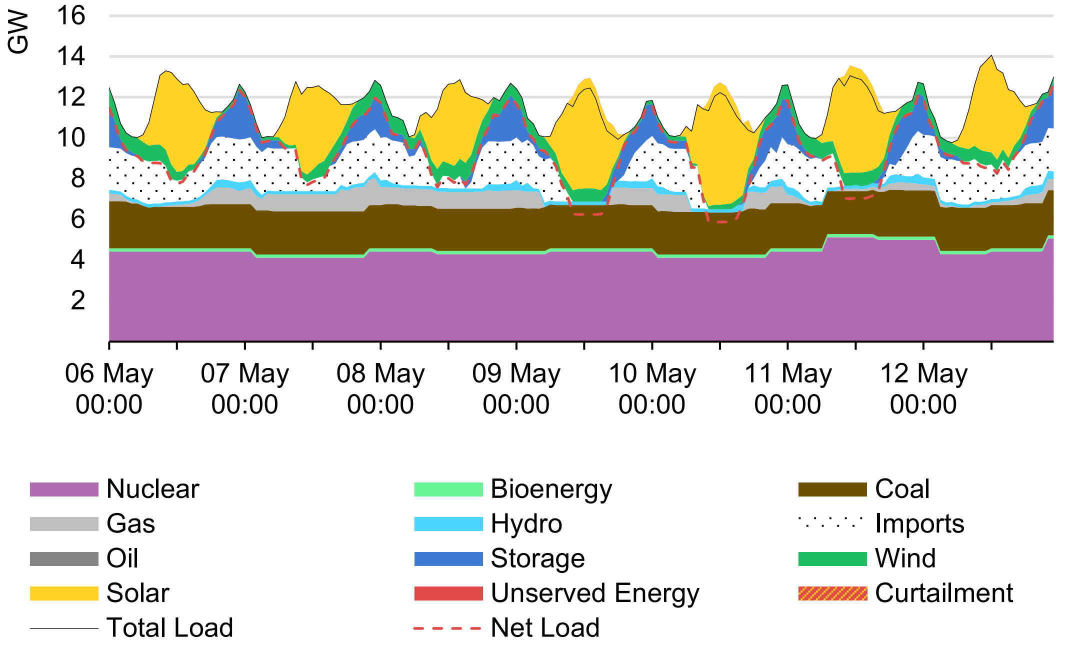
Minimum net demand



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Chapter 3. Charting a path to a secure, sustainable and decentralised future

The modelling results presented in Chapter 2 shows how distributed energy resources (DERs) can play a vital role in addressing Ukraine's immediate power system needs while supporting its longer-term objectives of decarbonisation and integration with the European Union (EU). With the right incentives and market framework, distributed solar photovoltaics (PV), batteries and wind generation could reduce the need for new gas-fired capacity by up to 3 GW while enhancing system resilience. However, to achieve these benefits, Ukraine must overcome several key challenges:

- Current market designs and regulations do not fully value DER services.
- Technical standards need updating. System operators lack adequate visibility and control over distributed assets.
- Existing financing mechanisms are not adapted to support smaller-scale projects.

The rapid deployment of DERs could help Ukraine avoid over-investment in fossil fuel infrastructure that risks becoming stranded as the country pursues its clean energy transition and progresses toward accession to the European Union. Yet the modelling also reveals that maximising the potential of DERs requires coordination on several fronts: implementing time-varying electricity prices that reflect system needs; enabling revenue stacking (i.e. leveraging multiple income streams) for storage assets; and strengthening coordination between transmission and distribution system operators. These findings underscore the importance of a comprehensive policy and regulatory framework to accelerate DER deployment while ensuring system security and affordability.

This chapter outlines seven key recommendations for Ukrainian policy makers and energy sector stakeholders to tackle these challenges and lay the groundwork for a modern, decentralised power system. They range from strategic planning recommendations to proposals for specific technical requirements, addressing both immediate actions to drive DER growth and longer-term reforms to fully integrate these resources into Ukraine's power system. By implementing these recommendations, Ukraine can address its immediate capacity needs while advancing toward a clean and resilient electricity system that aligns with its goal of closer integration with the European Union.

Seven key action areas for a more decentralised and modern power system in Ukraine

Action plan for a more decentralised and modern power system

- **Create** a vision of a decentralised system for Ukraine
- **Improve** the regulatory framework
- **Reform** electricity markets
- **Strengthen** capacity and coordination at the transmission and distribution level
- **Establish** clear technical standards and connection requirements
- **Enhance** asset visibility, predictability and control to ensure system security
- **Set** appropriate legislative foundations and financial instruments to scale up DER deployment

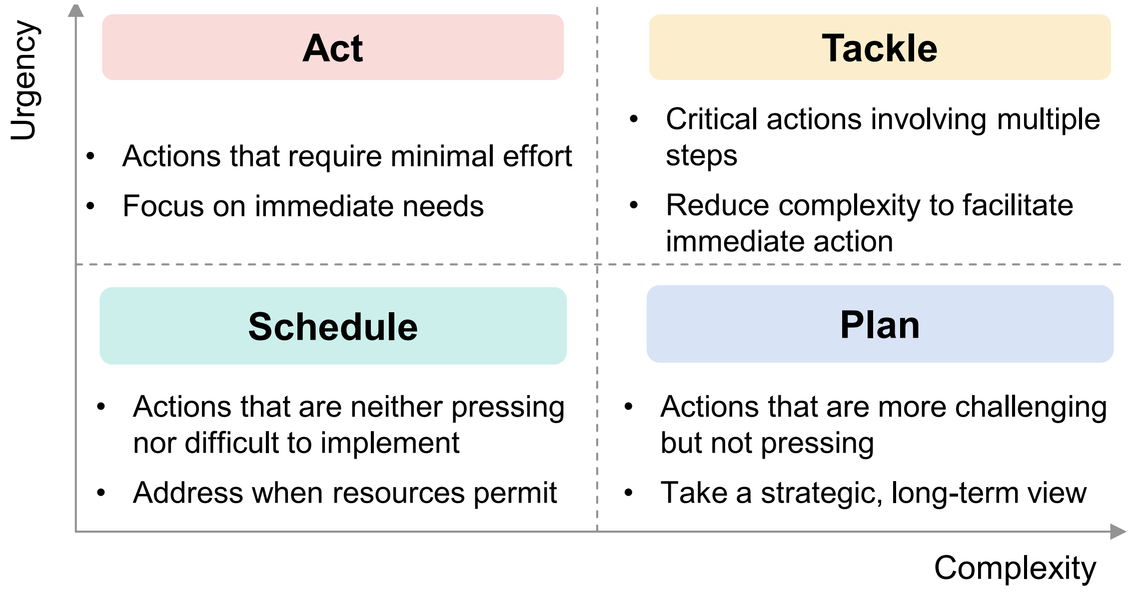
Framework for prioritising actions

To help prioritise the different actions and recommendations offered in this chapter, we rely on a qualitative framework to assess individual measures based on the following criteria:

- **Urgency:** The most critical actions are those that both lay the foundations for a more decentralised system and help address Ukraine's immediate system needs.
- **Complexity:** This considers factors such as the scope of the measures needed to implement recommendations and the extent to which certain measures are already in place, as well as any constraints that could limit their implementation.

Based on the classification across these two criteria, each main measure in the action plan can be assigned to one of four categories:

Prioritisation framework for implementation of the proposed actions



Act

- Actions that require minimal effort
- Focus on immediate needs

Tackle

- Critical actions involving multiple steps
- Reduce complexity to facilitate immediate action

Schedule

- Actions that are neither pressing nor difficult to implement
- Address when resources permit

Plan

- Actions that are more challenging but not pressing
- Take a strategic, long-term view

In the following action plan, each recommendation is assigned to one of these quadrants, as indicated by the colour of its bullet point. This reflects both its priority, and the level of action required from stakeholders.

Action plan for a more decentralised and modern power system

Create a vision of a decentralised system for Ukraine

● **Developing a holistic DER strategy, supported by detailed regulatory and legislative proposals, presents an opportunity for Ukraine to align its power system with future goals.** This framework would build long-term investor confidence and support sustainable energy deployment. A crucial first step for Ukraine is to thoroughly assess system needs and requirements. With this understanding, it can envision how DERs can support energy security and green transformation goals while maintaining affordability and equity. The recently published National Action Plan for Renewable Energy – which aims to increase Ukraine's targeted share of renewables in the electricity mix in 2030 to 27% – as well as the Strategy on the Development of a Distributed Energy System and the National Energy and Climate Plan (NECP) represent important steps. However, a more comprehensive approach is needed that ensures full alignment with and implementation of the Energy Community's Clean Energy Package as part of the path toward accession to the European Union.

● **Engaging all stakeholders and assigning clear roles and responsibilities is key.** This expansion requires a fundamental shift from centralised planning and operations toward distributed responsibilities across the electricity supply chain, affecting stakeholders at local, national and European levels. To implement this transition effectively, Ukrainian policymakers must update regulatory frameworks to establish appropriate incentives, while actively engaging citizens through clear communication about the benefits of decentralisation and their potential role in the new system, including measures to counter disinformation campaigns.

● **Resilience must be central to the vision of a modernised, decentralised power system**. While Ukraine has established a foundation of measures to mitigate physical (and other) risks to critical infrastructure facilities, through laws such as the Law on Critical Infrastructure and the National Cybersecurity Strategy (2021-2025), there is still a need to better define resilience, and ensure its explicit prioritisation in decision making and planning. Over the last year, passive defence measures have also been introduced for substations and other transmission infrastructure. As the deployment of DERs advances, resilience measures should be expanded to encompass grid codes and technical standards that ensure system security across all network levels.

○ **Scaling up supply chains and local manufacturing is essential to bridge the gap between Ukraine's immediate system needs and its long-term ambitions.** The rapid deployment of solar PV, batteries and other decentralised assets can help address Ukraine's immediate needs, but will require well-coordinated and functioning supply chains, and a skilled workforce. These DERs depend on diverse components including steel mountings, inverters and specialised materials, with many supply chains concentrated among few countries or companies, creating a risk of disruption. Additional expansion of manufacturing capacity will require diversification, while at the same time will demand strong regional cooperation to secure equipment supplies at the necessary scale, alongside streamlined cross-border import procedures to accelerate deployment.

○ **A just transition in the energy sector requires coordinated action among key stakeholders to upskill the work force for a modernised and decentralised system**. Ukraine's power sector modernisation demands rapid expansion of digital and technical capabilities, particularly in areas such as smart grid management, distributed energy systems and cybersecurity. The current workforce faces two critical challenges: insufficient size, with women particularly underrepresented in technical roles, and inadequate training in emerging fields. The adaptation to digital solutions during the invasion has highlighted both the potential and the skills gap in the energy sector workforce. To develop a skilled, adaptable workforce, a coordinated response across multiple stakeholders is required. Government institutions, such as the Ministry of Education, should consider developing comprehensive training programmes in digital technologies and cybersecurity, providing certifications to support international standards, with additional focus on educating women, while educational institutions can strengthen international partnerships to enhance curricula in these areas. Energy companies and system operators should consider launching internal upskilling programmes focused on smart grid management and storage solutions, while collaborating with educational partners to offer real-world training opportunities. This transformation can be supported by international donors through funding knowledge-sharing platforms and cross-border technology transfer partnerships, while local governments and community groups can promote awareness and training inclusivity in vulnerable regions.

Improve the regulatory framework

○ **Once the war in Ukraine ends, the regulator and government should consider a transition to cost-reflective and time-varying electricity prices.**

The current broad electricity subsidy scheme through the Public Service Obligation (PSO) mechanism, distorts market signals and hampers efficient grid operation, even as it provides crucial support during wartime. As conditions permit, the government should shift away from the broad PSO subsidy scheme towards cost-reflective and time-varying electricity prices, complemented by targeted income transfers, which can ensure affordability while introducing incentives for efficient and flexible grid operation. This transition requires establishing comprehensive smart metering infrastructure to enable dynamic tariffs, alongside clear communication strategies to help households understand and respond to price signals. Initial implementation could be piloted during summer months when system demand is lower, focusing first on regions with smart meter coverage and demonstrating the benefits of improved demand response to demonstrate political commitment to advancing DERs, decentralisation, and build investor confidence in the reformed electricity market.

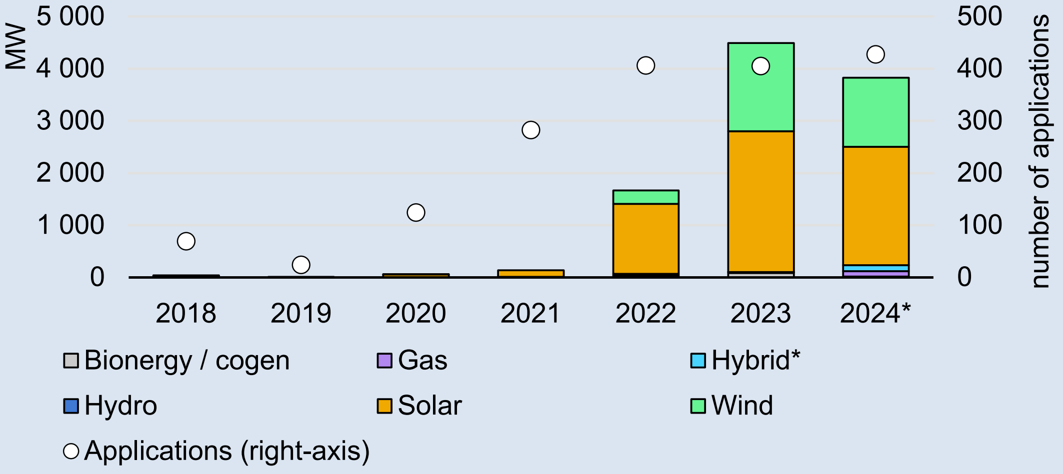
● **The government and regulator should consider addressing regulatory and administrative barriers that disproportionately affect the deployment of DERs.** While large-scale generation facilities are better equipped to navigate stringent licensing requirements and afford hefty connection fees, DER projects face disproportionate hurdles under the current regulatory framework. These barriers include onerous grid connection procedures requiring excessive documentation, a 20 MW limit on financial support, and protracted approval timelines. The government and regulator should consider simplifying the application process, standardising connection procedures, and providing fast-track approvals for smaller projects to alleviate these constraints. In addition, establishing renewable energy zones for quicker connection could complement these reforms. These reduced barriers would also ease the administrative burden of processing numerous applications, a frequent source of delays.

How regulatory changes spurred investment in distributed generation in South Africa

South Africa exemplifies how a supportive policy environment can open a pathway for rapid and large-scale deployment of distributed generation. In 2021, the South African regulator relaxed licensing requirements for private generation projects with a capacity between 1 MW and 100 MW. One year later, this was expanded to all private projects, regardless of capacity. What followed was a big jump in the number (applications) and scale (total capacity) of these projects – even in the absence of financial incentives such as a feed-in tariffs. This success stems from the price competitiveness and energy security advantages of DERs, with most projects intended for direct offtake.

A key takeaway for Ukraine is how South Africa used a registration system to monitor the development of these projects, thereby maintaining visibility over the response to regulatory changes. Although the risk of unregistered installations disrupting system operations remains, the approach has enabled regulators to track system needs as project rollouts and registrations progress. This demonstrates both the success of the regulation but also the possible need to adapt incentives for timely investment in flexibility, such as projects which are co-located with batteries and are able contribute to managing the system peak.

Registration of private generation facilities in South Africa, 2018-2024



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Notes: 2024* corresponds to data up until the end of November 2024. Hybrid = hybrid plants consisting of solar PV and batteries, or solar PV and gas.

Source: IEA analysis based on National Energy Regulator of South Africa (2024), Registered Generation Facilities (02/10/2024).

The incentive structure for the system operator should be revised to align with performance-based regulation. The current asset-based regulation model incentivises distribution system operators (DSOs) to prioritise capital-intensive and fossil fuel-based investments. This is unsustainable given DSOs' poor financial health and the scale of the rebuilding process, which is making financing for large grid projects very limited, while at the same time creating a barrier for DER deployment. Ukraine's National Energy and Utilities Regulatory Commission (NEURC) has taken initial steps through Resolution No. 2648 to provide financial relief to DSOs by remunerating grid connections put in place under martial law exemptions. Going forward, NEURC should consider moving to a performance-based regulation model that links utility revenue to a range of desired outcomes. This approach would make DERs, demand response programmes, grid-enhancing technologies and smart grids viable alternatives to traditional infrastructure expansion, while providing utilities with new revenue streams for improving system resilience through enhanced islanding capabilities and cybersecurity measures.

Reform electricity markets

🔴 **Removing market distortions and enhancing market granularity will open the door to a broader range of decentralised assets.** While Ukraine's day-ahead, intraday and balancing markets operate under high price caps, the ancillary services market requires reform to align its price caps with EU levels. Thanks to recent legislative changes, Ukrenergo can now sign long-term contracts with durations of more than one year for services in the ancillary market via long-term auctions. These measures will help cover investors' capital costs for building generating capacity or energy storage systems. Additional reforms should consider establishing new ancillary markets or market mechanisms that better reflect the value of flexibility and enable cost recovery for various asset types, including batteries and other distributed resources. To maximise market participation of DERs, technical requirements and procurement schemes should be tailored to accommodate different user categories and technology profiles, while allowing for smaller minimum bid sizes. This approach would help meet the growing system flexibility needs, while creating appropriate investment signals for a diverse range of grid-supporting assets.

🟢 **To improve the business model of DERs, regulator and system operators should improve access to electricity and ancillary markets, ensuring fair and equal participation for all players.** Currently, Ukraine's electricity markets are influenced by anti-competitive practices at the transmission system operator (TSO) level and, discriminatory tariff structures that affect market participation. While resources larger than 1 MW can access ancillary services markets, smaller-scale resources like DERs and batteries face barriers due to complex market structures and restrictive participation rules, preventing access to crucial revenue streams. To address these challenges, system operators should consider simplifying market structures and improving the harmonisation of their operations. Additionally, the regulator should consider establishing streamlined frameworks for aggregators and energy communities to ensure equal access to wholesale and ancillary markets, enabling them to better capture value from the increasing deployment of DERs and smart appliances across Ukraine.

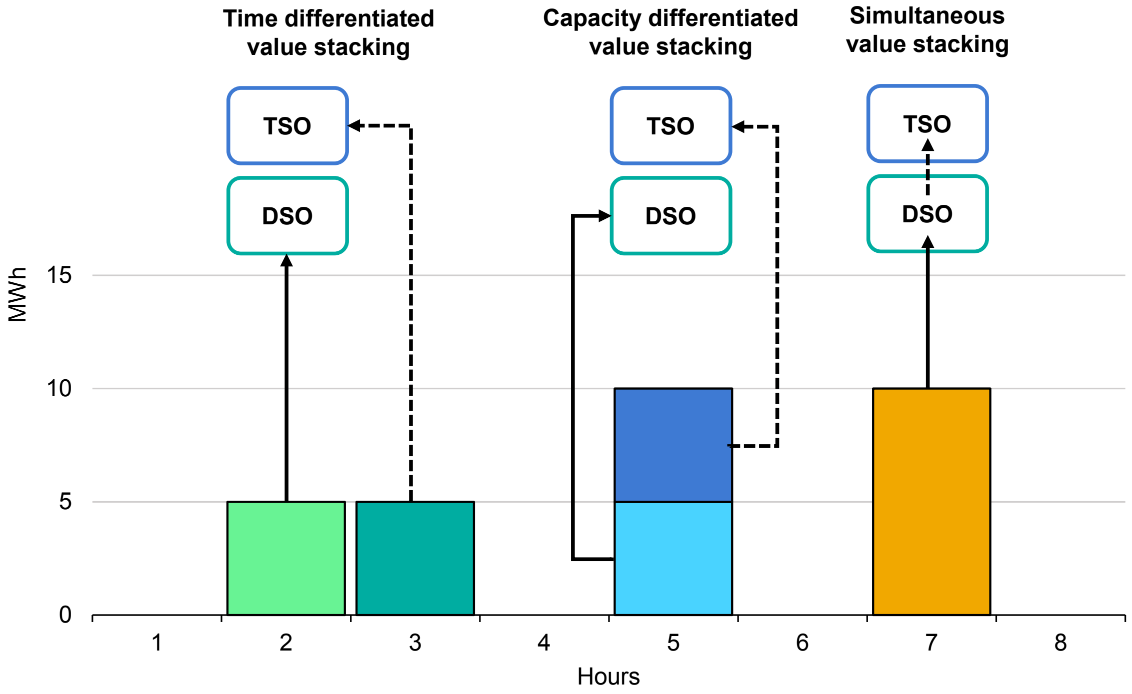
🟢 **Electricity markets should reflect decarbonisation policy and be compatible with the EU's Emission Trading Scheme (ETS).** Failure to include an adequate carbon price could have undesirable consequences for both the rebuilding and operation of the power system. It will also have cost implications, as energy-intensive goods will be required to reflect their embedded carbon emissions under the EU Carbon Border Adjustment Mechanism (CBAM) starting in 2026. This especially affects the iron and steel industry, as well as trade in electricity, aluminium, fertiliser and cement. Currently, Ukraine is seeking an exemption from the mechanism for 2025 due to the ongoing war. However, aligning with EU legislation will be crucial for Ukraine's economic recovery and competitiveness, as well as for its future strategy as an electricity exporter to the European Union.

○ **The regulator and market operator should improve the temporal granularity of electricity markets to better align the value of new resources with system requirements.** Ukraine's market design should be updated to properly value and reward the full range of benefits that new resources can offer. In electricity markets, "gate closure" refers to the point at which market participants submit their final offers for a specific period. In Ukraine, this occurs one hour ahead of the actual physical dispatch of the system. This means that the wholesale electricity market fails to properly account for the system's physical needs or value the resources that can meet them. Imbalances arising from supply and demand variability between gate closure and physical delivery must also be balanced by reserves, which are often costly. Shortening the time between gate closure and dispatch improves system efficiency and better values flexible resources. Additionally, reducing dispatch intervals to be shorter than one hour each can also help the system address variability more effectively. Aligning financial settlements with these shorter intervals for gate closure and dispatch ensures more accurate price signals. Flexibility markets could also evolve to combine long-term reserve capacity with near-real-time energy bids, improving system responsiveness.

○ **The regulator must reflect the locational value of resources in market design and network tariffs, to ensure resources are deployed where they are most needed.** Since DERs are connected to the grid edge and near demand centres, they can provide unique value to the system. This includes helping to relieve grid congestion and allowing for the deferral of investments in costly transmission and distribution infrastructure. In Ukraine, this can help regulators prioritise different grid repairs as well as reconstruction and modernisation projects in a way that best serves the system's immediate and long-term requirements. As an immediate measure, the regulator should factor prevailing conditions and grid requirements into network tariffs to better incentivise deployment of DERs where they can most effectively serve network needs. In the longer term, the regulator and market operators should design and implement zonal or nodal pricing in Ukraine to better reflect the network's locational needs.

○ **Regulator, system operators and market operators must ensure market design rules enable DERs and batteries to maximise their value across multiple applications, providing a broad array of services at both local and system levels**. However, the regulator must ensure that these and other versatile, distribution-connected resources (e.g. batteries) can deliver their full range of value by supporting multiple uses and revenue opportunities (i.e. "value stacking"). This can strengthen the business case for these resources while enabling more cost-efficient and affordable system services. Various stacking options exist, each offering distinct benefits to the system, along with challenges related to rules and implementation. For example, a system operator may restrict a resource that provides reserves from using that capacity for other services due to technical constraints. However, the regulator needs to establish rules that allow resources to stack multiple values – whether time-based, capacity-based or simultaneously – depending on the service, the resource characteristics and location.

Examples of "value stacking" to maximise usage and revenue



Source: IEA (2022), Unlocking the Potential of Distributed Energy Resources.

Strengthen capacity and coordination at the transmission and distribution level

Ukrainian energy sector stakeholders must shift from traditional supply-side planning to an integrated, coordinated approach. This will engage a broader range of stakeholders, including those outside the power sector such as heating and transport as well as supply chains, industry and telecommunications. The Transmission Development Plan for 2021-2030, produced by Ukrenergo, goes some way toward establishing a process for addressing transmission needs, recognising the differing lead times for transmission infrastructure and generation. As the share of DERs grows, however, planning processes will need to give more consideration to the needs of the distribution network, including low-voltage networks. This includes incorporating feedback from DER deployment in response to incentives to ensure the coordinated rollout of these resources and their associated infrastructure. Consumer engagement, either through municipal or community bodies, would further support this process. Investment decisions should align with Ukraine's long-term ambitions, including enhanced interconnection capacity with the system of continental Europe, grid modernisation and the strengthening of the west-to-east backbone to support supply and demand redistribution.

🔵 **Given the increasingly decentralised nature of the power system, it is essential that TSOs and DSOs coordinate their operations.** As more variable resources are connected to the distribution network, distribution system operators are poised to play a more prominent role in system operations. This evolution requires a clear framework for TSO-DSO coordination, particularly regarding the procurement of system services such as congestion management and reserves. For Ukraine's power system, two coordination approaches should be considered: a decentralised approach, where DSOs manage local markets independently before escalating to the transmission level, and a centralised approach that integrates TSO and DSO operations into a single market. Given the weakness of the distribution network – especially the low-voltage grid – a decentralised approach would be a natural starting point to ensure that DERs improve supply quality and reliability. Policy makers and the regulator should work with utilities to test whether a centralised approach – integrating TSOs and DSOs into a single market to coordinate services – can deliver greater system benefits. This would also support the alignment with the EU's Clean Energy Package (CEP), however, it will require closer coordination among system operators to allow for joint procurement of transmission and distribution services (e.g. congestion management) at distribution level, while also providing system services (e.g. peaking capacity or reserves) at the transmission level.

🟢 **Policy makers and regulator must take steps to redefine the roles and responsibilities of DSOs**. As the share of DERs and other distribution-connected resources grows, DSOs will need to adopt a broader role and coordinate a large part of the energy system. New responsibilities include acting as a neutral market facilitator to support local markets, bolstering their capacity for hosting new energy sources, and collaborating with TSOs to ensure reliability. Perhaps the most crucial new responsibility for DSOs will be procuring flexibility services to effectively manage congestion and voltage issues. Pilot projects from the Energy Community have attempted to demonstrate how DSOs can operate and pay for these services. There will also be a need for capacity building to ensure DSOs have the appropriate skills and resources to perform in their new role.

Establish clear technical standards and connection requirements

🟢 **Ukraine's transmission code should be amended to enable accurate forecasting of DERs, providing better information to system operators.** As DER integration progresses, maintaining system stability, reliability and quality of supply will become more challenging, requiring system operators to adopt robust strategies for managing the system. Ukraine's transmission grid code already requires DSOs to provide day-ahead forecasting for both demand and grid-connected distributed generation. As DER penetration increases – especially from variable renewables – there will be a need for more accurate representation of these resources, including real-time forecasts and more accurate forecasting models. This is especially true for behind-the-meter (BTM) resources, which are typically bundled into demand forecasts and therefore their do not account for weather dynamics such as cloud cover. In California, for example – where more than 15 GW of distributed solar PV was installed by 2024 – the system operator provides forecasts up to five minutes ahead of real time. These forecasts incorporate various inputs, including weather forecasts and actual inverter outputs, to predict BTM resources.

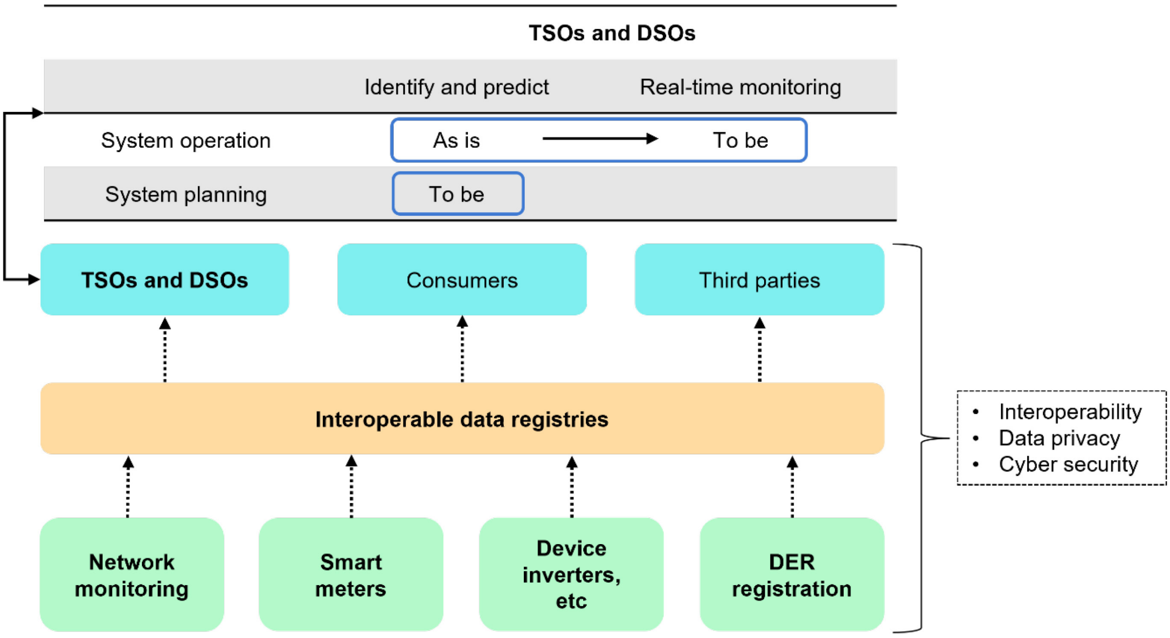
🔴 **The distribution grid code should require DERs to meet minimum technical performance standards to ensure the quality and reliability of supply**. This includes capabilities such as voltage and frequency ride-through, which ensures that DERs stay connected during minor disturbances, preventing large-scale disconnections that could increase system risk. One example of this approach took place in Australia, after a weather event in 2016 caused widespread blackouts across South Australia. Efforts to reduce load inadvertently triggered the disconnection of unmonitored distributed solar PV systems, complicating the system response and delaying service restoration. The Australian market operator subsequently updated its technical standards to ensure that new installations of DERs would continue to operate and contribute to the system during faults. In Ukraine, the low-voltage grid was not originally designed to manage significant distributed generation, and many solar installations have grid-tied inverters. As a result, a framework is needed for ensuring compliance with technical performance standards. To address this, the regulator – in coordination with Ukrenergo and DSOs – should identify minimum technical performance standards for the distribution grid. This will help ensure system security as DER penetration increases. Meanwhile, both DSOs and Ukrenergo should assess the performance of legacy installations to better understand the potential risks they pose to the system. The regulator can also work with the European Network of Transmission System Operators for Electricity (ENTSO-E) and the Agency for the Cooperation of Energy Regulators (ACER) to align the grid codes with European regulations.

🔴 **System operators and the regulator should work with Ukraine's standards body to establish technical standards for original equipment manufacturers (OEMs), ensuring compliance with grid codes and minimum requirements.** Such standards are crucial for demand-side resources, particularly those unmonitored by system operators, to respond predictably during grid events like faults or large-scale generation outages. They are also critical for ensuring the interoperability of different devices with modern metering infrastructure and that they communicate using compatible protocols. International bodies, such as the Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC) have developed standards for the performance of inverters, smart meters, distributed energy resource management systems (DERMS) and other related equipment. A framework for ensuring compliance of equipment with technical performance standards would also be beneficial. Ukrainian regulators and standards bodies should work with bodies such as European Standards to facilitate integration with the European power system.

Enhance asset visibility, predictability and control to ensure system security

🟡 **As they transition to a more decentralised system, power sector stakeholders must collaborate to identify data gaps and develop a plan to address them systematically.** Data is the backbone of decision making for both system planning and system operations. Depending on its purpose, the data itself has specific requirements, including factors such as timeframe and granularity. These can involve actual measurements (e.g. network monitoring) as well as short-term (e.g. renewables production) or long-term forecasts (e.g. system planning). As the share of DERs grows in the Ukrainian power system, there will be a need to identifying data gaps will become essential, particularly for the distribution network. Special attention should be given to the low-voltage (LV) network, which will host a significant share of this capacity. This can be assessed either through identification and prediction, or through real-time monitoring, as shown in the figure below. Ukrainian power sector stakeholders will need to develop a tailored approach for addressing data gaps, considering factors such as complexity and deployment speed. In the short term, DSOs may be able to use predictive models to help monitor the low-voltage grid. In the long-term, however, real-time monitoring and automation may be necessary.

Data gaps in low-voltage grid and DER operation, and a model for data management



Source: IEA (2022), Unlocking the Potential of Distributed Energy Resources

○ **Power sector stakeholders should work together to identify and address cybersecurity risks while ensuring robust data privacy protection measures.** As the share of DERs grows within the power system, so will its digital footprint, increasing vulnerability to malicious attacks. These risks can range from disruptions to power system operation to the theft of consumer data. System data needs to be protected at source, in transit and at its destination. Ukraine must align its cybersecurity protocols with EU standards and develop risk management strategies for key stakeholders. Meanwhile the regulator should ensure that DSOs, TSOs, market operators and market participants, develop a comprehensive plan to identify and mitigate against potential cyber risks. This should extend to the technical standards for original equipment manufacturers (OEMs) of consumer-side equipment, including smart meters and inverters, to ensure that DERs and their supporting infrastructure are secure.

○ **The rollout of advanced metering infrastructure (AMI) should be prioritised, and the government should offer incentives to households and businesses to optimise energy use.** Broad adoption of technologies like energy management systems should be a key goal for Ukraine in the medium- to long-term, since they could add significant flexibility. Currently, adoption remains low: only 12% of Ukrainian households were equipped with smart meters before the large-scale invasion. Broader deployment of smart meters and appliances (which can optimise usage according to time-of-use or dynamic tariffs) will require strong policy support and incentives from both central and regional governments.

🟢 **System operators should be encouraged to make targeted investments in monitoring equipment to ensure the safe operation of an increasingly decentralised system.** While large-scale adoption of DERs requires real-time monitoring, system operators can already forecast network conditions with high accuracy using minimal data. The key is to identify the optimal combination of available data, analytical tools, interoperability standards and new investments to ensure adequate visibility while maximising cost efficiency. The first step is to establish a resource registry to ensure visibility of DERs and other flexibility services across the grid. Regulators should then guide system operators in assessing the cost-benefit of additional monitoring equipment. This would allow them to make targeted investments to achieve a minimum level of visibility. Certain European countries already have plans to rollout monitoring equipment at scale: Finland, for example, has started requiring DSOs to install smart meters.

🔵 **System operators and the regulator need to work together to better manage and control DER assets.** In the short term, this should focus on identifying the minimum level of controllability, which can be achieved through basic inverter functions. Curtailment and supply restrictions can effectively manage DERs during periods of excess generation or grid congestion. However, as these measures may conflict with market dynamics, they should be defined in grid codes and reserved strictly for emergency use to avoid undermining incentives for deployment. In the longer term, DER controllability should expand to enable these resources to more fully support the system, maximising their value while unlocking system benefits and incentives. Achieving this will require Ukrainian stakeholders to develop and implement various aggregator models, including virtual power plants (VPPs). VPPs allow aggregated "portfolios" of DERs to function like traditional power plants, providing capabilities such as ramping power up or down as well as maintaining defined capacity limits. VPPs can actively manage and dispatch DERs to deliver electricity or ancillary services, making grid management more efficient and increasing system visibility. Introducing time-varying tariffs and accessible market structures will be essential for enabling VPPs to respond to real-time system needs, optimise DER utilisation and deliver valuable services to the grid system as well as consumers.

🔵 **To prepare Ukraine's grid for a DER-based system, system operators should focus on modernising infrastructure and implementing smart grid solutions**. Given the tight market for transmission equipment, system operators should develop a long-term plan to replace outdated Soviet-era equipment like autotransformers. As many legacy components are difficult to replace and vulnerable to Russian attacks, upgrading them would enhance the grid's resilience. Associated grid equipment such as protection relays should also be upgraded to conform to International Electrotechnical Commission (IEC) standards to ensure interoperability with the continental European system during normal, fault and post-fault conditions. Meanwhile, smart grid solutions (e.g. advanced forecasting methods and digital twins) can optimise grid operations by identifying real-time constraints and improving coordination with generators.

Set appropriate legislative foundations and financial instruments to to scale up DER deployment

🟢 **Blending public, donor and private funds can help reduce the high cost of capital in Ukraine's energy sector.** Exorbitant capital costs are driven by a combination of factors, including war risk, macroeconomic instability and the inherent weaknesses in the architecture of Ukraine's power system infrastructure. Developers are facing significant challenges in securing financing due to rising interest rates, while a lack of innovative war risk insurance products compounds the problem. These factors create an extremely difficult investment environment, hindering the recovery and modernisation of Ukraine's power sector.

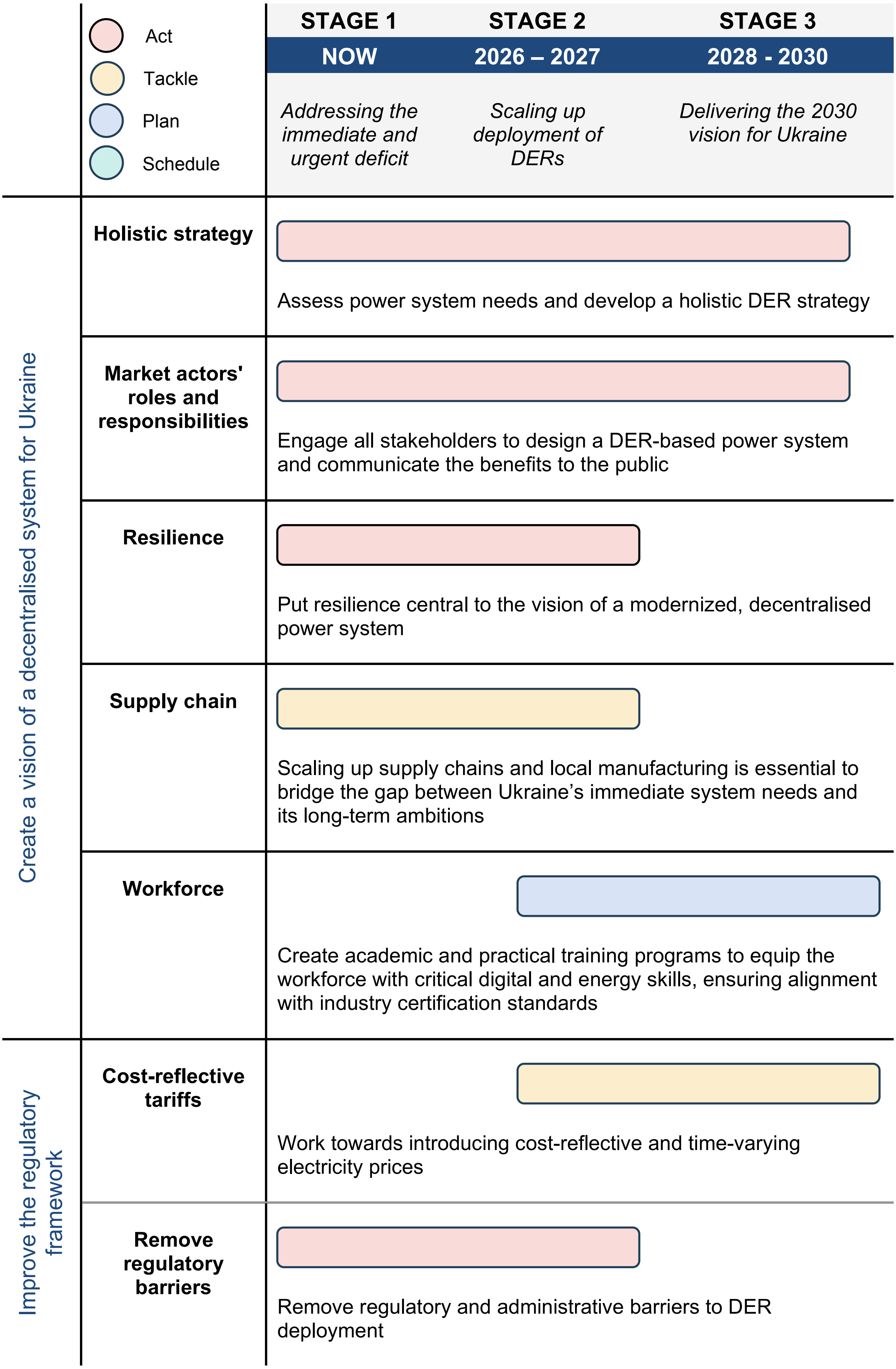
🟢 **To safeguard Ukraine against a reduction of foreign aid once the war ends, and to prepare for the large-scale integration of DERs, the legislative and regulatory frameworks for private sector investment must be established now.** This proactive approach is essential because DER deployment requires a different regulatory framework and investment model compared to the construction of large-scale power plants. A variety of financial mechanisms, ranging from public private partnerships (PPPs), concessional loans, loan guarantees, and war risk insurance can support this effort. Small-scale local DER installations would be good candidates for limited concessional loans, for example. These measures should be paired with a strong regulatory and legislative framework to ensure their effectiveness. The reliability and credibility of the offtake system, as well as the off-takers themselves, can be enhanced through risk-sharing facilities (e.g. loan guarantees) backed by international partners and/or the government. Political risk can be mitigated through international mechanisms that protect against physical losses, business interruption or transfer restrictions. For example, Germany provides war risk insurance, while export credit agencies such as the Danish Export and Investment Fund and the US International Development Finance Corporation also offer protection. Deploying DERs requires different investment strategies compared to large-scale generation projects, which are often more easily financed with local or national sources of capital. As a result, Ukrainian citizens, both domestically and abroad, can play a role in supporting the large-scale rollout of DERs.

🔵 **An enabling environment is needed that provides municipalities with access to financial support and capacity-building programmes.** Local communities play a central role in both Ukraine's recovery and its green energy transition. However, these communities often struggle due to the need for upfront investments for DERs, insufficient local budgets and a lack of human resources. To expedite grant implementation, international financial institutions (IFIs) could collaborate directly with local banks for capacity building, rather than relying solely on national ministries. Adequate technical assistance for local entities is a necessity, as they are best placed to work with communities. However, they often have limited exposure to IFIs and may therefore struggle to meet key funding requirements, such as environmental and societal standards.

A roadmap towards Ukraine's 2030 vision

This section provides a roadmap for Ukraine to work towards its vision of a more decentralised and modern power system. The roadmap is split into three stages: immediate (< 1 year), short- (1-2 years) and medium-term (2-5 years). Within each timeframe, the suggested measures work to achieve the following objectives:

- **Stage 1 (Now):** Tackling Ukraine's urgent power deficit through rapid interventions and critical system improvements.
- **Stage 2 (2026-2027):** Scaling up the deployment of DERs.
- **Stage 3 (2028-2030):** Delivering the 2030 vision for Ukraine.



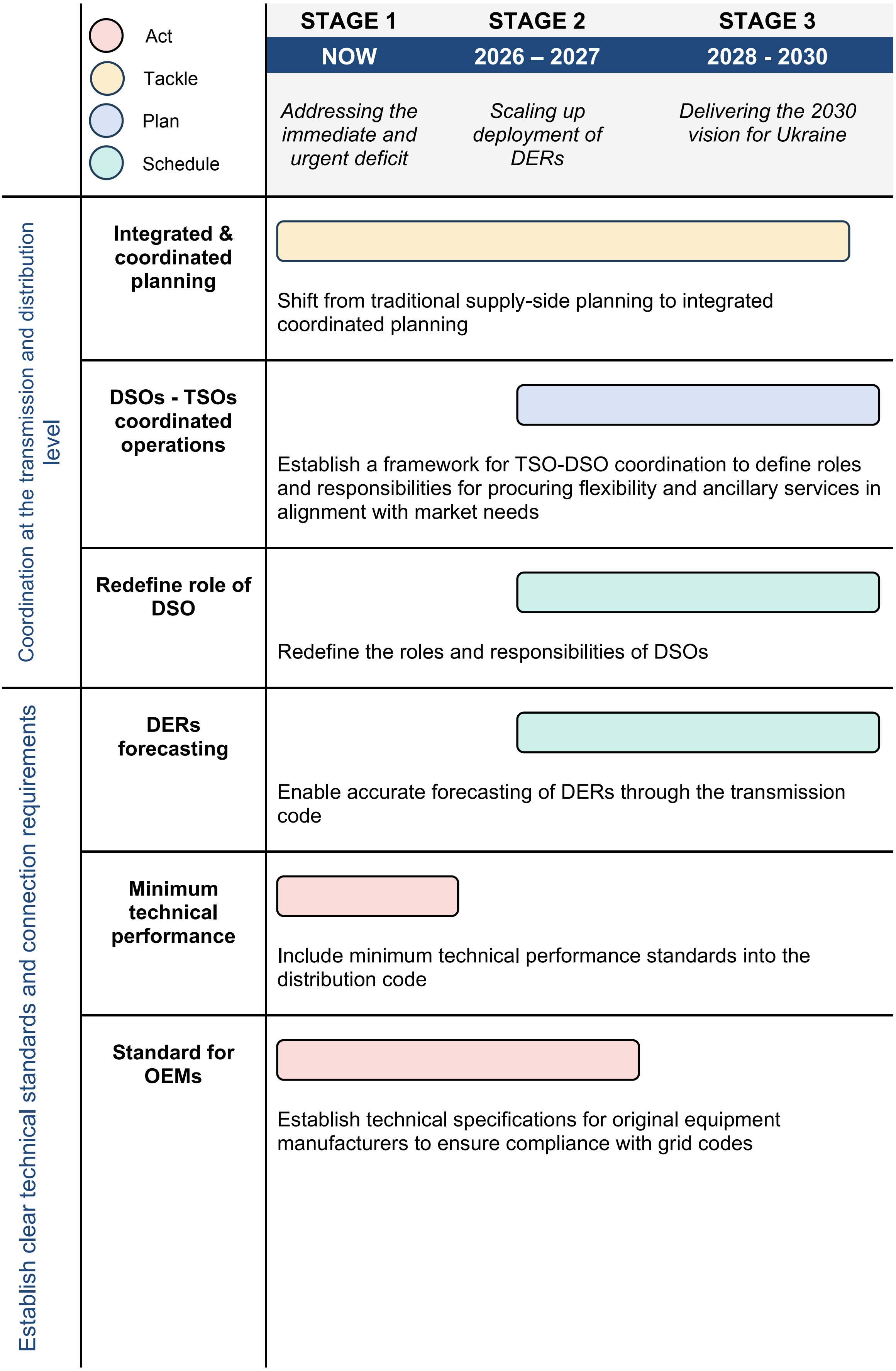
🟥 Act
🟨 Tackle
🟦 Plan
🟩 Schedule

		STAGE 1 NOW *Addressing the immediate and urgent deficit*	STAGE 2 2026 – 2027 *Scaling up deployment of DERs*	STAGE 3 2028 - 2030 *Delivering the 2030 vision for Ukraine*
Create a vision of a decentralised system for Ukraine	**Holistic strategy**	🟥	🟥	🟥
		Assess power system needs and develop a holistic DER strategy		
	Market actors' roles and responsibilities	🟥	🟥	🟥
		Engage all stakeholders to design a DER-based power system and communicate the benefits to the public		
	Resilience	🟥	🟥	
		Put resilience central to the vision of a modernized, decentralised power system		
	Supply chain	🟨	🟨	
		Scaling up supply chains and local manufacturing is essential to bridge the gap between Ukraine's immediate system needs and its long-term ambitions		
	Workforce		🟦	🟦
		Create academic and practical training programs to equip the workforce with critical digital and energy skills, ensuring alignment with industry certification standards		
Improve the regulatory framework	**Cost-reflective tariffs**		🟨	🟨
		Work towards introducing cost-reflective and time-varying electricity prices		
	Remove regulatory barriers	🟥	🟥	
		Remove regulatory and administrative barriers to DER deployment		

🟥 Act
🟨 Tackle
🟦 Plan
🟩 Schedule

Reform electricity markets

	STAGE 1	STAGE 2	STAGE 3	
	NOW	**2026 – 2027**	**2028 - 2030**	
	Addressing the immediate and urgent deficit	*Scaling up deployment of DERs*	*Delivering the 2030 vision for Ukraine*	
Performance-based incentives		🟦		Put in place performance-based regulation for system operators
Remove market distortions	🟥			Eliminate market distortions, such as price caps, and improve market granularity
DERs non-discriminatory participation		🟩	🟩	Ensure fair and equal access to electricity and ancillary markets for DERs
Carbon pricing		🟩	🟩	Integrate a robust carbon pricing mechanism into electricity markets to align with the EU's Emission Trading Scheme
Increased markets temporal granularity		🟦		Improve the temporal granularity of the electricity market and financial settlements
Increased markets locational granularity			🟦	Reflect the locational value of resources in network tariffs, while working towards zonal or nodal pricing
Revenue stacking			🟦	Explore various value stacking options and institute rules that allow resources to stack multiple values



STAGE 1	STAGE 2	STAGE 3
NOW	**2026 – 2027**	**2028 - 2030**
Addressing the immediate and urgent deficit	*Scaling up deployment of DERs*	*Delivering the 2030 vision for Ukraine*

Coordination at the transmission and distribution level

Integrated & coordinated planning

Shift from traditional supply-side planning to integrated coordinated planning

DSOs - TSOs coordinated operations

Establish a framework for TSO-DSO coordination to define roles and responsibilities for procuring flexibility and ancillary services in alignment with market needs

Redefine role of DSO

Redefine the roles and responsibilities of DSOs

Establish clear technical standards and connection requirements

DERs forecasting

Enable accurate forecasting of DERs through the transmission code

Minimum technical performance

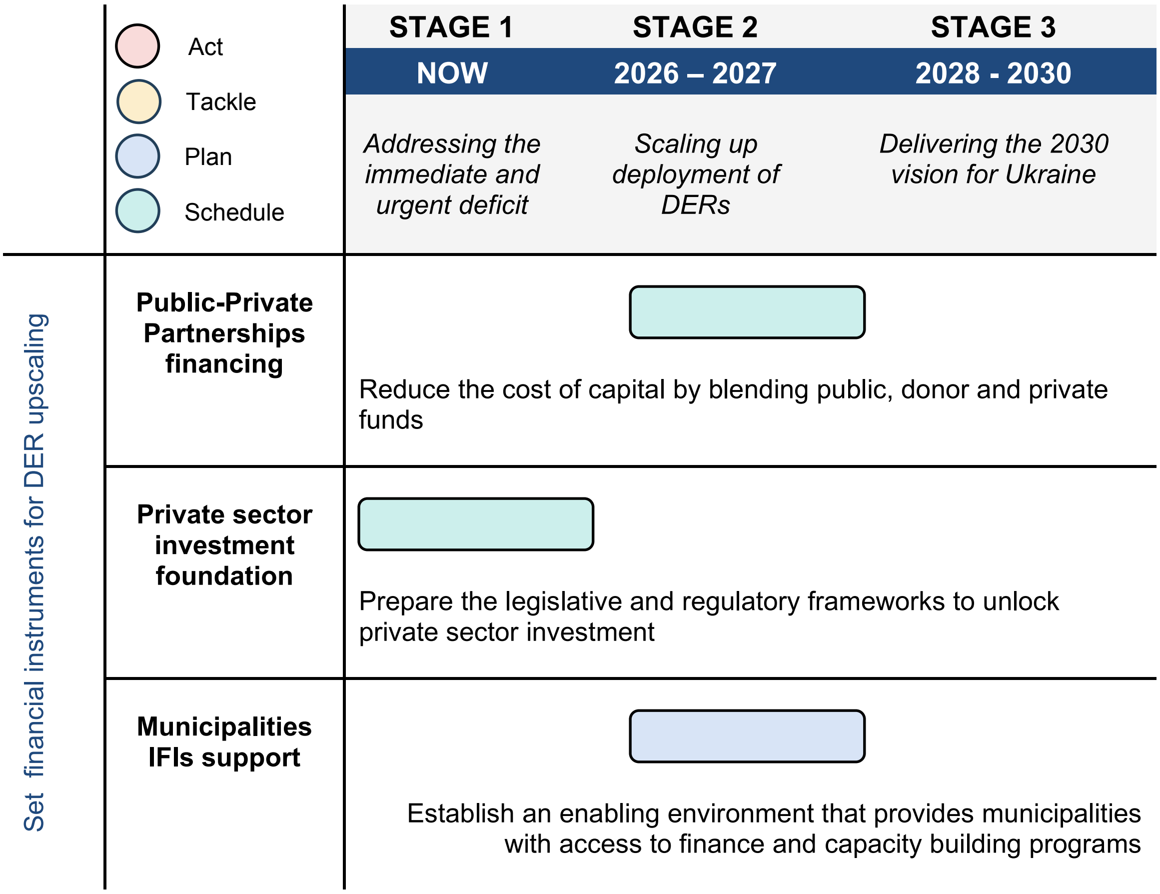
Include minimum technical performance standards into the distribution code

Standard for OEMs

Establish technical specifications for original equipment manufacturers to ensure compliance with grid codes

🟥 Act
🟨 Tackle
🟦 Plan
🟩 Schedule

		STAGE 1 NOW *Addressing the immediate and urgent deficit*	STAGE 2 2026 – 2027 *Scaling up deployment of DERs*	STAGE 3 2028 - 2030 *Delivering the 2030 vision for Ukraine*
Enhance asset visibility, predictability and control to ensure system security	**Address data gaps**	🟨	🟨	
		Identify data gaps to operate a decentralised power system and develop a plan to address them		
	Cybersecurity and data protection	🟨	🟨	🟨
		Identify and address cybersecurity risks and implement data privacy protection measures		
	AMI rollout		🟩	🟩
		Prioritise the rollout of advanced metering infrastructure and provide incentives for households and businesses to optimise their energy use		
	LV network monitoring		🟩	🟩
		Establish a resource registry and encourage targeted investments in monitoring equipment to ensure comprehensive visibility of DERs		
	Controllability			🟦
		System operators and regulators need to work together to better manage and control DER assets		
	Upgrading grid equipment		🟦	🟦
		Modernise grid infrastructure and implement smart grid solutions		



Addressing the immediate and urgent deficit

Scaling up deployment of DERs

Delivering the 2030 vision for Ukraine

Reduce the cost of capital by blending public, donor and private funds

Prepare the legislative and regulatory frameworks to unlock private sector investment

Establish an enabling environment that provides municipalities with access to finance and capacity building programs

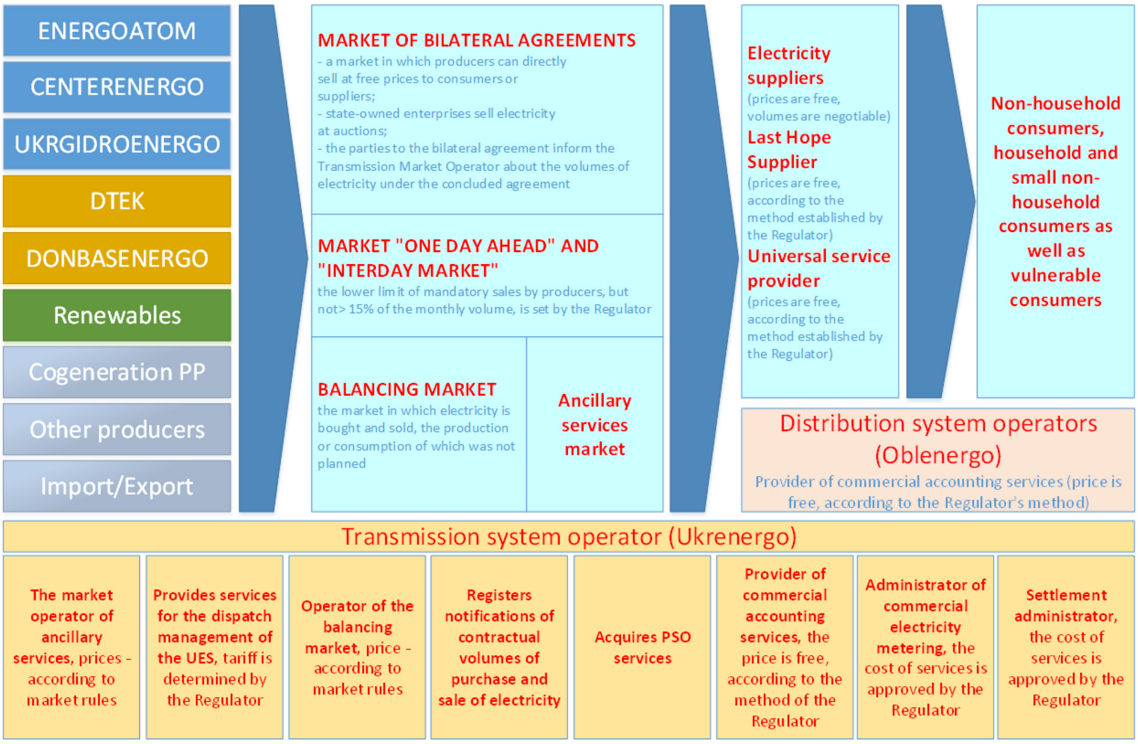
Annexes

Overview of Ukraine's power sector

Ukraine's electricity sector was largely unbundled and partly privatised in the 1990s, after the dissolution of the Soviet Union. About 70% of generation capacity remains state-owned (mainly hydroelectric and nuclear, with a few thermal and combined heat power plants). Most thermal power plants have been partially or fully privatised, and the private company DTEK controls the bulk of capacity as well as marginal production on the wholesale market. Most renewable capacity is also privately owned.

Ukraine's electricity sector is separated into distinct segments: generation, wholesale and retail markets and transmission system operations – as well as distribution and retail operations which are bundled together. The largest electricity generating companies are Centrenergo, DTEK, Dniproenergo, Donbasenergo, DTEK Zakhidenergo and DTEK Skhidenergo (thermal plants); Ukrhydroenergo (hydropower); and Energoatom (nuclear). There are also several companies that produce electricity from renewable resources. Ukrenergo, Ukraine's fully state-owned national power company, serves as the country's transmission system operator (TSO). Ukrenergo oversees the operation and technology of the Integrated Power System (IPS) and manages the transmission of electricity between generation and distribution networks. It is also the commercial metering administrator and responsible for Ukraine's power system in parallel with those of neighbouring countries.

Governance of Ukraine's power sector



ENERGOATOM
CENTERENERGO
UKRGIDROENERGO
DTEK
DONBASENERGO
Renewables
Cogeneration PP
Other producers
Import/Export

MARKET OF BILATERAL AGREEMENTS
- a market in which producers can directly sell at free prices to consumers or suppliers;
- state-owned enterprises sell electricity at auctions;
- the parties to the bilateral agreement inform the Transmission Market Operator about the volumes of electricity under the concluded agreement

MARKET "ONE DAY AHEAD" AND "INTERDAY MARKET"
the lower limit of mandatory sales by producers, but not> 15% of the monthly volume, is set by the Regulator

BALANCING MARKET
the market in which electricity is bought and sold, the production or consumption of which was not planned

Ancillary services market

Electricity suppliers
(prices are free, volumes are negotiable)
Last Hope Supplier
(prices are free, according to the method established by the Regulator)
Universal service provider
(prices are free, according to the method established by the Regulator)

Non-household consumers, household and small non-household consumers as well as vulnerable consumers

Distribution system operators (Oblenergo)
Provider of commercial accounting services (price is free, according to the Regulator's method)

Transmission system operator (Ukrenergo)

The market operator of ancillary services, prices - according to market rules

Provides services for the dispatch management of the UES, tariff is determined by the Regulator

Operator of the balancing market, price - according to market rules

Registers notifications of contractual volumes of purchase and sale of electricity

Acquires PSO services

Provider of commercial accounting services, the price is free, according to the method of the Regulator

Administrator of commercial electricity metering, the cost of services is approved by the Regulator

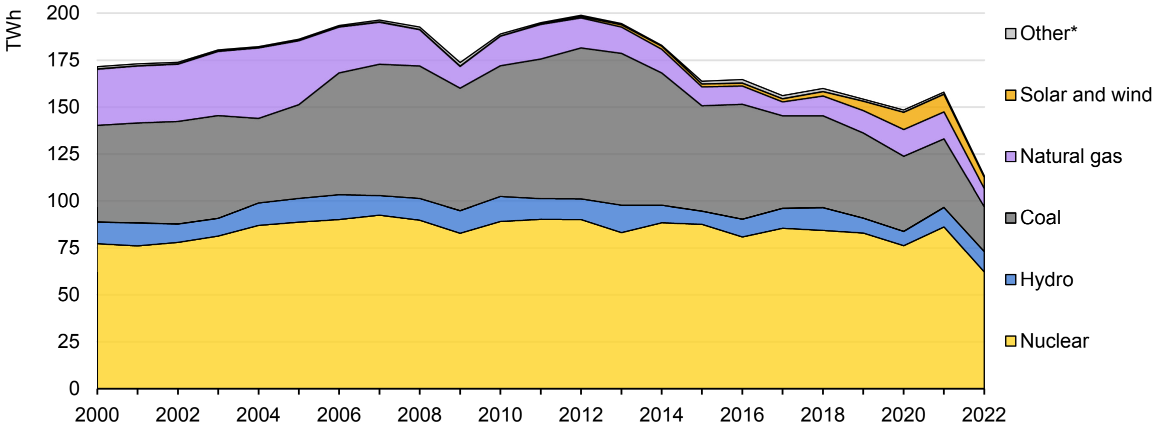
Settlement administrator, the cost of services is approved by the Regulator

Notes: PP = power producer; UES = United Energy System of Ukraine; PSO = public service obligation.

Electricity mix

Before Russia's full-scale invasion, Ukraine was heavily reliant on nuclear power for electricity generation (51% of capacity) and fossil-fuelled power plants, primarily by coal and natural gas. Renewable energy accounted for 11% of the electricity mix, with hydropower representing the largest share (6.5%) followed by solar (4.2%) and wind (2%).

Electricity generation in Ukraine by source prior to the full-scale invasion, 2000-2022

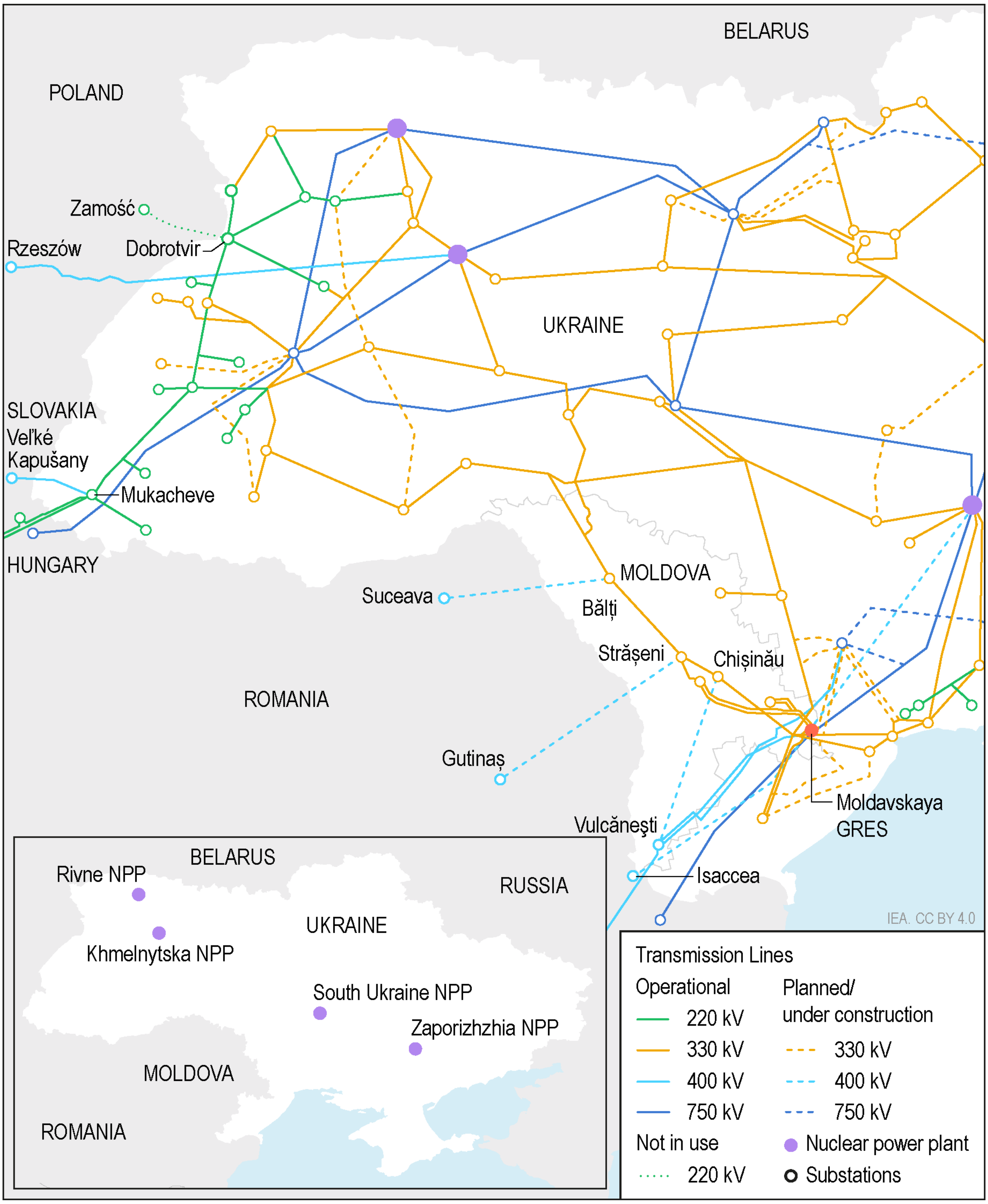


* Includes oil products, bioenergy, waste heat and industrial waste.
Source: IEA (2022), World Energy Statistics and Balances (database).

Electricity transmission and trade

Ukraine's high-voltage power transmission network, a legacy of the Soviet era, includes a 750 kV high-voltage backbone designed for large-scale supply or heavy industrial demand. Prior to the full-scale invasion, Ukraine (along with Moldova) was part of the post-Soviet Integrated Power System (IPS) which connected them to the grids of Russia and Belarus through 4.2 GW links. Plans had been in place since 2017 to synchronise Ukraine's grid with the continental European system by 2023. On the day of the invasion, Ukraine had just completed a planned disconnection from the Belarusian and Russian systems, conducting a test of "isolated mode" operations. Shortly thereafter, Ukraine and Moldova requested emergency synchronisation with Europe. This was achieved within a matter of weeks, thanks to the extraordinary efforts of the European TSOs and Ukrenergo as well as the European Network of Transmission System Operators for Electricity (ENTSO-E). Permanent disconnection from Russia's power system and synchronisation with ENTSO-E – a key milestone in Ukraine's energy strategy – was ultimately achieved in November 2023. The operators of continental Europe's transmission system agreed to increase the commercial capacity limit for electricity imports, allowing Ukrenergo to better absorb potential system shocks, such as further attacks or consumption spikes driven by colder temperatures.

Map of the western portion of the Ukrainian grid and its existing and planned interconnectors with Moldova and the continental Europe system



Note: The corridors for proposed/under construction transmission have been estimated based on substation locations.

Sources. ENTSO-E Transmission System Map, Green Deal Ukraina (2024).

Modelling methodology

To explore the potential for decentralisation in the reconstruction of the Ukrainian power system, the IEA developed a PLEXOS-based power system model built around least-cost optimisation. This model includes both a capacity expansion and a production cost model to first explore which options are best suited to address the power deficit in Ukraine. It then evaluates the measures that would be required to ensure those options can effectively contribute to the security of a rebuilt power system that that relies on increasingly decentralised generation sources.

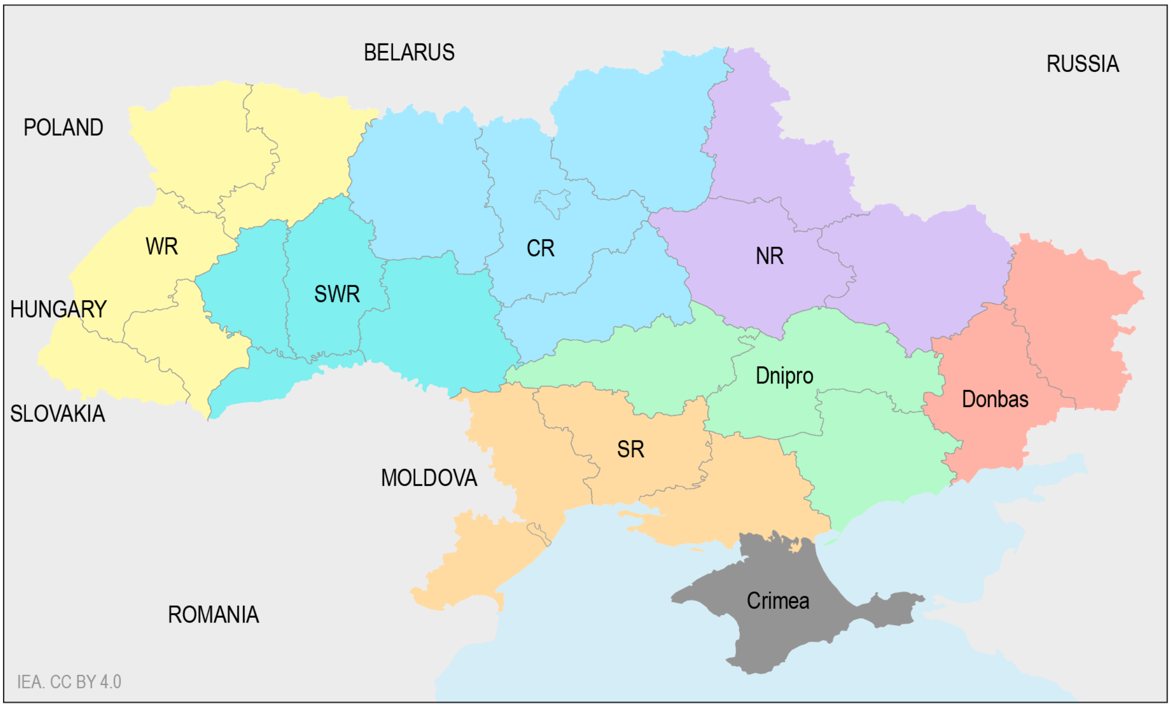
Regional representation and transmission

The model itself covers seven different regions, based on Ukrenergo's defined power regions, typically comprising multiple oblasts. Those parts of the occupied regions of Donetsk and Luhansk which remain interconnected with the Ukrainian Independent Power System (IPS) are aggregated as a single node (Donbas). Since Crimea is no longer part of the Ukrainian IPS, it has been excluded from the analysis.

Modelled regions of Ukraine and their respective oblasts

Region code	Region	Oblasts
CR	Central	Cherkasy, Chernihiv, Kyiv, Kyiv City, Zhytomyr
Donbas	Donbas	Donetsk, Luhansk
Dnipro	Dnipro	Dnipropetrovsk, Kirovohrad, Zaporizhzhia
NR	Northern	Kharkiv, Poltava, Sumy
SR	Southern	Kherson, Mykolaiv, Odessa
SWR	Southwestern	Chernivtsi, Khmelnytskyi, Ternopil, Vinnytsia
WR	Western	Ivano-Frankivsk, Lviv, Rivne, Transcarpathia, Volyn

Overview of the modelled regions



Notes: CR = Central Region, NR = Northern Region, SR = Southern Region, SWR = Southwestern Region, WR = Western Region.

The transmission capacity between each region is assumed based on existing lines between each region, assuming the transfer capacity based on the voltage level (using the surge impedance loading at each voltage level) and configuration of the lines. As the transmission system in Ukraine was traditionally designed to transmit electricity from east to west, it is assumed that the transfer capacity in this direction is half of the surge impedance loading.

Additionally, due to the incurred damage to the transmission system since the full-scale invasion, it is assumed that the transfer capacity between regions has been compromised in the regions closest to the front line (EOR, ER and SR). In 2025 (and in all validation scenarios since the full-scale invasion), it is therefore assumed that transmission capacity between regions is reduced by a third between EOR and all other regions, also by a third between ER and SR, and by half between ER or SR and other regions

Input assumptions for transmission capacity between modelled regions in Ukraine

Transmission corridor	Forward (Reverse) capacity [GW]	Derating due to damaged transmission in 2025
CR-ER	4 820 (2 410)	50%
CR-NR	410 (205)	N/A
CR-SWR	7 430 (7 430)	N/A
CR-WR	1 105 (2 210)	N/A
EOR-ER	3 920 (7 840)	33%
EOR-NR	405 (810)	33%
ER-NR	810 (810)	50%
ER-SR	4 525 (9 050)	33%
ER-SWR	205 (410)	50%
SR-SWR	205 (410)	50%
SWR-WR	2 615 (5 230)	N/A

Interconnections and the European power market

Inter-regional transmission and interconnection capacity to direct European neighbours (Hungary, Poland, Romania and Slovakia) are assumed based on available information around network infrastructure and transfer capacities between Ukraine and these neighbours in the modelled years, based on ENTSO-E input data for their European Resource Adequacy Assessment (ERAA) 2023 study. To represent the European market, all of Ukraine's neighbours as well as their immediate neighbours (Austria, Bulgaria, Czechia, Germany, Hungary, Lithuania, Poland, Romania and Slovakia) are represented at a national level with generation represented at an aggregate level, considering the transfer capacity between each country. For the purpose of this modelling exercise, Moldova is not explicitly represented in order to limit the uncertainty related to the operation of the 2 520 MW Moldavskaya State District Power Plant (MGRES), Moldova's largest power station, which is located in the breakaway region of Transnistria. However, Moldova's network is considered as a transit route for power imports from and exports to Romania.

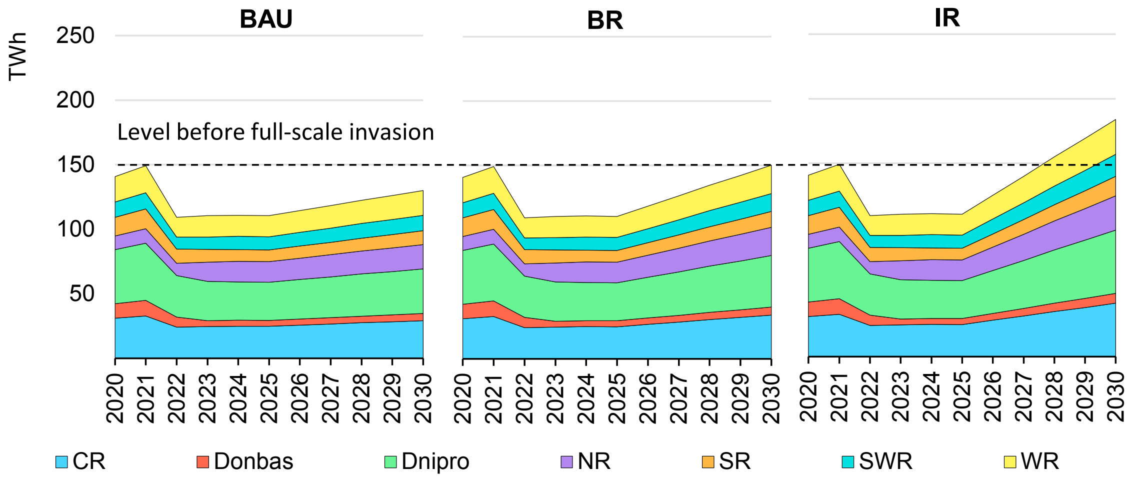
For validation models, the imposed limits for imports and exports to the European system are assumed based on the previous limits (as of February 2024) of 1 700 MW of imports and 500 MW of exports for the combined systems of Ukraine and Moldova. As Moldova has not been explicitly modelled, it is assumed that 200 MW of this capacity would be in use for its own electricity use. For 2025, the import limit from Europe increases to 2 100 MW in line with the recent announcement by ENTSO-E, and therefore the imposed limits are assumed to be 2 100 MW of imports and 500 MW of exports. For 2030, it is assumed that imports could be increased to 3 GW for Ukraine's exclusive use while exports could be increased to 1 GW.

Demand

Electricity demand for Ukraine in the model is based on a combination of historical hourly profiles at a national level, regional snapshots of hourly demand on specific days before and after the invasion, and future projections of annual and peak load growth (2025-2030) as per the Net Zero World Initiative's Clean Energy Roadmap for Ukraine. These projections are divided into three scenarios – Business as Usual (BAU), Base Recovery (BR) and Intense Recovery (IR). Each scenario considers different levels of economic recovery, electrification and energy efficiency measures to achieve sectoral emission reductions The resulting annual demand model is shown below, highlighting the drop in demand following the full-scale invasion, the shift in demand to the Northern region, and the recovery (at varying paces) across the different demand scenarios.

While demand had been expected to recover between 2022 and 2025, this is now assumed to be unlikely, given the escalation of attacks on the power system and Ukraine's current power deficit. The modelled demand for 2025 is therefore assumed to be unchanged from 2023 levels. It is assumed that demand recovery will then accelerate between 2025 and 2030, eventually reaching the levels in the NZWI scenarios.

Overview of assumed electricity demand growth across three different scenarios



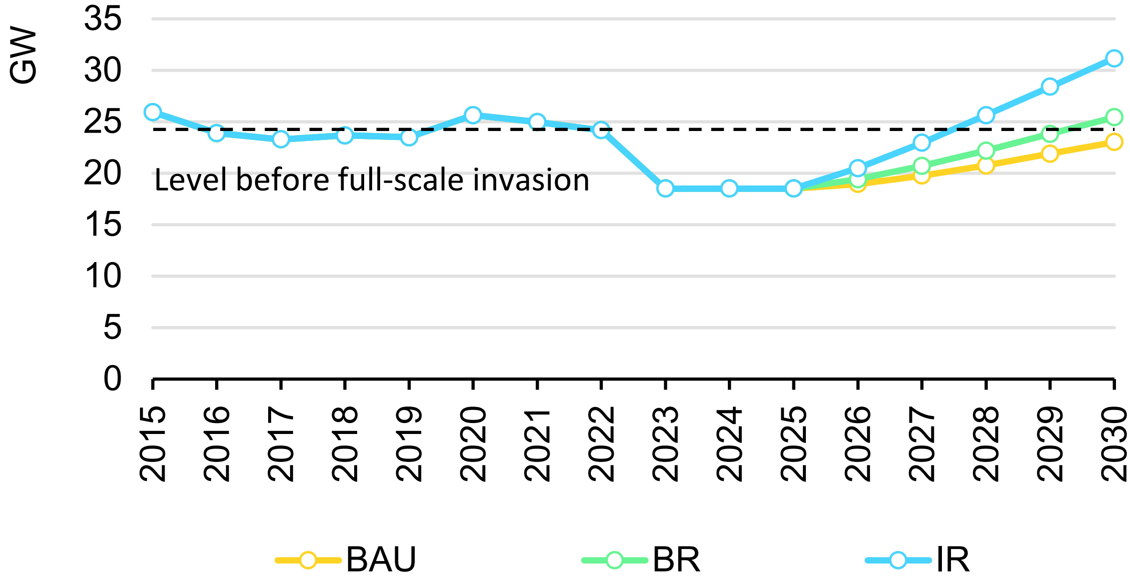
IEA. CC BY 4.0.

Notes: CR = Central Region; NR = Northern Region; SR = Southern Region; SWR = Southwestern Region; WR = Western Region; BAU = Business as Usual Scenario; BR = Base Recovery Scenario; IR = Intense Recovery Scenario.

Sources: IEA analysis based on Net Zero World Initiative (2023), Clean Energy Roadmap and enriched with information from Green Deal Ukraina (2024), Six options to boost power transfers from Continental Europe to Ukraine, for the next two winters, as well as data from Ukrenergo and the Ukrainian Ministry of Energy.

The primary requirements modelled by the IEA for the Ukrainian power system are based on its energy and capacity needs, which are driven by peak capacity requirements. This is in addition to operating reserve requirements, with spinning reserve based on the largest system contingency – one of the larger units of the nuclear fleet – and a portion of forecasted demand for regulating reserves. Peak demand, both historical and forecasted by scenario, is shown below.

Overview of modelled system requirements in terms of peak demand



IEA. CC BY 4.0.

Sources: IEA analysis based on Net Zero World Initiative (2023), Clean Energy Roadmap and enriched with information from Green Deal Ukraina (2024), Six options to boost power transfers from Continental Europe to Ukraine, for the next two winters, as well as data from Ukrenergo and the Ukrainian Ministry of Energy.

Generation

General characteristics

Generation capacity and its technical characteristics (i.e. heat rates, ramp rates, minimum up/down time, minimum stable level, outage rates and mean time to repair) and cost parameters (i.e. fuel costs, variable operation and maintenance costs) are based on data collected from various sources, including public domain information and direct data from utilities and the Ukrainian Ministry of Energy. In the absence of plant-specific data, generic characteristics were assumed based on plant technology and best practice. The availability of generation capacity is dynamic due to ongoing attacks on the power system in one direction, and repair campaigns and the building of new capacity in the other.

Data on installed and available capacities per plant has been validated against damage report assessments and public announcements to represent the available capacity by technology and region according to the latest available information and to more accurately model existing and future capacity deficits in Ukraine.

Generation is captured at plant level for existing large-scale generation such as thermal plants, large-scale hydropower and nuclear plants. For smaller-scale plants and variable renewables, these plants are aggregated by technology and region.

Hydropower

Except for large hydropower plants – which are represented at plant level – renewables are aggregated by technology and region. In terms of hydropower, these are either modelled as plants with a large reservoir or run-of-river. For run-of-river plants, it is either assumed that they have daily pondage or do not, depending on their size. Seasonal availability of hydropower is modelled based on a combination of IEA statistics (annual capacity factor for 2021) and the Atlite hydropower module to arrive at monthly average capacity factors for these plants.

Large reservoir hydropower plants are modelled with an annually constrained capacity factor and a monthly portion (30% of monthly capacity factor) due to environmental and multi-use constraints for river flows. Similarly, run-of-river plants with pondage are assumed to have a monthly constrained capacity factor with a daily portion (30% of monthly capacity factor) that is must-run.

Variable renewables

The locations for utility-scale solar and wind plants specified in the modelling scenarios are estimated using a wind and solar site selection methodology that considers the location of the best resource, annual demand in each region, proximity to existing transmission, terrain (i.e. slope and elevation) and protected areas, as well as current land use and land cover. In terms of existing plants, these sites are selected based on the location of these plants (by oblast) according to the collected data.

In terms of sites for distributed solar PV, this was based on a bespoke dataset produced for the purpose this project by the Juelich Institute, which identified the technical potential of rooftops for solar PV. The selection of the appropriate sites from this dataset was based purely on random site selection from the available rooftops.

Once the sites of both existing and future renewables were selected, a share of different PV and wind technologies were assumed for the utility-scale plants. For onshore wind, this consisted of a uniform share of both older and more advanced wind turbines of different types, as summarised below.

Assumed share of different wind turbines modelled and their characteristics

Turbine power (MW)	Turbine diameter (m)	Swept area (m^2)	Specific power (W/m^2)	Assumed share – 2025 (%)	Assumed share – 2030 (%)
2.0	90	6 362	0.314	50	20
2.0	100	9 503	0.210	50	20
3.6	117	10 752	0.335	0	15
2.2	120	11 310	0.195	0	15
4.0	150	14 527	0.275	0	15
4.0	150	17 672	0.226	0	15

For utility-scale PV, this was assumed to consist only of fixed-tilt panels in both 2025 and 2030. Finally, for distributed PV, the tilt and orientation of the solar panels are dependent on the distribution of rooftops in Ukraine. In the case of a flat rooftop, the optimal tilt, as used in a ground-mounted system, can be used. In the absence of specific data relating to the building stock in Ukraine, a distribution of orientation and tilt was assumed. It is also assumed that north-facing rooftops are excluded for deployment due to their poor potential.

Assumed distribution of rooftop tilt

Tilt	Share of rooftops (%)
Flat (optimal tilt)	10
15°	20
30°	30
45°	40

Assumed distribution of rooftop orientation

Orientation	Share of rooftops (%)
North	0
North-east	2.5
East	20
South-east	12.5
South	25
South-west	12.5
West	20
North-west	2.5

Hourly renewable production profiles are then built using Atlite, aggregated by region and technology, based on ERA5 data from the European Centre for Medium-Range Weather Forecasts (ECMWF). In the case of wind production profiles, the ERA5 dataset is upscaled using the average wind speed data from the Global Wind Atlas. The weather year for the model is assumed to be 2021.

Capacity expansion options

The model seeks to optimise the least-cost expansion and subsequent operation of the power system to meet modelled demand at an hourly resolution while also ensuring the security of supply by procuring spinning and regulating reserves at a national level.[1]

Key inputs into the model are the capacity expansion options available to address the existing deficit in capacity and energy, while also providing the necessary flexibility for the operation of such a system. These expansion options are represented at a regional level, capturing all technical characteristics and cost parameters. Specifically, this includes build costs, technical lifespan and financial assumptions, as detailed in the table below.

Overview of capacity expansion options for both 2025 and 2030 horizons

Technology	Typical capacity (MW)	CAPEX (USD/kW) - 2025	CAPEX (USD/kW) - 2030	Lead time (years)	Lifetime (years)	WACC (%)	OPEX * (USD/MWh)
Rooftop solar PV	0.1	752	597	0.1	40	9	74
Utility-scale solar PV	15	550	450	0.5	40	13	61-80
Gas engine	5	984	957	1	25	9	129
Small gas turbine	20	760	744	1.5	25	13	152
Onshore wind	4.6	1 185	1 147	1.5	30	13	41
Battery (1h)	60	395	331	0.2	20	13	410
Battery (2h)	60	619	518	0.2	20	13	410
Battery (4h)	60	1 001	837	0.2	20	13	410
Battery (8h)	60	1 667	1 396	0.2	20	13	410
Battery (behind-the-meter)	0.3	1 335	1 116	0.2	10	7	410

* OPEX corresponds to a combination of the variable operation and maintenance costs and fuel costs (based on the heat rate of the option)

Sources: IEA analysis based on DEA (2024), Urgent Technology Catalogue for the Ukrainian Power Sector, DEA (2024), Technology Data for Generation of Electricity and District Heating, IEA internal cost database.

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[1] Spinning reserves are based on the largest contingency in the system, while regulating reserves are based on 3% of the national demand.

One key assumption are the financial assumptions, and specifically the weighted-average cost of capital (WACC). While this is presented as a single value across the lifetime of the expansion option, the financial options available to consumers are more complex. These options are based on concessional loans, such as the 5-7-9 Affordable Loans programme for communities. For households, there is also a recently announced zero interest rate loan programme for solar PV and battery installations. Notably, many of these loans do not extend over the entire operating life of the installations (typically 5 years) and therefore would likely involve different interest rates at different times. Meanwhile, financing for larger energy projects such as small modular gas turbines may – at least for private investors – be more closely linked to Ukraine's benchmark interest rate, which currently stands at 13%. However, even these projects may require additional financing and could benefit from funds in the form of grants and other mechanisms. As a result, all DERs – except for behind-the-meter (BTM) batteries – are assumed to have a WACC of 9%. Due to their shorter operating life (10 years) and because they are able to access concessional loans over that entire period, we assume a 7% WACC for behind-the-meter batteries. Meanwhile, for larger grid-connected plants, the WACC is assumed to be the same as the benchmark interest rate.

As the expansion uses cost optimisation, there is a natural bias toward technologies with larger units and which benefit from economies of scale, such as utility-scale wind and solar PV. However, the full value that each technology offers to the system in terms of resilience is not fully captured. For example, small gas turbines can be easily concealed from potential attackers while gas engines can be deployed very quickly. Similarly, distributed PV systems are harder to target than utility-scale assets because they lack a single point of failure, such as a substation. Financing options, incentives and speed of deployment will vary significantly across all expansion alternatives. To capture the key differences between distributed resources and their utility-scale equivalents, specific constraints for 2025 and 2030 are imposed and detailed in the table below.

Overview of technology ratios in both 2025 and 2030 capacity expansion models

Technology	Expansion constraints – 2025	Expansion constraints – 2030
Gas	60% small gas turbine 40% gas engines	60% small gas turbine 40% gas engines
Wind	Not considered	Restricted to an approximate share of 70:30 of solar PV (utility-scale and DPV) to wind
Solar PV	100% distributed PV	25% utility-scale 75% distributed
Batteries	2 GW max utility-scale	50% utility-scale, 50% BTM

Reserves

The primary driver of the model is to meet electricity demand in least-cost while respecting system constraints such as the technical constraints of generation. However, spinning and regulating reserves are also modelled to capture important system requirements for electricity supply.

Both types of reserves are modelled at a national level. Spinning reserves are based on the largest system contingency, which in Ukraine is one of its large nuclear units. Meanwhile, regulating reserves are used for balancing of the system to cover for uncertainty in both demand and renewables forecasts. Given the complexity of factoring in the impact of renewables on balancing needs – driven in part by decisions on dispatch intervals and forecasting – the model focuses solely on demand, assuming a 3% load risk.

Abbreviations and acronyms

ACER	Agency for the Cooperation of Energy Regulators
AMI	Advanced metering infrastructure
BAU	Business as Usual
BESS	Battery energy storage systems
BR	Base Recovery
BTM	Behind-the-meter
CBAM	Carbon Border Adjustment Mechanism
CEP	Clean Energy Package
CHP	Combined heat and power
DER	Distributed energy resources
DERMS	Distributed energy resource management systems
DSO	Distribution System Operators
ECMWF	European Centre for Medium-Range Weather Forecasts
ETS	Emissions Trading System
EU	European Union
FLH	Full-load hours
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFI	International financial institutions
IPS	Independent Power System
IR	Intense Recovery
LCOE	Levelised cost of electricity
LV	Low-voltage
MGRES	Moldavskaya GRES
NECP	National Energy and Climate Plan
NEURC	National Energy and Utilities Regulatory Commission
NPP	Nuclear power plant
NZWI	Net Zero World Initiative
OEM	Original equipment manufacturers
PPP	Public private partnerships
PSH	Pumped-storage hydro
PSO	Public Service Obligation
PV	Photovoltaic

RES	Renewable energy sources
TPP	Thermal power plants
TSO	Transmission system operator
VPP	Virtual power plants
VRE	Variable renewable energy
WACC	Weighted average cost of capital

Units of measure

GW	gigawatt
GWh	gigawatt hour
kV	kilovolt
MW	megawatt
MWh	megawatt hour
TWh	terawatt hour
USD	United States dollar
USD/Kw	United States dollar per kilowatt
USD/MWh	United States dollar per megawatt hour

International Energy Agency (IEA)

Unless otherwise indicated, all material presented in figures and tables is derived from IEA data and analysis.

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