green deal UKRAINA

Modelling the Electricity Deficit in Ukraine and Potential Policy Responses for the period June 2024 – May 2025

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Green Deal Ukraïna

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List of abbreviations:

BAT: battery

BGP: bio-gas power plant

CHP: combined heat and power plant

CPP: coal power plant

GDP: gross domestic product

GW: gigawatts

GWh: gigawatt hours

HPP: hydro power plant

MW: megawatts

MWh: megawatt hours

NPP: nuclear power plant

NTC: net transfer capacity

OCGT: open-cycle gas turbine

PHS: pump hydro storage

PV: Photovoltaic (solar) power plant

PyPSA: Python for Power Systems Analysis

TWh: Terawatt hours

WPP: wind power plant (on-shore)

Introduction

Since the beginning of the Russian attacks on Ukraine, it has been a declared Russian goal to aggressively damage the country’s energy infrastructure. In addition to the occupation of power plants such as the Zaporizhzhia NPP (6 GW) and its disconnection from the Ukrainian electricity system, systematic aerial attacks at the transmission infrastructure, power plants and other energy facilities have crippled Ukraine's electricity system. The repeated attacks from the end of March until the time of writing in early June 2024 were another example of the aggressor's activities. The media reports on the destruction of thermal power stations, dams, hydroelectric power stations and other facilities necessary for supply.

The destruction and damage to power plants has substantially reduced the size of the operating fleet and put immense strain on the grid. As a result, already since the beginning of spring 2024 scheduled rolling power cuts are needed to balance the system. And this stress will increase with the onset of winter as electricity demand will go up, while solar and hydro power generation will decline.

In this paper, the team of the Green Deal Ukraïna Project at Helmholtz Zentrum Berlin tries to provide an objective and comprehensive picture of the current situation in terms of electricity balance. Moreover, different solutions to mitigate the severe deficit are tested in a system framework.

The purpose of this report is threefold:

1. Based on the modelling carried out, the authors want to make European policymakers and the public more aware of the scale of the current deficit and thus urge them to take further security and, above all, energy policy measures.
2. By analysing different possible technical options, the authors want to highlight that solutions are at hand, give a sense of the order of required capacities and stimulate a discussion on prioritisation.
3. The ultimate aim is to contribute to a discussion on minimising the consequences of power cuts for the Ukrainian population, especially for Winter 2024/25.

For data security reasons, we only provide results at lower temporal and technical resolution. A more comprehensive annex will be provided bilaterally to legitimately interested parties upon request. Please contact the authors for further information.

Model results for load shedding were used as a measure to describe the current situation. The key parameters here are the total amount of load shedding within a year in TWh, the number of hours in which load shedding can be expected in the system and the distribution of the amount of load shedding expressed in histograms.

Load shedding has increased in recent weeks. This is due to the Russian attacks in the spring. In addition, with rising temperatures and falling demand, the remaining nuclear blocks have entered their previously postponed maintenance periods. As a result, the system now has less capacity available than at the beginning of the year.

Our modelling results show that, despite the general risks to energy security, there are options that can at least reduce the impact on the population as well as system risks.

These are not equivalent either in terms of their contribution to energy security nor in terms of the financial and technical effort that would be required. In addition to a baseline and a limited repair scenario, six policy scenarios are discussed below. These represent the potential contributions to reducing load shedding from the addition of small gas-fired OCGTs, PV and increased import capacity.

1 Methodology

The aim of the analysis is to simulate the degree to which electricity demand cannot be met in Ukraine over the period June 2024-June2025 under different scenarios. Thereby, we are interested in 1) in how many hours at least some load-shedding needs to be applied (in hours), 2) how much demand cannot be met in total (in TWh), and 3) how often extreme load shedding needs to be applied.

To do so we employ a model of the hourly Ukrainian electricity dispatch (see 1.1) based on a carefully curated set of assumptions on the current state of the electricity system as well as hourly regional electricity demand (see 1.2). We then test the impact of several options (see 1.3) to reduce the degree to which electricity demand cannot be met.

1.1 Modelling framework

We use the open-source Python environment PyPSA (Python for Power System Analysis). PyPSA provides a toolbox for modelling and contains the essential mathematics such as a cost-minimising objective function, balance equations, as well as Kirchhoff's laws and unit commitment equations. It is thus a modelling environment that allows energy systems to be modelled with high temporal and spatial resolution, and thus to answer questions about the cost-optimal generation of electricity based on the merit order with a given power plant park.

PyPSA is used in various international research and consulting projects as well as by universities, and is characterised by a large, active and helpful community. PyPSA was originally developed at the Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany under the direction of Tom Brown (now at the Technical University of Berlin).

We do not use PyPSA's capability to derive optimal investment decisions - as we are interested in testing the individual effect of specific short-term fixes, and not a comprehensive investment trajectory.

1.2 System specifics and data

The current model represents the Ukrainian electricity system with nine regions (nodes) interconnected by transmission lines. Each node consists of generation capacities and electricity and heat demand trajectories at an hourly resolution. The planning horizon for the current analysis is June 2024 – May 2025.

A unit-level list of generators and their installed capacities as of 2020, about 55 GW, was taken as a starting point. Based on a large number of publicly available sources we assessed the state of these units in June 2024.

We classified each unit into the following categories: *operating*, *attacked-damaged*, *destroyed*, *occupied*, *mothballed due to war*, *non-operating*, *in project*, or *no information*. The *attacked-damaged* category represents generators that have confirmed damage, but the extent of which is unknown. We were able to largely verify this extensive list in bilateral exchanges with Ukrainian experts in Kyiv at the end of May. To determine the renewable capacities, we use the June data in the "Global Wind Power Tracker" and "Global Solar Power Tracker" from the "Global Energy Monitor".

From this new list, the generators of interest are those that fall into the categories of *operating* and *attacked-damaged* as these make up the fleet that either currently provide electricity to Ukraine or could theoretically be repaired before the winter.

For the baseline scenario, only units 'operating' at the beginning of June with a high degree of certainty are considered as actually available.

In all other scenario runs, the available capacities include generators still in operation, and 50 % of the capacities of generators known as attacked and (partially) damaged. Depending on the specific scenario, one or more type of generation/storage/import capacity are added as a policy response.

A conscience modelling decision was made to only allow newly installed capacities to be built between July 1st and October 1st 2024, after which capacity of the system remains fixed. This encourages construction to take place before demand increases substantially in the winter months.

Transmission line characteristics and resulting transmission capacities are taken from the PyPSA-Eur[1] modelling workflow that, to the authors knowledge, relies on ENTSO-E data. As network constraints were not a priority in the current analysis, the extent to which network destruction is relevant to load shedding was not analysed. Here, only based on sufficiently reliable data further analysis could indicate to which degree transmission grid constraints are an issue in the different scenarios.

To accurately assess potential electricity deficits (load shedding), the demand profile should reflect the current situation as closely as possible.

The following steps were taken to arrive at an adjusted demand trajectory for the period June 2024 – May 2025:

1) Total annual electricity net demand was derived from 2020 aggregated demand under consideration of sectoral shares (114 TWh according to the energy balance of Ukraine), GDP losses, migration, and the loss of territory due to occupation by RUS.
2) Historic (nationally aggregated) hourly demand data from 2020 were used as representation for hourly variation.
3) Under consideration of occupation, losses in GDP and migration, forecasted (see step 1) aggregated 2024/25 demand and hourly variation demand trajectories per node were assigned proportionately to regional GDP and population shares.

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[1] https://pypsa-eur.readthedocs.io/en/latest/

Based on this approach, we assume a net demand[2] of around 100 TWh for the period June 2024 – May 2025, i.e., a decline of around 20% compared to 2021. Gross supply (including own consumption of national generation, imports and covering grid losses) decreases from 158 TWh in 2021 to 128 TWh and net supply (including only imports and grid losses but no own consumption) from 131 TWh to 115 TWh. Note that demand trajectories remained the same for all scenarios.

For representing appropriate CHP behaviour, the annual trajectory of heat demand attributable to production in CHP per node was derived from historical CHP electricity generation, total heat supply in 2020 (energy balance), and information on heat/power efficiencies.

The extensive requirement of refuelling and maintaining nuclear power capacities are considered by defining unit specific maintenance periods. We base our 2024/25 assumptions on the length and timing of maintenance outages over the same time period in 2023/24. For this reason, unit-specific outages are calibrated based on aggregated nuclear generation.

1.3 Scenario definitions

To depict the impact of the capacity-shortfall, and different mitigation strategies ahead of the winter, we develop ten scenarios:

1) **Baseline**: Available capacity is restricted to only the generators in the *operating* category. Imports are set to the commercial maximum agreed with ENTSO-E of 1.7 GW. No new generators are installed.
2) **Limited Repairs:** Available capacity consists of all generators in the *operating* category, plus 50% of the capacities of generators in the *attacked-damaged* category. Imports are set to the commercial maximum of 1.7 GW. No new generators are installed.
3) **1.5 GW additional OCGT:** Available capacity as described in the "Limited Repairs" scenario, plus an additional 1.5 GW of newly installed OCGT capacity, distributed across nodes in proportion to demand.
4) **3 GW additional OCGT:** Available capacity as described in the "Limited Repairs" scenario, plus an additional 3 GW of newly installed OCGT capacity, distributed across nodes in proportion to demand.
5) **1 GW additional wind:** This scenario assumes an installation of 1 GW wind onshore capacities until end of September.
6) **5 GW additional PV:** Available capacity as described in the “Limited Repairs” scenario, plus an additional 5 GW of newly installed photovoltaic (solar) capacity, distributed across nodes based on shares of pre-existing PV.
7) **5 GW additional PV and 2.5 GW additional batteries:** Available capacity as described in the “Limited Repairs” scenario, plus an additional 5 GW of newly installed PV capacity and 2.5 GW of newly installed battery capacity.

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[2] excluding grid losses and energy sector own consumption that sum up to about 20% of net demand

8) **0.5 GW additional imports:** Available capacity as described in the "Limited Repairs" scenario. Import capacity from Poland is increased by 0.5 GW and added to node "UA_1" (the region bordering EU countries). No new generators are installed.
9) **1 GW additional imports:** Available capacity as described in the "Limited Repairs" scenario. Import capacity from Poland and Hungary is increased by a total of 1 GW and added to node "UA_1" (the region bordering EU countries). No new generators are installed.
10) **All-of-the-above (3 GW additional OCGT and 5 GW additional PV and 2.5 GW additional batteries and 1 GW additional imports):** This scenario includes all individual measures and checks whether a mix makes it possible to completely avoid load shedding.

These ten scenarios represent a range of ambitious yet still realistic policy options. Testing them individually allows to assess the impact of each technology on load shedding.

2 Scenario results

2.1 Scenario: Baseline

The baseline scenario is the lower boundary of our assessment of which capacities are still available (with the caveat that possible existing damage to lines and transformers has not been taken into account). Load shedding needs to happen in 7900 of the 8760 hours of the year, i.e. 90% of the time. The total amount of load shedding is 18.3 TWh, which is about 18% of the total annual demand. The hourly load shedding ranges from a few MWs up to 6.5 GW in certain hours. This scenario clearly shows that electricity consumption must be limited every single day by load shedding. Load shedding takes place throughout the period, driven by NPP maintenance schedules in the summer and increased demand in the winter. All other capacities run at their maximum (taking into account NPP maintenance) and imports amount to 14.6 TWh, which is about 98% of capacity utilisation.

Figure 1: Hourly load shedding in the baseline scenario

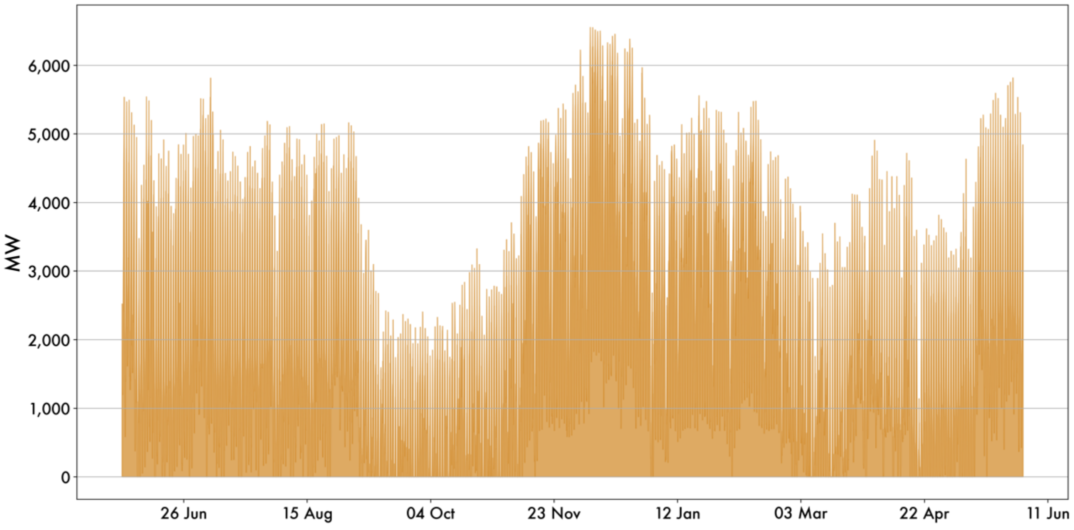
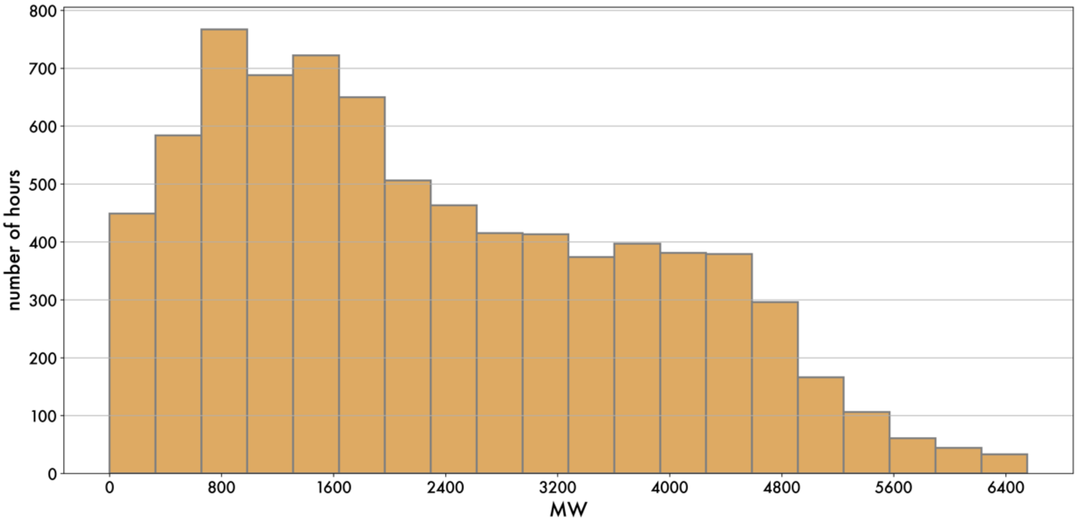


Figure 2: Histogram of load shedding in scenario “Baseline” – 89 % of the hours totalling 18.3 TWh



In addition to the problem of load shedding for electricity, the scenario shows that about 30% of the heat supply attributable to heat-production in CHPs cannot be compensated by the remaining CHPs. Thereby, a dire heat supply situation will exacerbate the electricity supply problems if households and other consumers switch to electricity for heating.

While this scenario is very dire, several additional risks might worsen the situation further:

- Nuclear availability: the biggest risk is that some of the nuclear units - that provide about two-thirds of domestic generation in this scenario - are not available when we expect them to. This might be due to unscheduled or particularly long maintenance of individual units, but also due to the overall fragility of the system.
- Further destruction: unless properly protected, remaining larger units will remain targets for Russia's inhumane attacks against critical civilian infrastructure. As imports are the second important remaining source of electricity supply and the most important flexibility provider in this scenario - corresponding infrastructure must be particularly protected.
- Electric heating: a dire heat supply situation will exacerbate the electricity supply problems if households and other consumers switch to electricity for heating. In a particularly cold year, this problem gets even bigger: In the past Ukraine featured a 400 MW higher load when temperatures dropped by 1° in winter[3].
- Gas supply: Unavailable gas infrastructure (currently not observed by us) or insufficient gas supply (also not currently indicated) would impair remaining gas fired units (mainly CHPs) and exacerbate the above-mentioned heating issue. Negative feedback might emerge, when power cuts impact electrical compressor stations in the gas transportation system.

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[3] https://greendealukraina.org/gd-tracker/figure-of-the-week/2024/daily-average-temperature-vs-peak-electricity-demand-ta-chp-generation

- Adverse selection: Ukraine currently manages load shedding through rolling power cuts, i.e., individual regions are disconnected from electricity supply for a certain number of hours. In addition, certain consumers are for good reasons (such as being defence-related or part of critical services and infrastructures) obtaining preferential treatment. But this treatment is not made transparent. Moreover, each consumer individually optimises its consumption by shifting demand to those hours where the corresponding consumer is connected. Richer consumers often use quite sizable batteries. Typically, poorer consumers and some services such as electric public transport do have less opportunities to do load shifting - hence more affluent consumers eventually get a higher share of the scarce electricity delivered by the grid, than poorer consumers. Especially at very high levels of load shedding - these uneven sharing of pain risks undermining cohesion in the Ukrainian society.
- Hydro and wind supply: we used a relatively modest hydro-generation year and assume that not much hydro capacity is left - hence even a very bad hydro-year might only add a few hundred GWhs of load shedding. The same goes for wind-generation.

2.2 Scenario: Limited repairs

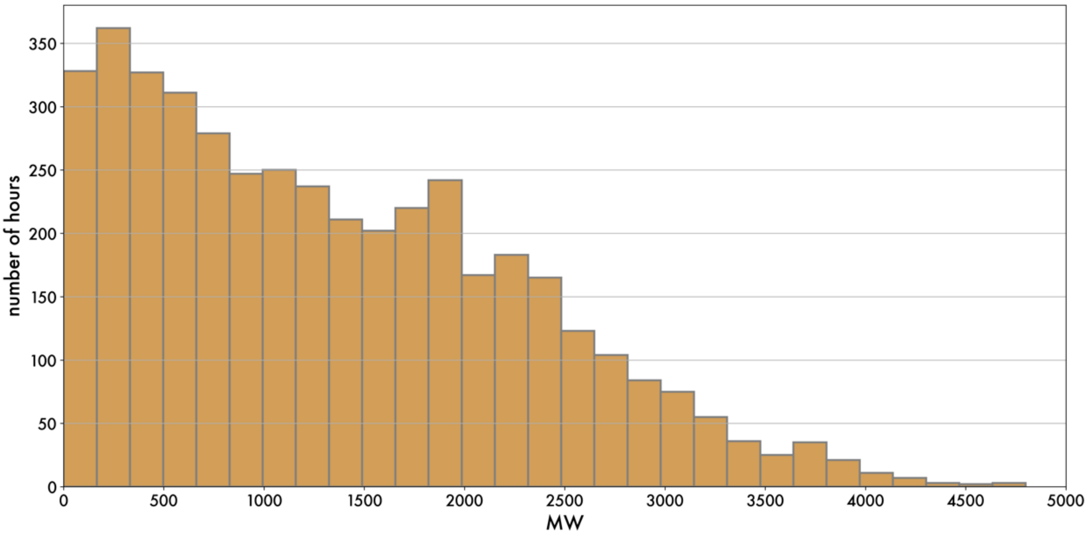
In the limited repairs scenario half of the reportedly attacked but not fully destroyed units are brought back to operation. As the state each unit is in is different and there are for good reasons only very limited public information, it is very uncertain to which degree this can be pulled off. It has, however, been widely reported that based on spare parts from other attacked or mothballed Ukrainian plants as well as deliveries from partners (e.g., spare parts from decommissioned plants in Germany) Ukraine is running a substantial repair campaign. The different lists of sought-for parts are a testament to these efforts.

A limited repair scenario reduces the number of load shedding hours from 89% to 49% and the total amount to 5.8 TWh. Hence, repairs are an essential and often the most speedy and economic solution to bring back capacities ahead of the winter. From the outside, getting the engineers and the most appropriate spare parts to the most promising repair-sites looks like a complex logistical and prioritisation exercise.

But even if half of the reportedly attacked but not totally destroyed units can be brought back, in more than half of the hours, the system cannot meet demand and power cuts are necessary. As in the baseline, load shedding takes place throughout the year, with a peak in winter. All other capacities, except imports, run at full capacity. Total imports shrink to 12 TWh (80% utilisation).

In 2020 about 30% (37 TWh) of electricity was consumed by households and 40% in industry (46 TWh) according to the latest publicly available energy balance. Assuming load shedding of 5.8 TWh is only done by households - they would have to reduce their demand by about 20%. If all load-shedding would be conducted by industry, they would have to reduce consumption by 15-18%.

Figure 3: Histogram of load shedding in Scenario “Limited repairs” – 49 % of hours totalling 5.8 TWh



All following scenarios build on and compare to the presented "limited repairs" scenario (in grey in the following histograms).

2.3 Scenario: 1.5 GW additional OCGT

The installation of 1.5 GW of highly flexible OCGT capacity by the end of September significantly reduces winter load shedding. Currently very different types of "gas-fired power plants" are considered. They range from large open cycle gas turbines with up to 500 MW, via mobile turbines with some 5-30 MW (e.g., the USAID delivered 28 MW unit[4]) down to - sometimes containerised - gas-engine based power generators with up to 10 MW. Some types of units are quickly available "off the shelf", others might be obtained on the secondary markets, while especially larger units can require substantial lead times in procurement. Like all other solutions, building and connecting gas-plants will compete over scarce engineering capacities.

Going for many small, decentralised units has the substantial advantage in terms of being resilient to Russian attacks and being able to help with local bottlenecks. But it also typically comes at higher per MW cost and lower efficiency (hence more gas need) as well as significant challenges in terms of centrally managing such a system to ensure system stability. Understanding and evaluating the criteria for a good mix of generation assets goes beyond the scope of this paper.

The total number of hours is now reduced to 2041, or 23% of the year. The summer 2024 load shedding is not significantly affected as a gradual installation of new generators is assumed. Maintenance of the nuclear fleet again forces outages in summer of 2024 and from April 2025, but at a lower level.

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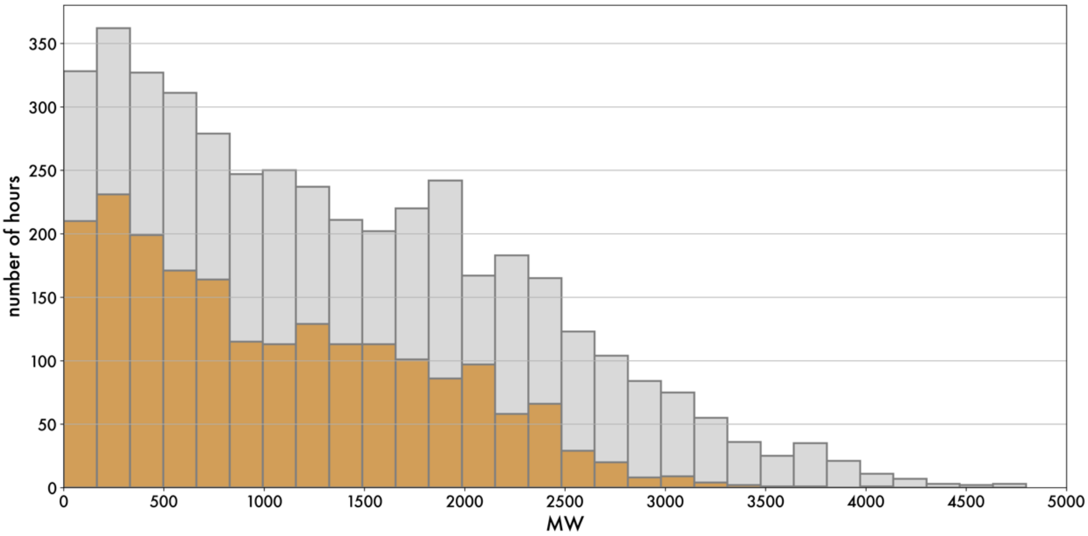
[4] https://energysecurityua.org/helping-ukraine/

Generation from all other capacities is unaffected, with one exception. While imports are 12 TWh in the limited repairs scenario, they fall to 8.6 TWh in the 1.5 GW OCGT scenario.

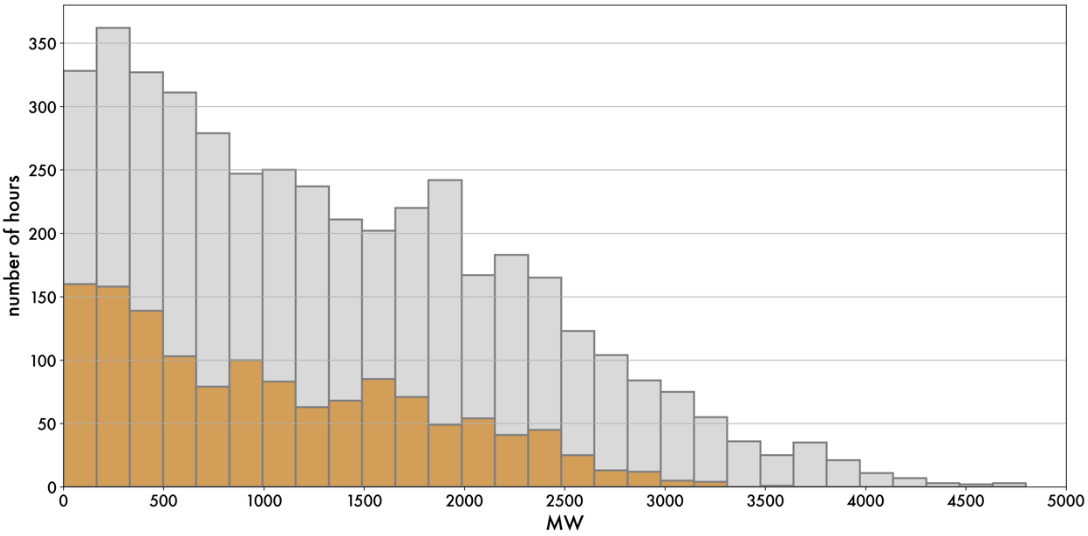
Figure 4: Histogram of load shedding in scenario "1.5 GW additional OCGT" – 23% of hours totalling 2.1 TWh (compared to the "limited repairs" scenario in grey)



2.4 Scenario: 3 GW additional OCGT

By installing 3 GW of flexible OCGT capacity by the end of September, load shedding after that date can be almost entirely avoided. The expected total number of load shedding hours until the end of the planning period is 1357, or 15% of the time. In this scenario, imports fall to 4.4 TWh, which is only 30% of capacity utilisation. All other capacities run again at their specific maximum. This scenario reflects a reasonable possibility for Ukraine to stabilise supply before the next winter and it is the one with the lowest expected load shedding of all the scenarios.

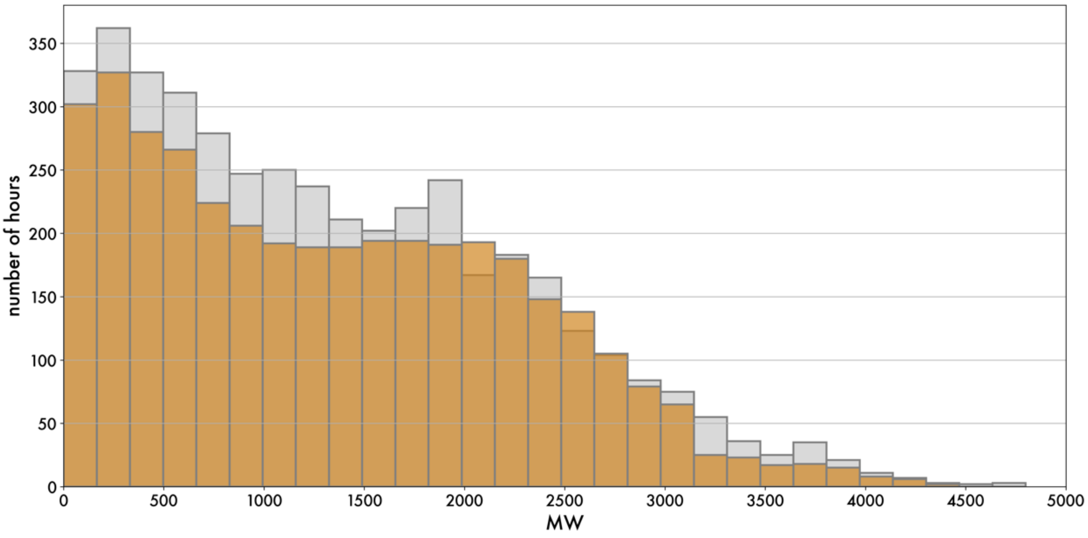
Figure 5: Histogram of load shedding in scenario "3 GW additional OCGT" – 15% of hours totalling 1.4 TWh



2.5 Scenario: Policy 1 GW additional wind

The installation of 1 GW of onshore wind capacities by October 2024 has a visible but limited effect on load shedding in the analysed period. The volume of 1 GW is not completely unrealistic, as there is a pipeline of several GW of projects with secured land-plots and connection agreements. Moreover, a pragmatic solution could be to procure used wind turbines that were made redundant through re-powering campaigns in Western Europe and install those. Their benefit would be low cost, quick availability, less structural investments (as unit capacities are lower) – but their big disadvantage is that logistics, certification and engineering might be more expensive. [5]

Figure 6: Histogram of load shedding in scenario "1 GW additional wind" – 43% of hours totalling 5.1 TWh



2.6 Scenario: 5 GW additional PV

Given the significant generation potential of PV solar in Ukraine, this source will play an important role in the country's post-war decarbonisation. For this reason, it is worth considering as an option for securing electricity supply in the coming months. It has been reported that 80 GW of unsold PV panels were stored in EU warehouses[6]. Hence even a massive installation of 5 GW of solar PV by the end of September (for comparison, France will add around 3 GW this year, but Germany installed 3.5 GW in Q1 2024 alone) is not completely unconceivable - especially if conducted as ground-mounted projects.

But given the sun-driven generation pattern, this would not significantly reduce load shedding in October 2024-May 2025. The capacity factors will fade as days shorten over the course of autumn, and solar radiation will be limited during the winter. It is only from next spring that one can expect to see an impact. Even then, load shedding between late afternoon and early morning will be

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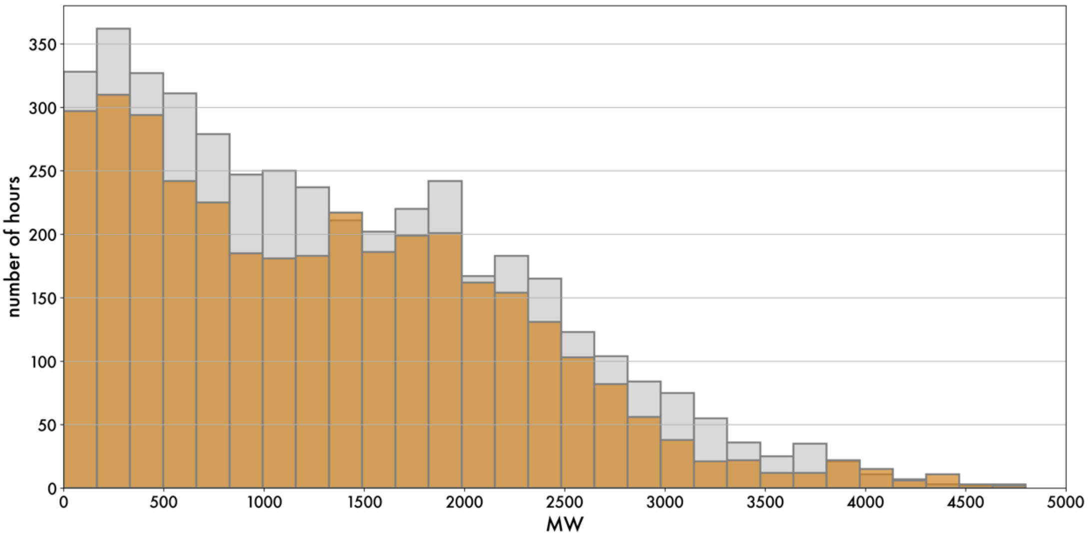
[5] Yet, the contribution of even a smaller capacity factor of solar in Winter to e.g. keeping the water system run or the heating systems should equally not be neglected.

[6] https://www.pv-magazine.com/2023/10/05/european-warehouses-now-storing-more-than-80-gw-of-unsold-solar-panels/

significant. On this basis, load shedding hours happens in 41% of the hours and totals 4.7 TWh (around 5% of net demand). PV generation increases the use of pumped storage by approx. +50% (1.6 TWh PHS generation). This shows the efficient use and distribution of PV yields over time. However, in periods without significant PV irradiation, no significant contribution to the reduction of load shedding in the period September 2024-May 2025 can be made.

Figure 7: Histogram of load shedding in scenario “5 GW additional PV“ – 41% of hours totalling 4.7 TWh

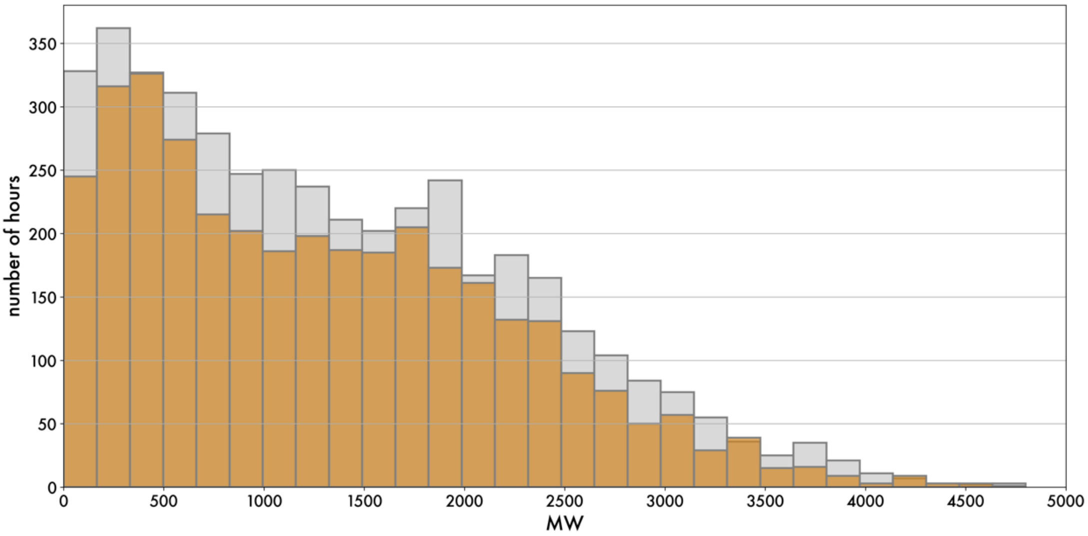


2.7 Scenario: Policy 5 GW additional PV & 2.5 GW additional batteries

As the higher utilisation of pumped storage plants in the previous scenario has shown, storage can help to reduce the extent of load shedding. For this reason, an additional installation of 2.5 GW of batteries is taken into account in this scenario. This reduces the load shedding by about 5% in hours and 8% in TWh relative to the “5 GW additional PV” scenario. Relative to “limited repairs” scenario the drop is about 20 %. The effect is relatively small, as even in off-peak hours there is little excess electricity. This will only change with higher shares of PV/wind. The histogram shows that the range of load shedding (in MW) does not change significantly.

This might underplay the importance of batteries, as our "hourly analysis" does not consider the value of the ancillary services (such as frequency restoration and frequency control) that are essential for the system and that can be provided by batteries. On the pure hourly market, batteries will not break even.

Figure 8: Histogram of load shedding in scenario “5 GW additional PV & 2.5 GW additional batteries“ – 40% of hours totalling 4.6 TWh



2.8 Scenario: 0.5 GW additional imports

Imports have a similar effect on load shedding as the installation of OCGTs. After the synchronisation of Ukraine the transmission capacities - available for exchanges - have been gradually stepped up to 1.7 GW (assumed in all previous scenarios) with the total NTC being 2.4 GW. The limit to this capacity is largely due to constraints on the side of the neighbouring countries, and here in particular in Romania and Hungary. There are various technical and regulatory options to increase this capacity. A detailed analysis of those will be provided in a comprehensive GDU study, available by October 2024.[7]

Those options are:

- Improve the networks in Hungary and Romania to allow increasing the exports closer to the NTC limit.
- Increase the ENTSO-E reserve of 3 GW to at least 5 GW to allow for greater transfers to Ukraine.
- Complete the Pivdneukrainsk-Isacea 400 kV line with Romania by 2026, not 2028.
- Complete the Mukacheva- Kapuszany 400kV line with Slovakia as fast as possible, by 2025 or 2026.
- Increase cross-border capacity with Hungary by strengthening a substation that forms a bottleneck on the Hungarian system.
- Install power generation on the Polish side of the Zamość-Dobrotvir line as a first pilot, to be replicated in all other bordering countries.

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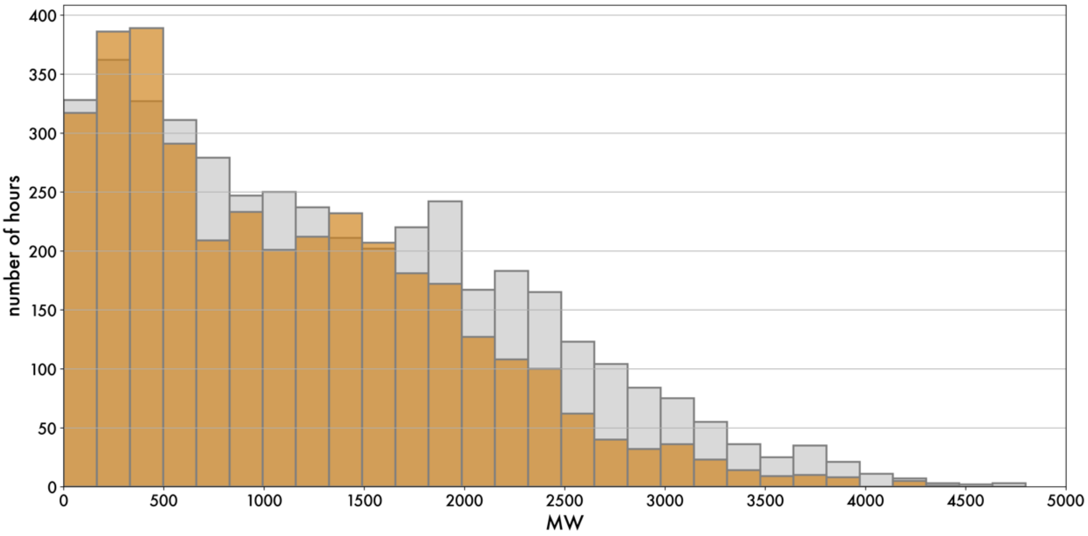
[7] The below list is based on substantial preliminary work by Susanne Nies. Within the GDU project she prepares a comprehensive study on ´regional electricity exchanges Ukraine with the neighbouring countries´ that will be available in October 2024.

- There is a substantial number of cross-border 110 kV lines with Poland that might be considered for commercial exchanges.
- Technical: there are technical solutions to increase the capacity of existing lines. Dynamic line rating allows to load the lines more depending on weather (cold weather, wind) and would maximise the use of the line by about 10% (this particularly helps in critical winter month). FACTS devices and Statcoms are often cost-effective solutions too, in very simplified terms, improve the manageability of power flows. This allows lower security margins and hence higher capacities on the same lines.
- Build a European factory for spares in a neighbouring country: to boost the European supplier Industry for grid technologies, to support Ukraine effectively and fast.

All these options require careful technical and economic study - but some of them are relatively quickly implementable.

Assuming an additional transmission capacity of 0.5 GW from Poland, load shedding can be reduced by 700 hours, and the total number of load shedding hours comes down to 41% (compared to 49% in the "limited repairs" scenario). This amount of new capacity supports the Ukrainian system but is insufficient to fully address the deficit. Imports increase to 15.4 TWh (compared to 12 TWh in the limited repairs scenario). The import capacity utilisation remains stable at about 80%.

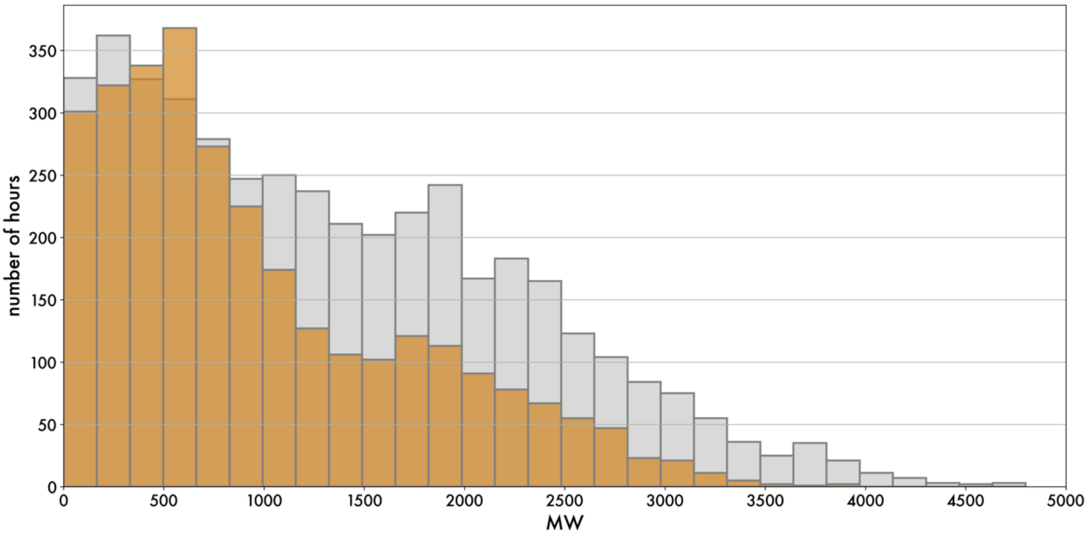
Figure 9: Histogram of load shedding in scenario “0.5 GW additional imports“ – 41% of hours totalling 4.1 TWh



2.9 Scenario: 1 GW additional imports

Even an additional transfer, e.g., from Hungary, of another 500 MW capacity contributes to a further reduction of 600 hours (total number of hours of load shedding would be 34 %). In addition, the import utilisation drops again, reaching 70% in this scenario. The total load shedding falls to 2.9 TWh.

Figure 10: Histogram of load shedding in scenario “1 GW additional imports“ – 34% of hours totalling 2.9 TWh



2.10 Scenario: All-of-the-above

The different options, limited repairs, +3 GW of OCGTs + 1 GW wind + 5 GW of PV + 2.5 GW batteries + 1 GW of imports can theoretically be combined. In a corresponding optimistic policy mix scenario, load shedding can be completely avoided from the time all additional capacities are fully installed, respectively when nuclear generation increases after maintenance[8]. Based on our assumptions, this would be the case from end of August 2024 when a large part of nuclear production comes back into the system. The new capacities installed in this scenario are utilised to varying degrees. PV and wind generation is fully utilised while OCGT and imports decrease. This would, for example, reduce gas consumption by 0.5 bcm compared to the +3 GW OCGT scenario.

This is not an optimised scenario - and it would likely not be realistic in terms of local deployment capacities to pull it off that fast. Hence, some prioritisation on how to use limited resources for achieving the largest impact would likely be needed to realistically reduce the required power cuts.

3 Conclusion

Russia is determined to destroy Ukraine's electricity and heat supply infrastructure, aiming at leaving populations and economy without energy. After the full invasion, over 80 percent of Ukraine's conventional power plant capacity has been occupied, destroyed, or attacked, resulting in a significant supply-demand mismatch that necessitates scheduled power cuts.

If the damaged power plants remain unrepaired, some Ukrainians could face electricity shortages for up to 90 percent of the winter hours, leaving one-fifth of the overall electricity demand unmet. However, this dire situation is not inevitable. The cornerstone of securing Ukraine's power supply

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[8] I.e., the reported load shedding of up to 4000 MW and totalling 1.4 TWh in Table 1 refers solely to the time during summer, before the contemplated generation investments, import increases and repairs have taken place.

next winter lies in strengthening its air defense systems. Without robust air defense, repair efforts and new investments are futile, and even securing contractors for these tasks would be challenging.

Several complementary measures can further mitigate risks on the energy side:

- Repairing partly damaged power plants: This can quickly and cost-effectively restore significant capacity. Therefore, ensuring the timely delivery of necessary parts into the country is critical.
- Deploying small gas generation units: These units, ranging from container-sized to full-scale gas turbines, can bolster a decentralized and resilient system without heavy investment in fossil assets. However, their deployment hinges on the availability of gas and gas infrastructure.
- Enhancing electricity imports from the EU: This requires regulatory adjustments and specific investments, such as upgrading a sub-station in Hungary. Additionally, integrating well-connected power units from outside Ukraine can be considered.
- Investing in renewables and batteries: These technologies offer long-term benefits beyond the immediate crisis. Second-hand wind turbines can generate power during winter, while solar panels can maintain electricity supply during summer nuclear plant refuelling.

A combination of solutions is feasible and desirable. In an ideal world without resource and timing constraints deploying “all-of-the-above solutions” can basically avoid load shedding once new capacities are operational. Given that load shedding is also anticipated in the upcoming summer due to nuclear power plant maintenance, the rapid implementation of these measures is crucial. To effectively utilize limited engineering, construction, and material resources, a clear strategy and prioritization of feasible steps to fortify Ukraine’s electricity system is imperative.

Table 1: Load shedding comparison of the scenarios

	TWh	% of net demand	hours	% of time	maximum MW
Baseline scenario	18.3	18%	7893	90%	6550
Limited repair scenario (LRS)	5.8	6%	4314	49%	4800
LRS + 1.5 GW OCGT	2.1	2%	2041	23%	4000
LRS + 3 GW OCGT	1.4	1%	1357	15%	3600
LRS + 1 GW wind	5.1	5%	3774	43%	4300
LRS + 5 GW PV	4.7	5%	3572	41%	4800
LRS + 5 GW PV & + 2.5 GW batteries	4.6	5%	3535	40%	4700
LRS + 0.5 GW import	4	4%	3603	41%	4300
LRS + 1 GW import	2.9	3%	2971	34%	3900
All-of-the-above	1.4	1.4%	980	11%	6550

4 Annex

We do not present the complete annex to the broader audience due to security concerns. In case of special interest, please contact the authors.