Low Carbon Ukraine
Policy advice on low-carbon policies for Ukraine

Supported by:

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

based on a decision of the German Bundestag

Policy Paper Series [PP/01/2018]

Balancing of fluctuating renewable power sources

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Berlin, November 2018

Implemented by

Berlin Economics

About Low Carbon Ukraine

Low Carbon Ukraine is a project that continuously supports the Ukrainian government with demand-driven analyses and policy proposals to promote the transition towards a low-carbon economy. In particular, the project has the mandate to support the work of the Vice Prime Minister as he coordinates the implementation of the Energy Strategy 2035.

This project is part of the International Climate Initiative (IKI) and is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) on the basis of a decision adopted by the German Bundestag.

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The authors acknowledge excellent research assistance from Elias Spiekermann and Clemens Stiewe.

Date of submission: 16th November 2018

Executive summary

Ukraine plans to substantially increase the share of renewable energy sources (RES) in its power mix. This prospect has stimulated an important debate on the technical capacity of Ukraine's power system to accommodate growing shares of fluctuating generation from wind and PV-solar. In this context, one crucial question is whether the current power plant park is able to balance the fluctuations from wind and solar generation.

Based on a dispatch optimisation model approach[1], we assess that the current Ukrainian power system can balance fluctuations of up to 15 GW of wind and solar. This assessment is based on the observed flexibility of the Ukrainian power plant fleet (nuclear, thermal, big hydro, pump hydro and cogeneration). Only with very high shares of renewables (15 GW), some excess generation from renewables must be curtailed. But even then, curtailment losses remain limited to about 10%.

In the short term, the existing power plant park should be sufficient to balance fluctuations from renewables. However, the aging stock of conventional power capacities as well as a potential increase of power demand will create pressure for action in the medium and long term. Furthermore, an integration of RES above 15 GW as part of a decarbonisation strategy will require the development of a power system that is much more flexible than the current one. Investment into power capacities, grids and substations need to take the long-term perspective into consideration.

Different technological and non-technological options for balancing fluctuating renewable generation – such as storage, the variable use of biogas, a market for balancing energy, increased cross-border integration and demand response – have to be considered in the development of the future power system.

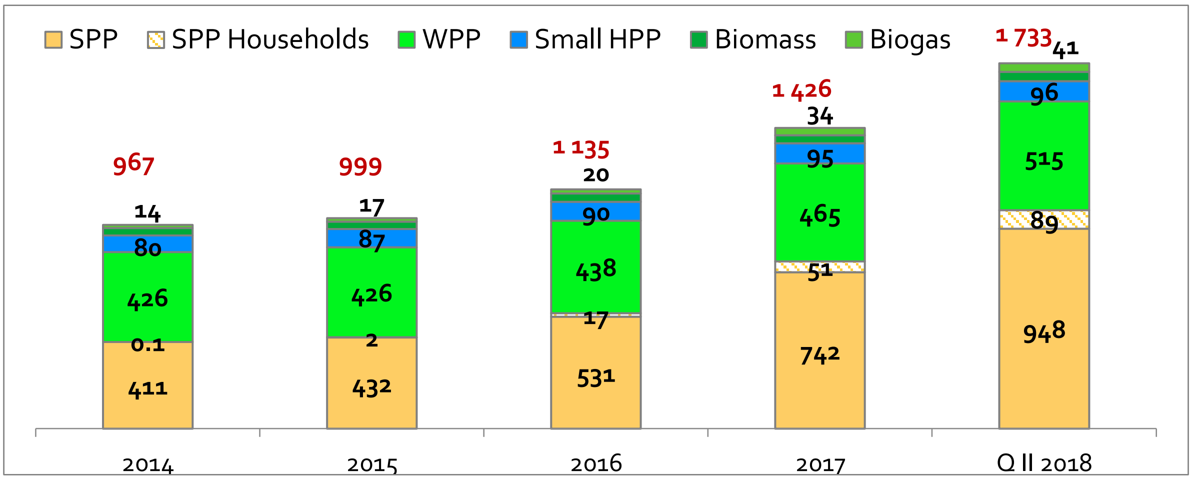
[1] Optimal dispatch model (ODM) version 1.0 from October 2018

Contents

1 Background and challenges

Thanks to an attractive green tariff scheme, falling technology cost, improvements in the overall business environment, and the significant technical and economic potential, the installation of renewable energy sources accelerated recently in Ukraine. From end 2016 to end of second quarter 2018, wind capacities grew by about 18 % and Photovoltaic-solar (PV-Solar) capacities by about 78 %.

Figure 1: Installed capacity of renewable energy objects under the "green tariff"



Source: SAEE (2018)

Increasing penetration of variable renewable energy resources (RES) – mainly wind and PV-solar – brings about new challenges for the development and operation of the electricity system. We want to discuss three challenges in this policy paper:

Challenge 1: Excessive fluctuations that cannot be balanced sufficiently quickly

The main challenge from an increasing integration of RES sources into a power system results from short-term load fluctuations triggered by weather events. Analysing this challenge requires assessing the relative size of fluctuations and whether, and if so, how they can be balanced.

Short-term fluctuations in weather-dependent RES either increase or decrease power supply, which leads – ceteris paribus – to market imbalances. An increase in RES capacities and generation could therefore result in imbalances of power supply and demand, which in turn pose a significant challenge for the power system.

Challenge 2: Excess power in cases of low consumption and high feed-in

Excess power results if current power supply exceeds power demand[2]. Such situations become more likely when a lot of renewable capacities are installed. This happens e.g. when the wind is blowing and the sun is shining but nuclear plants need to be kept running while demand is low. This poses a problem, as putting more energy into the system than is consumed will damage the system.

Challenge 3: Lack of power in cases of high consumption and low feed-in

In contrast to excess power, lack of power arises if demand for power exceeds power supply. Typically, such situations result if on the one hand power generation by renewables is low and on the other hand, demand by households and industry is high. This situation might arise when more and more conventional plants are replaced by renewable power capacities[3].

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[2] Given, that imports and exports are neglected and thus demand equals consumption.

[3] This might, for example, happen when the load factor (i.e., the hours they run per year) of conventional plants decreases as cheaper reneables are dispatched. If prices in the hours where the conventional plants are still

We want to answer following question: **Does the current power plant fleet allow for the integration of a higher share of fluctuating renewable power sources in Ukraine and which balancing options are appropriate?**

The analysis is based on available power load figures for 2017. Despite increasing RES capacities, the current power plant fleet is assumed to remain constant. In this analysis, we do not include potential constraints arising from technological challenges in power transmission.

This policy paper is organised as follows: First, we present the dispatch optimisation model we use for analysing the integration of renewables into the current power system. Second, we will analyse whether, and if so to what extent, the presented challenges impair the Ukrainian power sector in the short term and which appropriate solutions could be employed. A final chapter presents concluding remarks and an outlook.

We will discuss seven options to cope with the fluctuations from renewable energy sources. Thereby, the individual options can to a different degree address the three discussed challenges (see Table 1). Furthermore, long-term balancing options that are not described in this policy paper are depicted. (The number of '+' indicates to what extend the respective option can be used for dealing with a challenge.)

Table 1: Balancing options and assignment to challenges

Balancing option	Challenge 1 Fluctuations of RES	Challenge 2 Excess power	Challenge 3 Lack of power
Optimising the mix of wind and PV	++	++	++
Optimising the location of renewable capacities	++	+	+
Optimised use of conventional and biogas capacities	+++	++	++
Storage of power through pump accumulation	+++	+++	++
Curtailment of renewable power		+++	
Export of excess power	+	+++	+
Further, balancing options (not analysed):			
Demand response	++	+++	+++
Improved weather forecast	+++	++	++
Other storage technologies (P-t-X, batteries, CAS)	+++	+++	+++

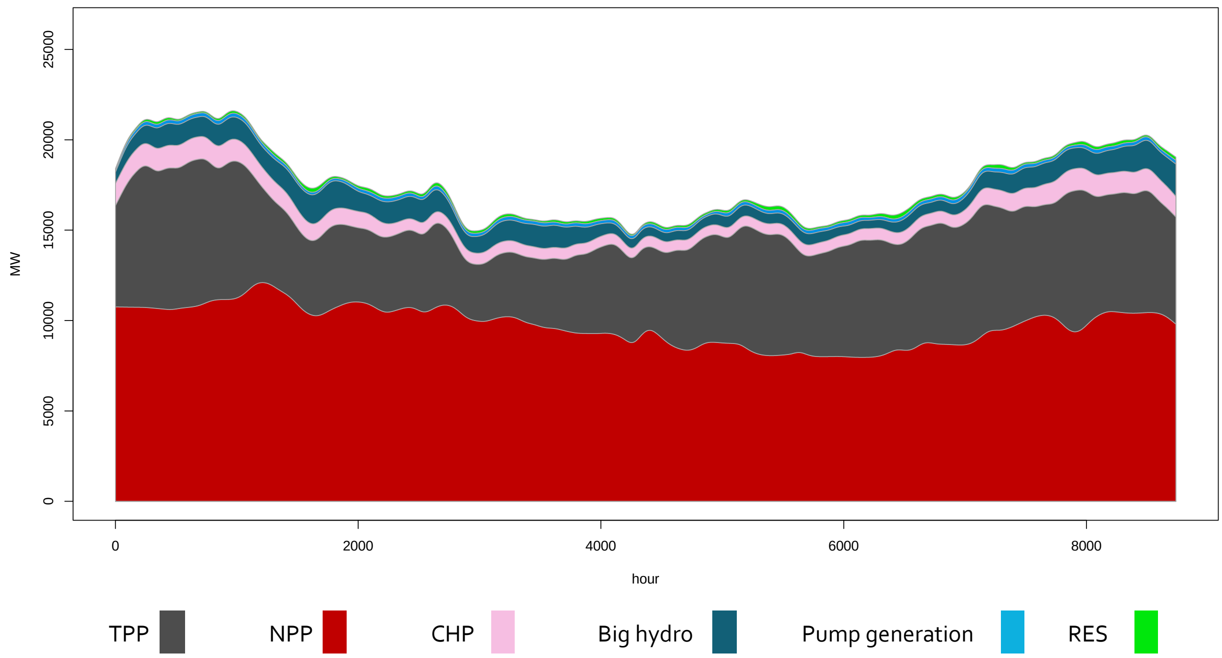
Source: Own presentation

needed to covert he demand are too low to cover the fixed costs of the conventional plants, those might exit the market.

2 Simulating increasing renewable power generation in a dispatch optimisation model (ODM)

We aim at analysing the effects of an increasing power generation by renewable energy sources (RES) on conventional power plants. This includes an analysis of effects on aggregated electricity generation, whether RES fluctuations lead to excess or a lack of power, and if they can be balanced by the power system. A comprehensive answer requires at least an analysis of hourly changes of power loads and the contribution of renewable sources to the aggregated power generation. The optimisation is based on hourly power load figures of Ukraine for 2017 (see Figure 2).

Figure 2: Power load Ukraine 2017



Source: Own presentation based on Ukrenergo

For answering this question, we develop an optimisation model that minimises the cumulated marginal (variable) costs of power generation. We employ the optimisation model for three different RES scenarios:

Table 2: Scenarios of RES generation for ODM V1.0

Scenario	Unit	Scenario I	Scenario II	Scenario III
Installed capacity	GW	5	10	15
Theoretical power generation by RES	TWh	12	24	35

Source: Own presentation

The optimisation is based on power load figures 2017 for Ukraine. The data differentiate between thermal (TPP) and nuclear (NPP) capacities, combined heat and power (CHP), big hydro, pump capacities, and pump storage as well as imports and exports. Furthermore, the data give the aggregated power generation by wind, PV-solar and small hydro (RES).

The optimisation routine minimises the annual aggregated and cumulated power generation costs by optimising the hourly dispatch of existing NPP, TPP and big hydro capacities and the utilisation of pump storage subject to technical constraints for each generation type. CHP generation is to a large extent driven by the demand for heat. Therefore, this power generation is assumed to be exogenously given and import as well as export is neglected[4].

RES generation is also given exogenously. In this first model version, 2017 RES power loads are simply scaled-up by a fixed factor in order to match the three scenarios. Thus, if the wind has not been blowing and the sun has not been shining in a certain hour in 2017, generation of wind and solar will also be zero in this hour in all our scenarios. The current model version neither includes ramping costs nor transmission constraints or maintenance needs.

The main model constraint is that aggregated power generation has to be equal to the exogenously given consumption trajectory at each point in time.

Different constraints regarding the capabilities of the different generation options (NPP, TPP, pump hydro and big hydro) are deduced from observed dispatch decisions in 2017. Two constraints restrict the power generation of each independent variable: upper and lower bounds of load and upper and lower bounds of hourly variability. While the first type of constraint makes sure that power capacities are utilised in the same range as they were in reality (2017), the second makes sure that hourly power load changes are limited to realistic values. Values for upper and lower load bounds are defined by the load bounds of 2017. For hourly variability changes we disregard the 88 most extreme hours (see Table 3). To replicate the annual seasonality, we restrict power generation of big hydro to monthly cumulated figures as realised in 2017.

Table 3: Constraints for bounds of independent variables for ODM V1.0

Independent variable	min load	max load	99% quantile hour-to-hour	
			decrease	increase
NPP	7,500 MW	13,000 MW	130 MW	120 MW
TPP	2,300 MW	10,000 MW	960 MW	760 MW
Big hydro	0	380-1,000 GWh cumulated per month depending on month 1,800-3,100 MW moving average of 24 hours depending on month	900 MW	860 MW
Pump hydro	0	1,300 MW	-	-

Source: Own presentation

[4] Currently cross-border transmission does not support international trade as an appropriate balancing option.

3 Analysis of balancing needs for Ukrainian power system

3.1 Excessive fluctuations that cannot be balanced sufficiently quickly

3.1.1 Reduction of variability through use of different variable energy sources

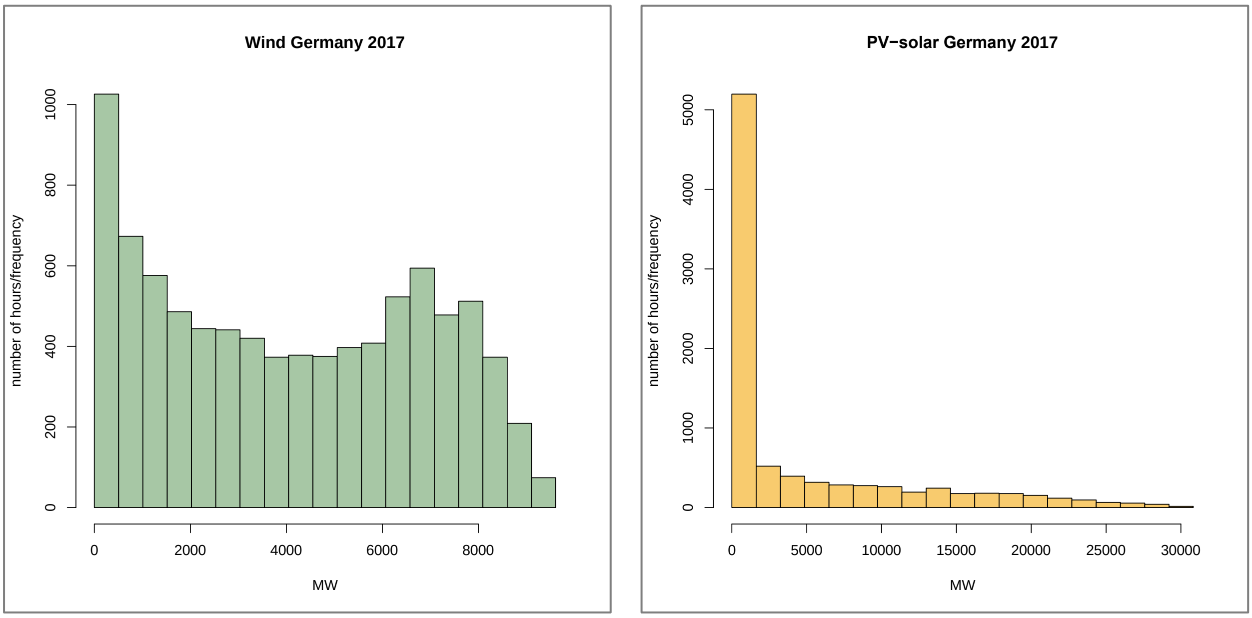
Figure 3The following figures depict histograms for the power generation of renewable energy sources in Germany and Ukraine. They indicate that the different types of RES are – to some extent – able to balance each other's fluctuations in power generation.

The share of hours with low power generation from solar-PV is higher than for wind (see Figure 3 for Germany 2017). Furthermore, PV-solar is more fluctuating because of variation in solar irridiation during the day. The variation coefficient[5] of PV-solar within 24 hours is 1.5 and 0.94 between 6 am and 7 pm. Compared to that, the variation coefficient of wind is 0.67.

Aggregating different variable RES reduces the variability of the power load. The variation coefficient for combined wind and PV-solar generation in Germany for 24 hours is 0.8 and thus approx. 80 % smaller than that of PV-solar in the same time range, but slightly higher than that of wind alone. During daylight hours (6 am – 7 pm), the variation coefficient for wind and PV-solar combined is 0.61, which indicates a decrease of fluctuations.

Furthermore, the fluctuations of higher aggregates of RES – wind, PV-solar, small hydro, and biogas (see Figure 4) – decrease again. In this case, Ukraine exhibits a variation coefficient of 0.7, while Germany's is 0.48 in 2017.

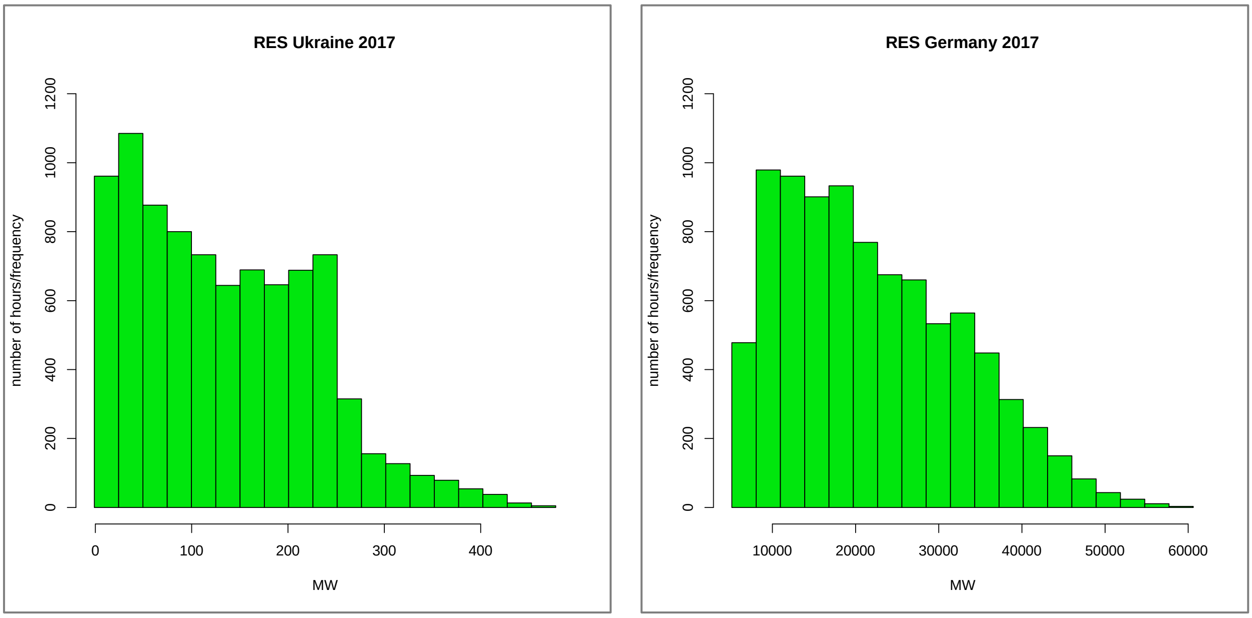
Figure 3: Histogram of power loads of wind and solar-PV in Germany 2017



Source: Own presentation

[5] Measured through Variation Coefficient: standard deviation of power load divided by mean power load

Figure 4: Histogram of power loads of RES capacities in Ukraine and Germany 2017



Source: Own presentation

Result: Wind and solar generation are largely independent from one another. A well-chosen mix of both generation technologies reduces the balancing needs.

3.1.2 Location selection of renewable capacities

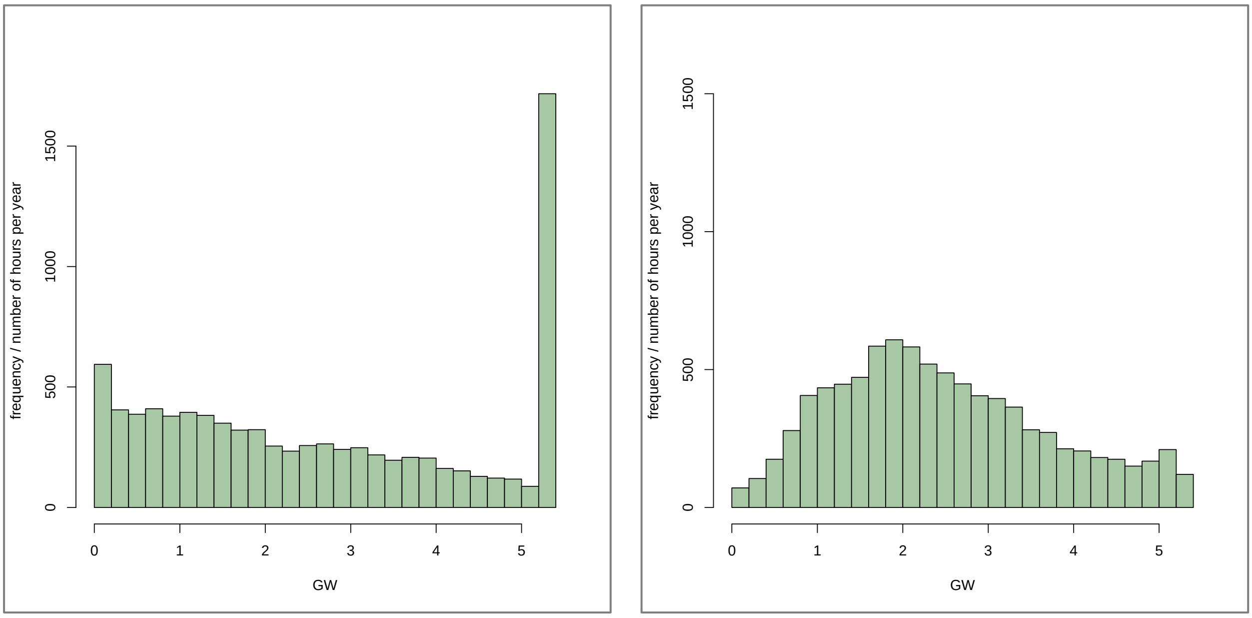
Power generation of variable RES depends on the current solar radiation and wind speed at the specific location. The more widely wind and solar installations are spread the less variable will their total generation get (this phenomenon is called “geographic averaging”). With a surface of approx. 603,000 km2 and located within five different climate regions, Ukraine has a considerable amount of heterogeneous locations for the development of renewable energy capacities. A utilisation of these differences allows a balancing of fluctuating renewable power generation solely by location selection for licensing renewable power plants.

Figure 5 presents histograms for two different wind power distribution scenarios. While in the first scenario, 5.3 GW of wind power capacities are located in one region only (with a maximum cumulated annual wind speed and thus power generation), the second scenario distributes the same installed capacity on 25 different locations in Ukraine (selection based on regions defined by Makarovskiy & Zinych (2013)). As depicted in

Table 4, power generation at the location with the “best” wind resources allows to produce 2 TWh per year more (+10 %), than spreading installation over many different – often less windy – locations. However, higher power output corresponds to higher fluctuation of loads, i.e., higher maximum hour-to-hour load changes (3.1 GW vs. 1.8 GW), with a larger number of hours without power generation (586 vs. 2 hours), and a larger number of hours with power generation below 10 % of installed capacities (1,241 vs. 282 hours).6

[6] Neither different locations for RES nor a differentiation between wind and PV-solar are considered in the version 1.0 of the Optimal dispatch model. An integration will follows in version 2.0.

Figure 5: Histogram for two wind power distribution scenarios – best location (left) and homogeneous (right)



Source: Own presentation

Table 4: Comparison of different location distributions of wind power in Ukraine

Power plant distribution		Concentration	Even distribution
Annual power generation	TWh	23	21
Maximal hour-to-hour load change	GW	3.1	1.8
Number hours of zero power generation	hours	586	2
Number hours load < 530 MW	hours	1,241	282

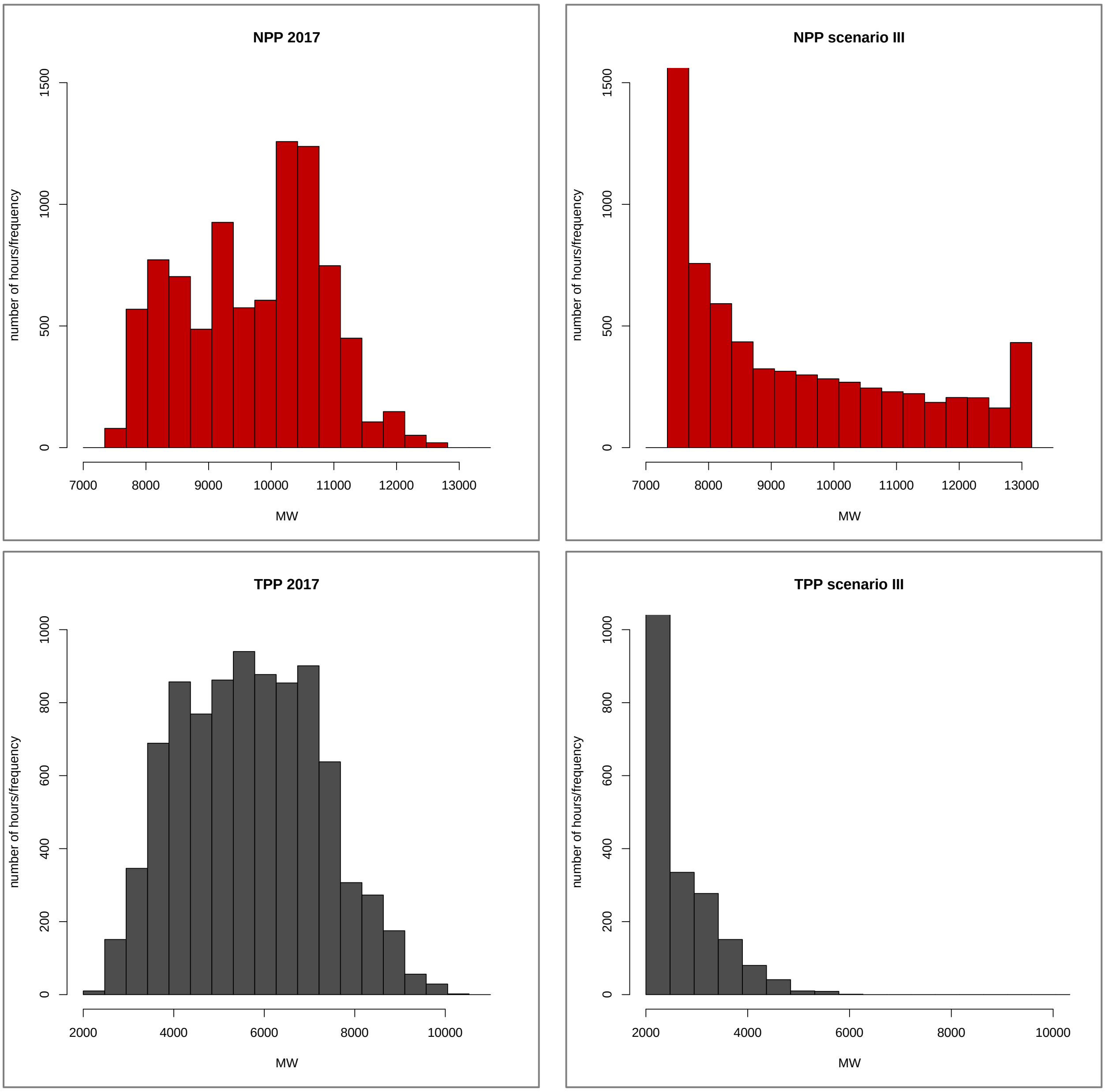
Source: Own presentation

Results: Locating weather-dependent fluctuating renewable energy heterogeneously in the territory of Ukraine reduces the need for other balancing options. Authorities responsible for licensing new wind and PV-solar power capacities should consider to provide specific incentives for a wider distribution of installations across the country, as otherwise investors might just concentrate all plants in the most sunny/windy regions.

3.1.3 Variable use of conventional capacities

We strived for assessing whether, and if so to what extent, NPP and TPP capacities can balance fluctuations of RES. As described above, we assume that both types of generation are used in the same load ranges as in 2017. However, hour-to-hour load changes are restricted to the range between 1% and 99% percentile of actual realisations (i.e., we considered the 175 hours with the most extreme observations as outliers and ignored them). Figure 6 depicts the histograms of power loads for NPP and TPP in 2017 (left part of figures) and as result of the optimisation for scenario III. Furthermore, Figure 7 gives the hour-to-hour changes of power loads for both power generation types in 2017 (left) and scenario III (right).

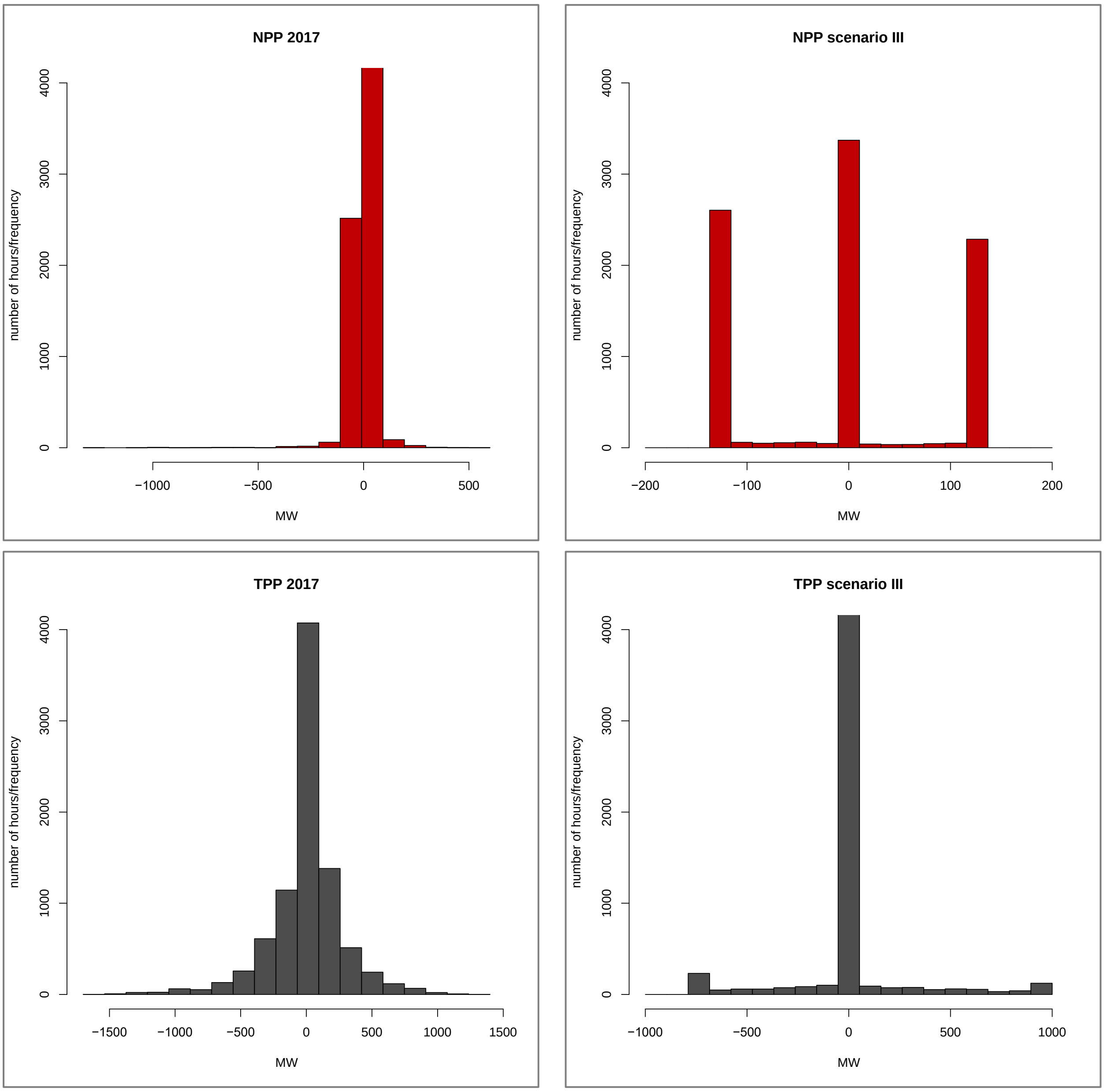
Figure 6: Histogram of NPP and TPP power loads 2017 (left) and scenario II (right)



Source: Own presentation based on ODM V1.0

The figures show that due to increasing balancing needs through higher integration of RES capacities (here in scenario III ~14 GW), NPP and TPP capacities operate more often at the upper and lower bounds. This holds especially for NPP capacities because power generation by them is – following our assumption – less expensive than that of TPP. Furthermore, in the optimisation approach, hour-to-hour load changes of NPP and TPP are less homogeneous than in 2017. This is a strong hint that load changes in 2017 were not driven by balancing needs but other technological requirements.

Figure 7: Histogram of hour-to-hour load differences of NPP and TPP 2017 (left) and scenario III (right)



Source: Own presentation based on ODM V1.0

Results: Through variable use of existing NPP and TPP capacities power load differences resulting from fluctuations of wind and PV-solar capacities can be balanced. We can show that without adaptation of hour-to-hour variability or with changes of power load range of TPP and NPP, 15 GW of RES can be integrated into the power system.

3.1.4 Storage of power through pump accumulation

Storage of power by pump accumulation enables balancing of renewable energy for an unlimited time up to the limit of installed pump storage volume and with loads up to installed pump capacities. Pump storage has the advantage of very fast reaction to changing power needs but leads to efficiency losses of about 30 % for a full cycle of pumping up the water and then releasing it to generate electricity.

Pump storage capacities in Ukraine amounted to approx. 1.3 GW (Mishra, 2017), while power generation by pump was approx. 1.5 TWh in 2017. An analysis of the correlation with renewable power generation reflects that these capacities were not used significantly for balancing renewable energy power fluctuations[7]. One reason might be the low overall RES power generation in 2017 did not require balancing.

Based on the optimisation model, we estimate how pump storage capacities would be utilised under different renewable power scenarios. In scenarios I and II (representing 12 and 24 TWh of renewable energy), the utilisation of pump generation remains limited. With an increasing penetration of renewable power sources, the utilisation of pump storage increases too. In scenario III, power generation by pumps amounts to 2.8 TWh per year. Furthermore, the correlation between power generation by RES and pump becomes significant at 0.44 in scenario III (see Table 5).

Table 5: Figures for utilisation of pump storage and pump generation in different scenarios

		Original power load 2017	Scenario I	Scenario II	Scenario III
Power generation by RES	TWh	1.2	12	24	32
Power generation by pump	TWh	1.5	0.00	0.6	2.8
Correlation between pump accumulation and RES power generation		-0.23	-	0.24	0.44

Source: Own presentation based on ODM V1.0

Result: With increasing RES utilisation, pump storage will contribute more to balancing of fluctuating renewable capacities.

3.1.5 Storage through and variable use of biogas capacities

Biogas currently is the least weather-dependent renewable energy source. Typically, biogas plants operate on a constant basis. Biogas plants operate approx. 7,800 hours per year, which represents a utilisation rate of ca. 90 % (Rohrig *et al.*, 2011). Therefore, on the one hand, power generation from biogas plants does not have to be balanced. On the other hand, biogas plants can be used for balancing variable renewable power sources, such as wind and PV-solar. Balancing through biogas leads to a demand-driven power generation. This can be achieved either by flexible biogas production concepts or biogas storage (Dzene and Romagnoli, 2015). The former can be guaranteed through influencing the anaerobic digestion process "[...] by changing the substrate composition and feeding rate or by changing substantially the configuration of a biogas plant" (ibidem).

We want to assess whether biogas storage might be an option for storing excess power in the short term.

[7] Power generation by pump is defined as outflow from storage capacities and defined as negative numbers. Here we present correlations by describing pump generation as positive values.

Biomass (biogas) provided approx. 200 GWh of power to the Ukrainian grid in 2017. This represents approx.20 % of the entire power generation from RES. Only 40 MW of installed capacity operate under green tariff schemes. Assuming a significant increase of wind and PV-solar – as presented in scenarios II and III – biomass power generation capacities would need to grow significantly for balancing fluctuations of wind and PV-solar through storage, or storage capacities would have to be much larger.

Therefore, balancing options through biogas remain limited in the short term. However, Ukraine's bioenergy sector has great potential for further development. Especially the generation of biogas offers reasonable costs and environmental advantages compared to liquid biofuels (1st and 2nd generation). Moreover, Ukraine's agricultural sector provides a significant amount of plant and animal residuals for biogas feedings.

The balancing options of biogas have to be taken into account in the further development of the biofuel sector. Entailing support schemes should differentiate between plants that provide balancing power through storage capacities and those that do not. Such support schemes can be part of the development of a balancing power market.

Furthermore, biogas production can be integrated into the natural gas sector. Due to high up-front investment needs, this poses a long-term solution only. Biogas production would ideally take place in locations with a high disposability of biogas feedstocks, which reduces transport costs. Biogas could then be fed into the natural gas grid and used either for export, domestic power generation, or domestic heat generation. The insertion of biogas into the grid here acts as a storage.

Result: Due to high up-front investments, biogas storage is not an appropriate option for balancing RES power generation in the short term. However, with an increasing share of biogas and biomass-fuelled electricity generation, balancing RES by biogas and biomass could play more prominent role.

3.2 Excess power in cases of low consumption and high feed-in

Excess power describes a situation that is characterised by power supply exceeding power demand. In principle, this can be resolved by decreasing supply or increasing demand. In practical terms, this can be achieved by the temporary curtailment of fluctuating renewable energy sources or exports of excessive electricity.

3.2.1 Curtailment of renewable power

Curtailment is a reduction of power generation below the possible level that a power system can generate under given conditions. Typically, curtailment needs are associated with situations of high RES generation, low power demand, and the inability to reduce loads of conventional sources or power storage by pump accumulation.

Curtailment volumes differ significantly between countries, regions, and thus individual power plants. Because of that, a high share of renewables does not indicate a high need for curtailment. Even though the total amount of variable renewable energy sources integrated in a power system theoretically influences the need for curtailment, better grid integration, an appropriate regulatory regime, and better forecasting reduce the amount of curtailment in a power system.

China is the country with the highest power generation from renewables. Yet, the share in total power production is moderate with approx.25 %. E.g., wind has a share of just 3 %. Nevertheless, significant curtailment in the wind power sector takes place. According to Brookings (2018), China had to curtail 49.7 TWh of wind power in 2016, which represents 20 % of the overall power generation by wind.

A recent analysis depicts wind power curtailment in England and Germany by (Joos and Staffell, 2018). Thus, offshore wind farms in England had an average curtailment rate between 0 % and 0.63 %. For Germany, they give an average curtailment rate of just 2.98 % (ibidem).

The analysis of curtailment effects has to differentiate between the macro and micro level. While curtailment options increase the flexibility of the power system and the degree of freedom for system operators, they reduce the income of energy producers. On the micro level, curtailment is economically inefficient in general as long as no compensation for lost profits takes place.

Economic efficiency on the macro level depends on the amount of curtailment, generation costs of all sources, costs for grid expansion and for regulation.

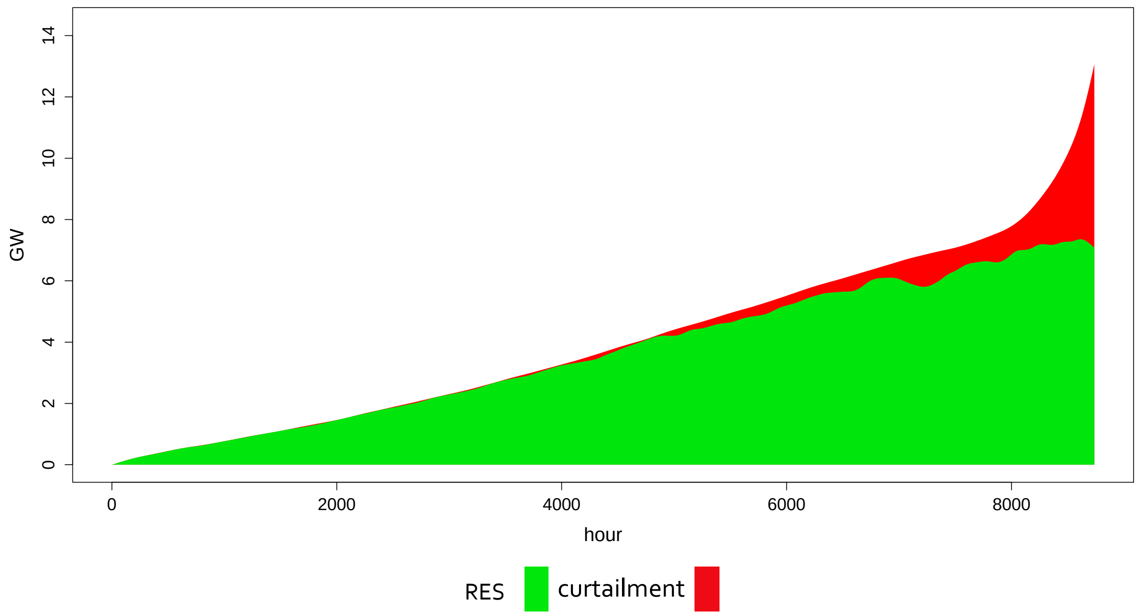
Table 6 presents the absolute and relative curtailment losses for the three RES scenarios8. In scenario I, curtailment is zero, scenario III has low losses of approx.1 % of RES power generation, while scenario three gives losses of approx. 10 %. For scenario II, it further holds that in approx. 50 % of hours, power generation exceeds the exogenously determined demand (see Figure 8.) The relative share (10 %) of curtailment losses is – according to Joos & Staffell (2018) – equal to the average losses of Scotland's wind power generation in the period 2012-16. However, installed capacity (of wind power) is twice the number assumed for Ukraine in this scenario.

Table 6: Curtailment losses in different RES scenarios

		Scenario I	Scenario II	Scenario III
Installed capacity	GW	5	10	15
Theoretical power generation by RES	TWh	12	24	35
Realised power generation by RES	TWh	12	24	32
Curtailment	TWh	0.00	0.30	3
Relative curtailment losses	%	0.0%	1.3%	10%

Source: Own presentation based on ODM V1.0

Figure 8: Curtailment of renewable power – 31 TWh (ordered for increasing power load per hour)



Source: Own presentation based on ODM V1.0

8 Figures resulting from our dispatch optimisation model version 1.0 October 2017.

Result: Even under the assumption that neither structure nor variability of existing power plants (except RES) change, curtailment losses of RES for avoiding excess power would not exceed 10 % in the given scenarios. Curtailment losses remain in a tolerable range up to a capacity of 15 GW of RES and could be further reduced by adaptation power generation of NPP, TPP and big hydro.

3.2.2 Export of excess power

According to Energiewende team (2015), international trade (export and import) of power plays a limited option for balancing power. The main reason for this is that "[...] bidding time frames for exports and imports (i.e., multiple days in advance, not day-ahead or intra-day) are too long to provide balancing functionality." In Germany, imports are prohibited from participating in the balancing markets (ibidem).

Given the fact that the Ukrainian power system is only modestly prepared for cross-border power balancing and the methodological challenges described above, export of power in cases of excess power remains a limited option in the short term. However, in the long run European power markets will have to deal with increasing fluctuations all over the continent. Cross-border power exchange will enable balancing fluctuations in large-scale regions in the future. This option is preferable over the development of power storage capacities (batteries) from an economic point of view.

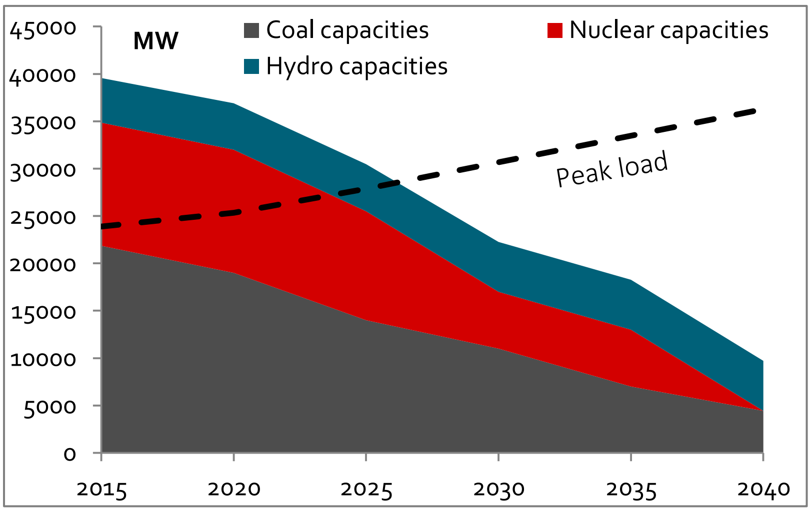
Result: A further integration of the Ukrainian power system with the EU system increases the potential compensation of excess power through exports.

3.3 Lack of power in cases of high consumption and low feed-in

Firstly, we want to analyse whether, and if so to what extent, the risk of lack of power is critical for Ukrainian power system in the short, medium and long term. Lack of power describes a situation where electricity demand exceeds supply. We want to differentiate between a structural and temporary lack of power. While the first results from insufficient capacities, the second typically results from fluctuations of (mainly renewable) power capacities that cannot be balanced through conventional capacities.

We want to analyse whether a structural lack of power is a risk for Ukraine. As described above, TPP and NPP power capacities are the backbone of the Ukrainian power system. Existing capacities currently exceed the maximal load, defined by power demand, by more than 30 % (see Figure 9). In the short term, existing capacities are therefore appropriate for covering peak loads.

Figure 9: Forecasted nameplate capacity for Ukraine

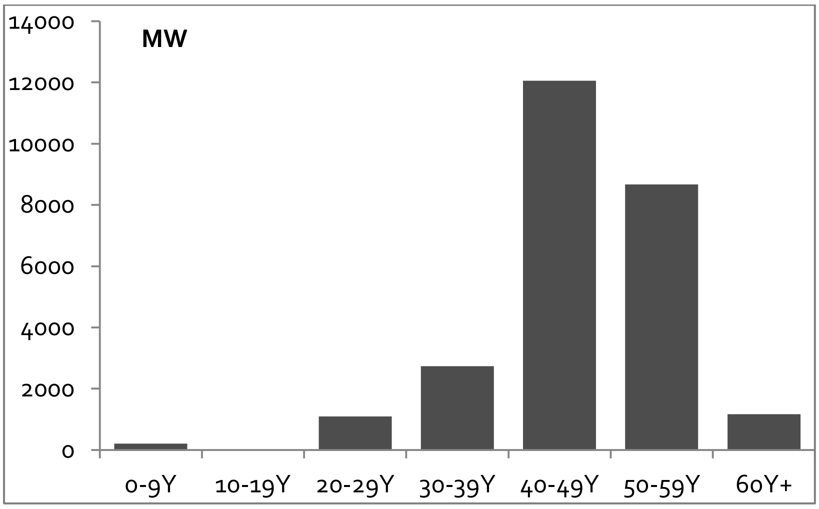


Source: Energy Strategy of Ukraine 2035, Savitsky (2016) and Ukrenergo baseline scenario

However, an increasing demand (reflected by higher peak loads) and a decline in usable conventional power capacities will lead to imbalances of supply and demand from mid of the next decade on. The main reasons for this imbalance are the age structure of NPP and TPP capacities and, to a lesser extent, an increase in power demand.

Figure 10 depicts the age structure of existing TPP and CHP power capacities in Ukraine, reflecting approx. 30% of installed capacities 2017. The average age of depicted capacities is 47 years, compared to the average age of coal power plants in Germany, which is 27 for hard coal and 30 for lignite, while the US average is 39 years. 85 % of installed TPP and CHP capacities in Ukraine are older than 40 years. Thus, a significant share of plants has reached the real lifetime of coal-fired power plants of 40-45 years (Markewitz, Robinius and Stolten, 2018).

Figure 10: Structure of TPP's and CHP's capacity by age



Source: National Plan for emission reduction; Energy conversion efficiency of 40% is assumed

Typically, the lifetime of power plants can be exceeded. However, aging capacities increase the costs of maintenance and the need for repair. Furthermore, ageing power plants increase the risk of unexpected shutdowns, which in turn increase the risk of lack of power.

Result: The current amount of installed capacities of NPP, TPP and big hydro in Ukraine provides an appropriate power supply to cover peak demand. From mid of the next decade on, an increasing demand as well as a decrease of available power capacities – triggered by aging power plants – will increase the risk of lack-of-power events. This effect has to be considered in the development of a new energy strategy.

4 Conclusion, recommendations and outlook

We find that – *apart from potential problems resulting from a lack of grid capacities or the absence of a market for balancing power* – the Ukrainian power system can integrate RES up to an installed capacity of 15 GW. Excess and lack of power are – from our point of view – no risks in the short term. Until around 2025, the Ukrainian power system should be able to balance fluctuations of renewable power either with the existing plant fleet or – to a small extent – by curtailment.

However, Ukraine needs to focus on socio-economic, political and technological developments that will affect the country's power sector in the future. Even if today's energy supply is mostly secured, path dependencies resulting from the long-term use of capital stocks in the power sector (power plants, substations and grids) could impair its further development. In the long term, such path dependencies might be very costly.

The following trends pose challenges for Ukraine's power sector.

Increases in power demand and peak load as well as structural changes of power demand

As described above, aging power plants threaten the supply of power in Ukraine. At the same time, economic growth boosts power demand and peak loads. Moreover, the structure of power demand might change due to increasing E-mobility, the development of smart homes and automatised production.

Technological progress of renewable power capacities

Due to technological progress, the costs of renewable power generation have dropped significantly during the last years – and are likely to decrease even more in the future. Furthermore, new technological developments (such as power to gas) will continue to offer better solutions to manage imbalances. Therefore, building new fossil power plants today might hinder the development of more cost-effective renewables in the future.

Further decarbonisation needs in power generation

It cannot be ruled out that international efforts strive for more binding GHG-reduction strategies of the global community in the next decades if carbon emissions continue to rise. An efficient preparation for such scenarios requires the development of an understanding of various emission reduction strategies in a country and an assessment of the macroeconomic costs related to them. A premature rejection of options through, e.g., focusing on fossil power capacities reduces the scope of action and might lead to second-best results in terms of economic efficiency.

Apart from focusing on the country's energy security today, Ukrainian decision makers need to take a long-term perspective on energy policy. This implies taking into account the entire scope of socio-economic, political and technological developments that could affect the country's energy sector.

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