REPORT 2

Integration of Renewables in the Ukrainian Electricity System

Acronyms

Acronym	Explanation
ACE	Area Control Error
ACE CL	Area Control Error - Closed Loop
ACE OL	Area Control Error - Open Loop
AFPCS	Automatic Frequency and Power Control Systems
AFR	Automatic Flow Restriction
aFRR	Automatic Frequency Restoration Reserves
BioPPs	Power plant on biogas or/and biomass
CBA	Cost Benefit Analysis
CE	Region Continental Europe (RG CE)
CENTREL	Union of electric power utilities in Central Europe (from Czech Republic, Slovakia, Poland, and Hungary)
CHPPs	Combined heat and power plant
CIS	The Commonwealth of Independent States
CTIS	collection and transfer information systems
ENTSO-E	European Network of Transmission System Operators for Electricity
FCR	Frequency Containment Reserves
FCR-D	Frequency Containment Reserve for Disturbances
FCR-N	Frequency Containment Reserve for Normal operation
FRR	Frequency Restoration Reserves
HVDC	High Voltage Direct Current
IPS	Integrated Power System of Ukraine
LFC Area	Load Frequency Control - Area
LFC Block	Load Frequency Control - Block
MAF	Mid-term Adequacy Forecast
MC	Monte Carlo
mFRR	Manual Frequency Restoration Reserves
NES	New energy Strategy till 2035
NGCA	Non-government-controlled area
NPC	National Power Company
NPP	Nuclear Power Plant
NTC	Net transfer capacity
NWP	Numerical weather prediction
PSO	Public special obligations
PV	Photovoltaic solar station
PVPP	Photovoltaic Power Plant
PWR	Pressurized water reactor
RES	Renewable Energy Sources
RR	Restoration Reserves
SOGL	System Operation Guideline EU 2017/1485 Guideline on electricity transmission system operation
TYNDP	Ten-Year Network Development Plan
TPP	Thermal Power Plant
TTC	Total transfer capacity
TSO	Transmission System Operator
UCTE	The Union for the Co-ordination of Transmission of Electricity
UCTPE	The Union for the Coordination of Production and Transmission of Electricity
UPS	The Unified Power System of Russia
WTGS	Wind Turbine Generator System
WPP	Wind Power Plant

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Introduction

The introduction of renewable energy sources (RES) power plants is a certain trend in the development of energy in the world today. The main argument for the feasibility of such a decision is justified by a constant decrease in the necessary investments in the construction of renewable power plants, which primarily concern solar and wind power plants and electricity storage systems.

But considering the integration of RES power plants, it is necessary to ensure correct consideration of the specific features of the power systems to which they are implemented. This is especially important for non-synchronous power plants, which include wind and solar power plants, because the effectiveness of their implementation largely depends on the climatic conditions (including consumption) and the existing generating portfolio.

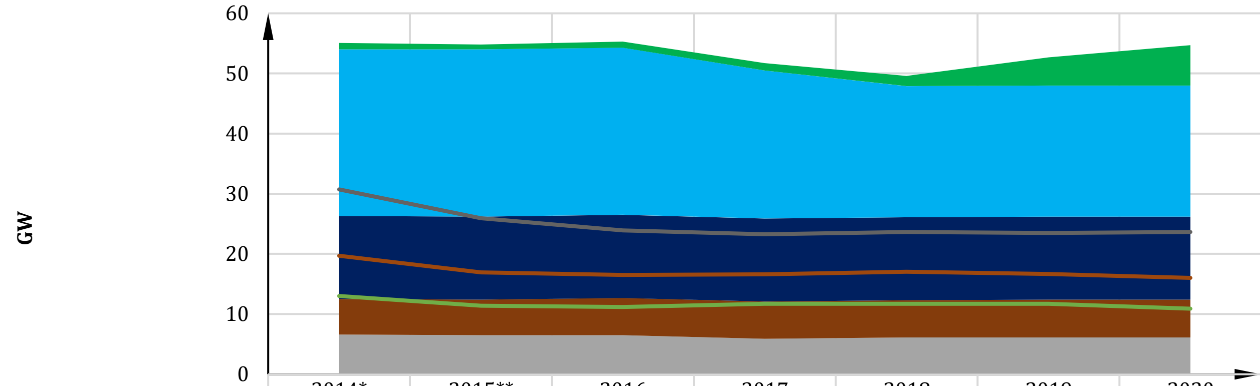
In this context, this report presents the results of the analysis of the development and functioning of the IPS of Ukraine in the conditions of integration into its composition of significant RES capacities and identified the main problems regarding the possibility of further increase of RES capacity, as well as possible directions for their solution.

1 Barriers

1.1 Review of the current state of the IPS of Ukraine with focus on power market

Currently, the IPS of Ukraine consists of the main part of the IPS of Ukraine and the Burshtynska TPP island. Annual consumption of the Burshtynska TPP island does not exceed 5% from the total annual consumption of the IPS of Ukraine (while the annual peak load does not exceed 1.1GW, and installed capacity in the Burshtynska TPP island is equal to 3GW, so this part of the IPS of Ukraine is an electricity exporter). The last one has interconnectors with ENTSO-E (directly with Hungary, Poland, Slovakia, and Romania), while the main part of the IPS of Ukraine has interconnectors with UPS (directly with Russia, Belarus, and Moldova).

The total installed capacities (see Figure 1) of power plants in the IPS of Ukraine (excluding units located in the Crimea and in the temporarily non-government controlled (NGCA) areas of the Donetsk and Luhansk regions) amounted to 54.7GW as of the end of 2020 with 52.9% of the total provided by thermal power plants (TPPs) and combined heat and power plants (CHPPs), 26.2% by nuclear power plants (NPPs), 11.9% by hydropower plants (HPPs) and pumped storage power plants (PSHPPs), 8.9% by wind power plants (WPPs), solar power plants (SPPs) and biogas/biomass power plants (BioPPs).



	2014*	2015**	2016	2017	2018	2019	2020
RES	1,1	0,8	1	1,2	1,7	4,7	6,7
TPP	27,7	27,8	27,8	24,6	21,8	21,8	21,8
NPP	13,8	13,8	13,8	13,8	13,8	13,8	13,8
HPP & PSHPP	5,9	5,9	6,2	6,2	6,2	6,3	6,3
CHP	6,6	6,5	6,5	5,9	6,1	6,1	6,1
Min consumption	13,0	11,4	11,2	11,7	11,7	11,7	10,9
Avarega consumption	19,7	16,9	16,5	16,6	17,0	16,7	16,0
Max consumption	30,7	25,9	23,9	23,3	23,7	23,5	23,6

years

Figure 1: Dynamics of Installed Capacities Structure of Power Plants in the IPS of Ukraine for period 2014-2020
** after 2014 without the Crimea.*
*** after 2015 without NGCA of Donetsk and Luhansk regions.*

It should be noted that, for example, in 2020 (see Figure 2):

1) Total transfer capacity (TTC) of interconnectors (in ENTSO-E and UPS directions) is equal to 4.635GW (235MW with Poland without possibility to import electricity, 700MW with Moldova, 900MW with Belarus, 2200MW with Russia, 650MW with Hungary, Slovakia and Romania), but for today it has been artificially (by presidential decree) reduced to 1GW in direction with Russia due to the military conflict in eastern Ukraine. Additionally, it should be noted that the net transfer capacity (NTC) is always less than TTC;

2) Maximum available TPPs capacity does not exceed 13GW (due to conservation, unsatisfactory technical condition of equipment, maintenances, lack of qualified personnel, high gas prices, which are much higher than price-caps, etc.);
3) Maximum available CHPPs capacity does not exceed 4.1GW due to a lack of heat load (most CHPPs operate in district heating mode) and due to high gas prices, which are much higher than price-caps;
4) In some periods during the year maximum available RES capacity does not exceed 80MW due to climatic conditions;
5) Full HPPs capacity is not available throughout the year due to a lot of environmental constraints.

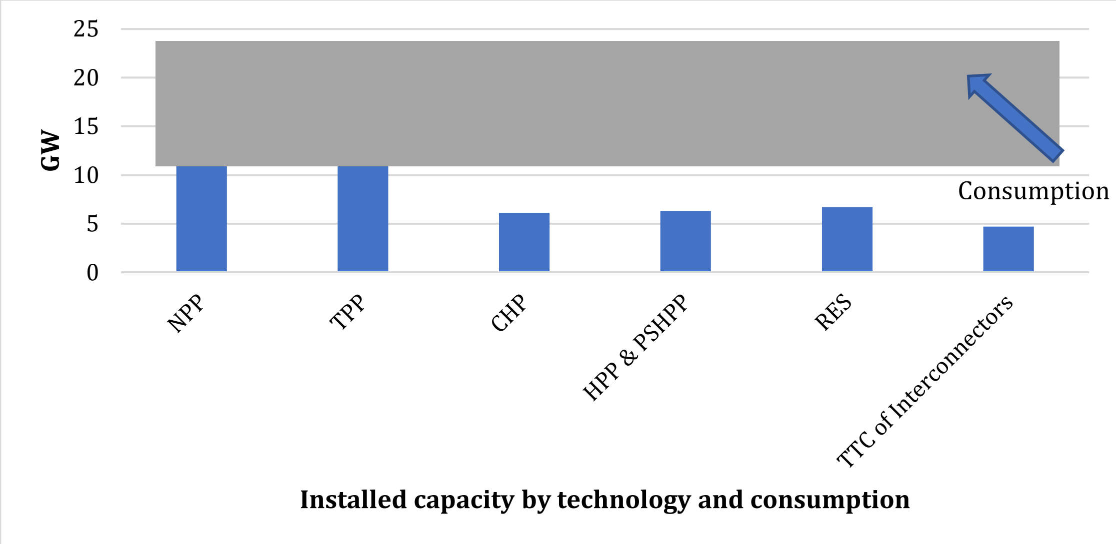


Figure 2:. Installed Capacities Structure of Power Plants in the IPS of Ukraine in 2020

The table below shows Capacify Factors for the Ukraine's generating fleet.

Table 1. Capacity factors [%] for generation fleet in the IPS of Ukraine (including the Burshtynska TPP island)

Year	NPPs	TPPs	CHPPs	WPPs	SPPs	HPPs	PSHPPS
2020	63	21	27	37	17	14	9

Low Capacity factors can be explained by the fact that:

1) even in winter 1-1.5GW of coal generation capacity are not available due to scheduled/planned maintenance;
2) 3.5-4GW of NPP capacity are not available due to scheduled/planned maintenance;
3) about 1GW (and in some periods up to 3GW) of coal TPP units are not available due to forced outages;
4) 1GW of coal TPP units are in reserve (as a replacement reserve);
5) 2.2GW of coal TPP units are not available because they are in a state of preservation before mothballing;
6) 4.6GW of gas TPP units are not available due to the lack and / or high cost of natural gas, and units with a unit capacity of 800MW have not been included in operation for over 9 years (perhaps some of the equipment has already been looted);
7) 3.1-3.6GW of CHP units are not available due to lack of heat load;
8) a number of capacities at HPP units are not available due to the lack of sufficient volumes of primary energy sources (in particular, water resources);
9) 2-2.5GW of coal TPP units are not available due to the unsatisfactory state of fuel supply, which has a cyclical nature.

For these reasons, the available operating installed capacity in the UES of Ukraine is close to the maximum electrical loads in the power system, while during the last 5 years during periods of maximum loads:

1) TPPs capacity are less than 9.6GW (with an installed capacity of 21,842GW at the end of 2020);
2) NPP capacity are less than 10–10.5GW (with an installed capacity of 13,835GW at the end of 2020);
3) HPP capacity are less than 3GW (with an installed capacity of 4,828GW at the end of 2020);
4) RES capacity sometimes is less than 0.1–0.2GW (with an installed capacity of 6,474 GW at the end of 2020);
5) CHPP capacity are less than 3 GW (with an installed capacity of 6,105GW at the end of 2020).

The main generation facilities of the IPS of Ukraine are found at (Figure 3):

- four nuclear plants (15 power units, including 13 rated up to 1,000MW each and two rated at 415MW and 420MW);
- cascades of seven hydropower plants on the Dnipro and Dniester rivers comprised of the total of 103 hydroelectric units, as well as three pumped storage hydropower plants (11 hydroelectric sets rated from 33MW to 324MW);

Figure 3: Location of Key Elements in the IPS of Ukraine.

— 12 TPPs with unit ratings of 150MW, 200MW, 300MW, and 800MW (75 power units, including six units rated at 150MW; 31 units rated at 200MW; 32 rated at 300MW; and six rated at 800MW), and three turbine generator units, as well as three large CHPPs with four units rated at 100(120)MW and five units rated at 250-300MW;
— RES power plants rated for the total of 6,700MW.

The majority of NPPs units have VVER-1000 series (model V-320) reactors with specifications similar to foreign-make pressurized water reactors (PWR). Nine nuclear power units are already past their 30-year design life and their service life has been extended by another 10-20 years (Table 2). Design life of three more nuclear power units is to expire shortly. One of the priorities of the NPPs Operator (State Enterprise National Nuclear Energy Generating Company Energoatom) is extending the service life of the existing power units after expiry of their design life. A reasonable duration of additional service life of NPPs units is from 10 to 20 years as determined in each case based on the results of safety re-evaluation procedure.

Table 2. Time in Service of NPPs in Ukraine

Power plant	Unit number	Electric power, MW	Reactor type	Date of commissioning	Design life expiry date	Status of work of power unit life extension
Rivnenska NPP	1	420	V-213	22.12.1980	22.12.2010	Service life extended to 22.12.2030
	2	415	V-213	22.12.1981	22.12.2011	Service life extended to 22.12.2031
	3	1 000	V-320	21.12.1986	11.12.2017	Service life extended to 11.12.2037
	4	1 000	V-320	10.10.2004	07.06.2035	In planning
Yuzhno-Ukrainska NPP	1	1 000	V-302	31.12.1982	02.12.2013	Service life extended to 02.12.2023
	2	1 000	V-338	09.01.1985	12.05.2015	Service life extended to 31.12.2025
	3	1 000	V-320	20.09.1989	10.02.2020	In planning
Zaporizka NPP	1	1 000	V-320	10.12.1984	23.12.2015	Service life extended to 23.12.2025
	2	1 000	V-320	22.07.1985	19.02.2016	Service life extended to 19.02.2026
	3	1 000	V-320	10.12.1986	05.03.2017	Service life extended to 05.03.2027
	4	1 000	V-320	18.12.1987	04.04.2018	Service life extended to 04.04.2028
	5	1 000	V-320	14.08.1989	27.05.2020	In planning
	6	1 000	V-320	19.10.1995	21.10.2026	In planning
Khmelnytska NPP	1	1 000	V-320	22.12.1987	13.12.2018	Service life extended to 13.12.2028
	2	1 000	V-320	07.08.2004	07.09.2035	In planning

Hydropower plays an exceptionally important role in operation of the IPS of Ukraine, as HPPs and PSHPPs are, in fact, the only source for its peak loads. In addition, pumped storage power plants make a significant contribution to smoothing out nighttime off-peak loads, first of all because all NPP and some TPP units unable to reduce their power output at night.

PrJSC Ukrhydroenerho is the largest hydropower company is Ukraine. The company has nine hydropower plants: the Kyivska HPP (440MW), Kanivska HPP (500MW), Kremenchutska HPP (687.4MW), Kamianska HPP (388MW), Dniprovska HPP (1,563.1MW), Kakhovska HPP(343.2MW), and Kyivska Pumped Storage Power Plant (PSHPP) (213.8MW) on the Dnipro river, and the Dnistrovska HPP (702MW) and Dnistrovska PSHPP (972MW), phase one of which is operational and phase two is in the pipeline, on the Dnister river. The IPS of Ukraine also includes the Tashlytska PSHPP (302MW, operated by Energoatom) whose construction is in progress and which is one of the components of the South Ukraine Electric Power Complex. The remaining HPPs operating as part of the IPS of Ukraine have a total installed capacity of 184.4MW.

The technology of thermal power generating facilities is dominated by coal-based power units with critical steam parameters (13MPa, 545°C) rated for 150-200MW, and coal-based and oil/gas power units with supercritical steam parameters (24MPa, 545°C) rated for 300MW and 800MW. The power plants with 150MW units were built and put in operation in 1959-1964, those with 200MW in 1960-1975, 300MW in 1963-1988, and 800MW in 1967-1977. So the youngest TPP unit in Ukraine was built more than 40 years ago. However, due to high manufacturing standards and a high margin of safety in the domestic energy sector, most units are still able to operate.

As of 1 January 2020, TPPs had 75 power units with installed capacities of 21,562MW, including:

- 68 coal-fired units with the capacities of 16,962MW, including 6 mothballed units and 1 unit under reconstruction (a breakdown taking into account the conversion of units to using G-brand coal):
  - 23 units firing A-brand coal with the capacities 6,439MW (5 units with the capacities 1,280MW are mothballed);
  - 45 units using G-brand coal with the capacities 10,523MW (1 unit of 300MW is mothballed and 1 unit of 300MW is under reconstruction);
  - 7 oil/gas units with the capacities 4,600MW (1 unit of 800MW has been mothballed).

No one of oil/gas power units were engaged in operation within the IPS of Ukraine for period more than 8 years (so the probability that they can be able to work is very low).

About 20% of TPP units have undergone reconstruction so far. However, the issues of bringing the environmental parameters to present-day requirements were not addressed in such reconstruction. In addition, such reconstruction had practically no effect on the change of technical parameters, except for the possibility of using coal of another brand.

The remaining power units are kept operational through overhauls and routine repairs; however, their deterioration is constantly worsening (Figure 4) and is approaching threatening levels in terms of possibility of their further operation without alteration.

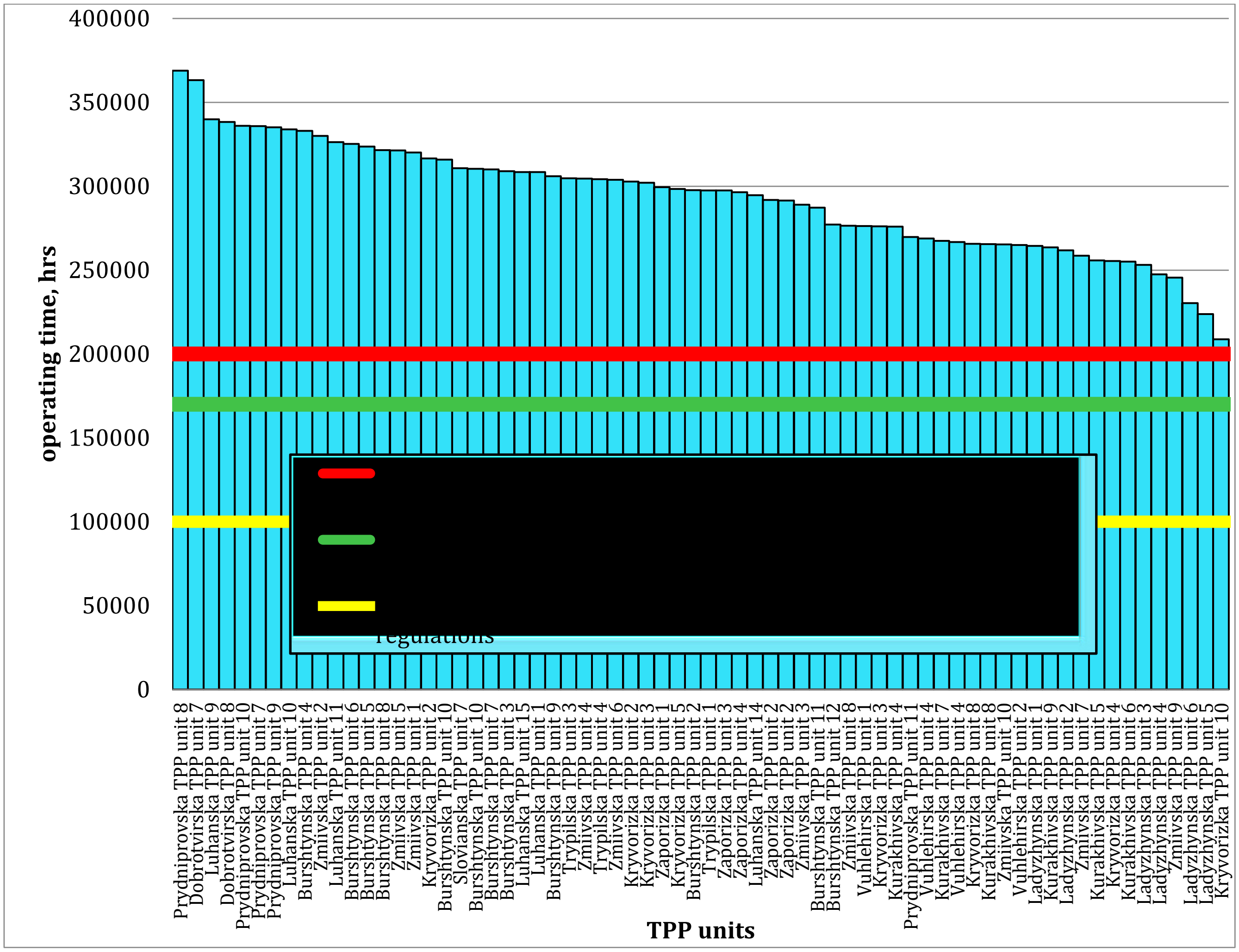


Figure 4: Accumulated Operating time of TPPs Units in Ukraine

There are three large CHPPs in Ukraine (Kyivska CHPP-5, Kyivska CHPP-6, and Kharkivska CHPP-5) which have power units with extraction turbines rated for 100/110MW and 250MW with the total capacity 1,670MW. In addition, there are in Ukraine a lot of small CHPPs with total installed capacity 4.43GW, but capacity of which for the last more than 5 years did not exceed 2.5GW.

By providing one of the highest feed-in tariffs in Europe the state has achieved a rapid increase in RES capacity for recent years, (Table 3). Taking into account state support and decreasing investment costs installed capacity of RES reached 3.6% in the overall capacity structure or 5.5 billion kWh in 2019 (e.g., the total electricity export from Ukraine's IPS to Eastern Europe amounted to 5.8 billion kWh).

Table 3. Dynamics of Commissioning of RES Generation Facilities

RES technology	RES year-on-year growth 2013-2020, MW							
	years							
	2013	2014	2015	2016	2017	2018	2019	2020
WPPs	108.9	137	-81.1	-123.6	20.4	60.6	636	86.2
SPPs	245.6	18.6	-222.9	98.9	300.4	466.4	2565.9	1807.2
BioPPs	0	35.4	17	10.2	34.3	1.8	43.8	57

A reduced growth of generating facilities using wind power in 2018 is explained by exclusion of WPPs located in NGCAs from the dataset.

The installed capacities of RES plants in the IPS of Ukraine, which are directly connected to the system and supply electricity amounts to:

— WPPs — 1,111.2MW;
— SPPs — 5,362.6MW;
— BioPPs — 199.5MW.

1.2 Analysis of Operational Modes of Generating Plants in the IPS of Ukraine

The structure of electricity generation experienced significant changes in 2013-2020 as shown in the Table 4.

Table 4. Structure of Electricity Generation in the IPS of Ukraine in 2013-2020, billion kWh

Years	2013	2014*	2015**	2016	2017	2018	2019	2020
Total	193.6	181.9	157.3	154.8	155.4	159.3	153.96	148.85
NPPs	83.2	88.4	87.6	80.9	85.6	84.4	83.0	76.2
%	43.0	48.6	55.7	52.3	55.1	53.0	53.9	51.2
TPPs	78.9	78.3	49.4	49.9	45.0	47.8	44.9	36.9
%	40.8	43.0	31.4	32.2	29.0	30.0	29.2	26.6
CHPPs & block-stations	16.6	14.3	12.3	13.3	12.4	12.5	12.6	12.8
%	8.6	7.9	7.8	8.6	8.0	7.8	8.2	8.6
HPPs & PSHPPs	14.2	9.1	6.8	9.1	10.6	12.0	7.9	7.6
%	7.3	5.0	4.3	5.9	6.8	7.5	5.1	5.1
WPPs, SPPs, BioPPs	1.2	1.7	1.5	1.5	1.9	2.6	5.5	10.9
%	0.6	0.9	1.0	1.0	1.2	1.6	3.6	7.3

* — without the Autonomous Republic of Crimea since April 2014.
** — without the Autonomous Republic of Crimea since May 2015 and without NGCAs of Donetsk and Luhansk regions.

Such a production structure is due to the specifics of Ukraine's energy sector generating facilities, which has excessive base-load capacities (NPPs and majority of thermal power units) and experiences an acute shortage of maneuverable capacities.

It is because of this that TPPs units designed for base-load operation are used as maneuverable capacities, and their significant proportion operates in off-design peak and midrange modes.

In this situation the TPPs coal-fired units of 150MW, 200MW, and 300MW serve as the main facilities for controlling the load schedule. Due to an unfavorable capacities structure (low proportion of maneuverable capacities, limits HPPs control range), it is common in the power system to practice daily stoppages of seven to ten units for the period of night-time load reduction followed by their startup for morning peaks, stoppages during daytime (to compensate for increased SPPs generation) and startups during evening peak loads. Such operating modes lead to additional equipment wear-and-tear, increased breakdown rate or excessive fuel consumption.

Taking into account the abovementioned factors, as well as the base load of HPPs during floods, an increasingly greater number of TPPs units is engaged in daily stoppages/startups during spring/summer seasons.

The total number of startups of power units (unit groups) of TPPs rated for 150MW to 300MW remains at a rather high level and amounted to 1,943 over 12 months of 2017, 2,255 over 12 months in 2018, and 2,478 during 12 months of 2019 [44].

It should be noted separately that following the events of 2014, when nearly all the Ukrainian coalmines which supplied anthracite and lean coal (ranks A and P) were left in NGCAs, a new problem arose for the Ukrainian energy sector with respect to permanent shortage of coal of these ranks. To reduce dependence on coal imports the generating companies have converted the TPPs units using anthracite coal to fire gas coal (see Table 5).

Table 5. TPPs Units on A-brand coal converted to fire G-brand coal

TPPs	Unit #	Installed power	Conversion started	Conversion ended	Duration, calendar days
			2017		
Zmiivska TPP	2	175	01.12.2016	01.09.2017	274
	5	185	15.04.2017	15.09.2017	153
Prydniprovska TPP	7	150	01.07.2017	26.10.2017	117
	8	150	01.08.2017	01.12.2017	122
			2018		
Trypilska TPP	4	300	26.10.2017	30.06.2018	247
Zmiivska TPP	6	185	15.06.2018	31.12.2018	199
Prydniprovska TPP	9	150	02.04.2018	31.10.2018	212
			2019		
Trypilska TPP	3	300	06.06.2018	31.03.2019	298
Prydniprovska TPP	10	150	03.05.2018	05.03.2019	306
Kryvorizka TPP	1	315	21.04.2019	31.10.2019	205

As the result, the use of anthracite coal decreased significantly in Ukraine from 9.2mil tonnes in 2016 to 4.9mil tonnes in 2017, 4.1mil tonnes in 2018, and 3.6mil tonnes in 2019 (estimate) and has been replaced with domestic G-brand coal [7].

In this situation, the relevance of availability of capacities of the power units using coal (G-brand) for covering the load schedule of Ukraine's IPS is growing substantially.

At the same time, the costs borne by TPPs to keep their power units operational are increasing, given further worsening of their operating conditions. In this case, of special importance is the performance of such activities (modernization, retrofitting, and repairs) at TPPs, which allow to restore/approach the design power ratings and control range parameters vis-à-vis actual values.

In some periods of 2019 and 2020, the NPPs operation additionally experienced balance restrictions, which required to reduce the NPPs capacities in the daily load schedule. Notably, during operation under the previous electricity market model in effect before 1 July 2019, the restrictions had been set by the market operator (State-owned Enterprise Energorynok) when preparing daily load schedules. In the new market model, electricity generation by the Ukrainian NPPs was limited by TSO based on balance reliability of the IPS of Ukraine due to a lack of balancing services. The dispatching restrictions on NPPs capacities were due, among other things, to the abnormally high ambient temperatures in the autumn and winter period and the resulting drop in power consumption.

Such operating conditions have again raised the issue of possibility of engaging NPPs units for daily load balancing, which in turn would require in-depth studies and trials to be followed by appropriate modernization of equipment in case of positive findings for such possibility.

In addition, one should also consider the option of exporting NPPs electricity surplus in terms of power system balance. In doing so one should provide for an appropriate mechanism of compensation for an increased electricity cost due to "leaching" of cheaper NPPs electricity from the balance, using the funds earned from export of NPPs electricity.

HPPs and PSHPPs are the most mobile peaking electricity producers. However, their installed capacities are not supported by water resources for regulating the daily load schedule in full, especially in recent low water years. For example, in 2020, in particular, HPPs electricity generation was the lowest in the last five years (such events are cyclical, accordingly for every 10 years there are about 5 dry years, 2 wet years, and 3 normal years). Also, the 2019/early 2020 autumn and winter period weather conditions were characterized by abnormally high temperatures, low precipitation, absence of accumulated snow, which will also impact the availability of water resources and HPPs operating conditions. Besides, operation of the Dnistrovska PSHPP is influenced by the existing network infrastructure, which leads to operational restrictions when plant storage pumps are used in normal pump operation.

The launch of the new electricity market has caused a number of problems of both economic and technical nature for the operating conditions of HPPs and PSHPPs. This is due to that deviations of actual electricity use from planned load scheduled have been occurring significantly more often since 1 July 2019 than was the case with the previous market model. Accordingly, the number has increased of dispatch instructions to HPPs and PSHPPs to change capacities in order to maintain the power system balance. Still, HPPs and PSHPPs continue to be engaged in automatic and manual frequency and load control, as well as controlling voltage and reactive power, thus assuring balancing in the Ukraine's IPS, including to compensate for any imbalances created by green tariff generators. In addition, as a party responsible for the balance, PrJSC Ukrhydroenerho must independently settle its own imbalances. Over the time, the market has stabilized (including by improving load forecasts, and by gaining experience of participants in a competitive electricity market, ie under the new market model, which has been launched 1 July 2019).

Obviously, increasing the share of RES requires increasing flexibility. However, the IPS of Ukraine is hard to characterize as flexible. This is indicated by follows (the main):

1) Not small start times for all TPPs units (the average value is equal to 10 hrs and with increasing units installed capacity, this value only increases);
2) Huge start times for all NPPs units (the average value is equal to 23.2 hrs);
3) Regulation range for all TPPs is too small (the average value of minimum stable generation level - as a proportion of nominal capacity - is not less than 25-35% below nominal capacity;
4) Regulation range for all NPPs is paltry (the average value of minimum stable generation does not allow for more than a 2-3% reduction to the power output relative to nominal capacity. In comparison typical European plants can reduce the power output with about 40%);
5) Most of all CHP units cannot work without heat load (therefore most of the year do not work at all) and in the periods when they can work, CHPPs supply electricity on a flat schedule (caused by the technological features of such power plants);
6) Regulation range for all PSHPPs units is equal to 0% (i.e. on/off);
7) All reserves (including FCR and FRR) allocated on TPP, HPP and 1 CHPPS units (all the rest do not take participation in providing ancillary services).

Therefore, given the above described problems, one can conclude that the existing sources of generation in the power system are at a phase of exhausting their physical resources to assure daily control and frequency containment and restoration reserves, which points to an urgent need to address the problem of increasing the flexibility of the IPS of Ukraine (using new flexible generating facilities, flexible demand and interconnectors).

One of the providing role in power system operation is given to interconnectors. Analysis of their work indicates that they are currently:

1) In Burshtynska TPP island mainly serve as a tool for electricity exports to ENTS0-E member countries (both in summer and winter periods);
2) In the main part of the IPS of Ukraine serve as a balancing tool and a tool for import (in winter period) / export (in all other periods of the year).

However, given that no significant geographical redistribution of consumption in Ukraine is expected by 2030 (see Figure 5), it is necessary to envisage the restructuring of the most of the Ukrainian high voltage grids (including substations), as all electricity flows will be carried out through the Zakhidnoukrainska Substation, which capacity factor for now are already close to their design maximum (see Figure 6).

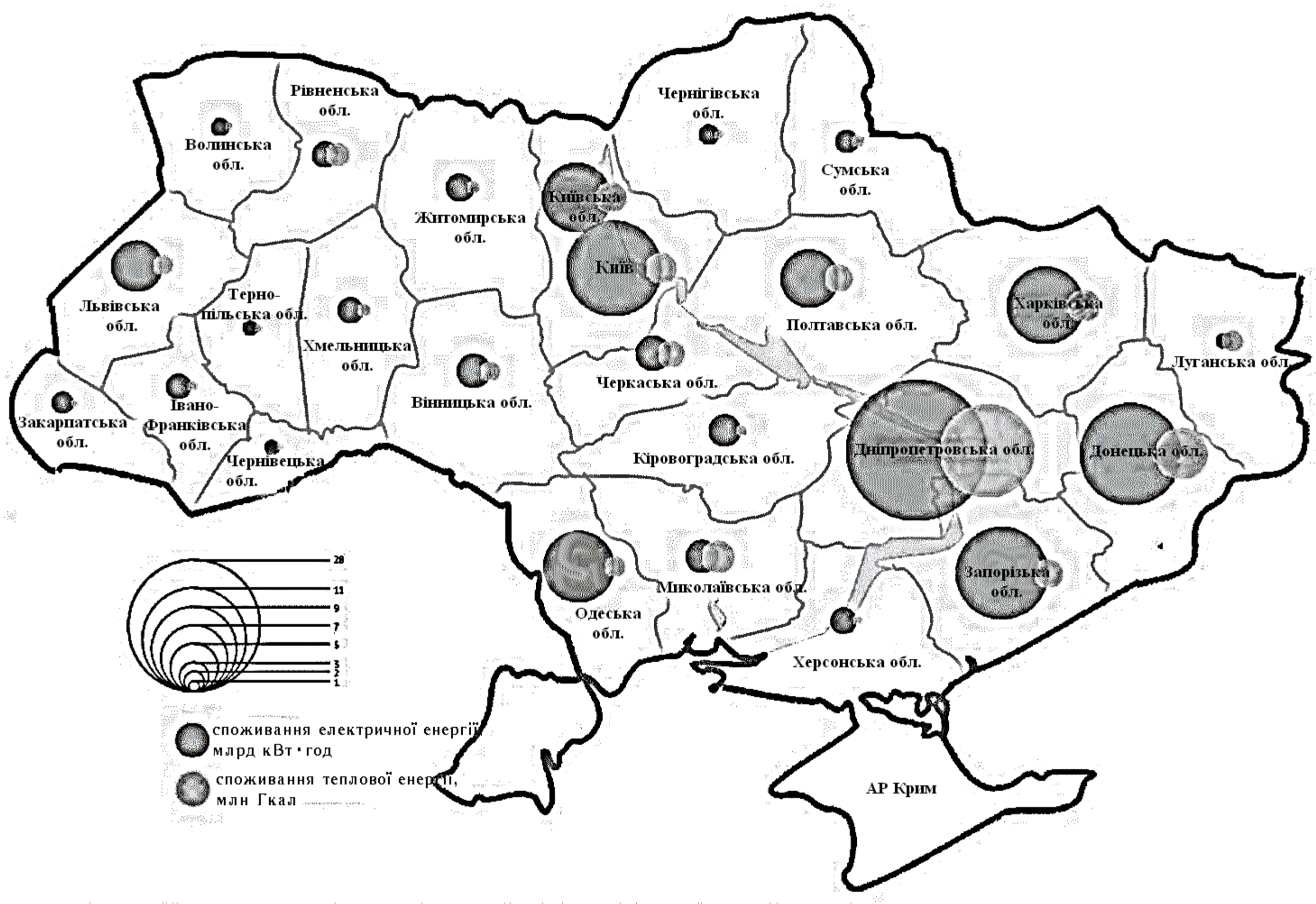


Figure 5: Electricity (dark grey) and heat (light grey) consumption density map of Ukraine in 2020

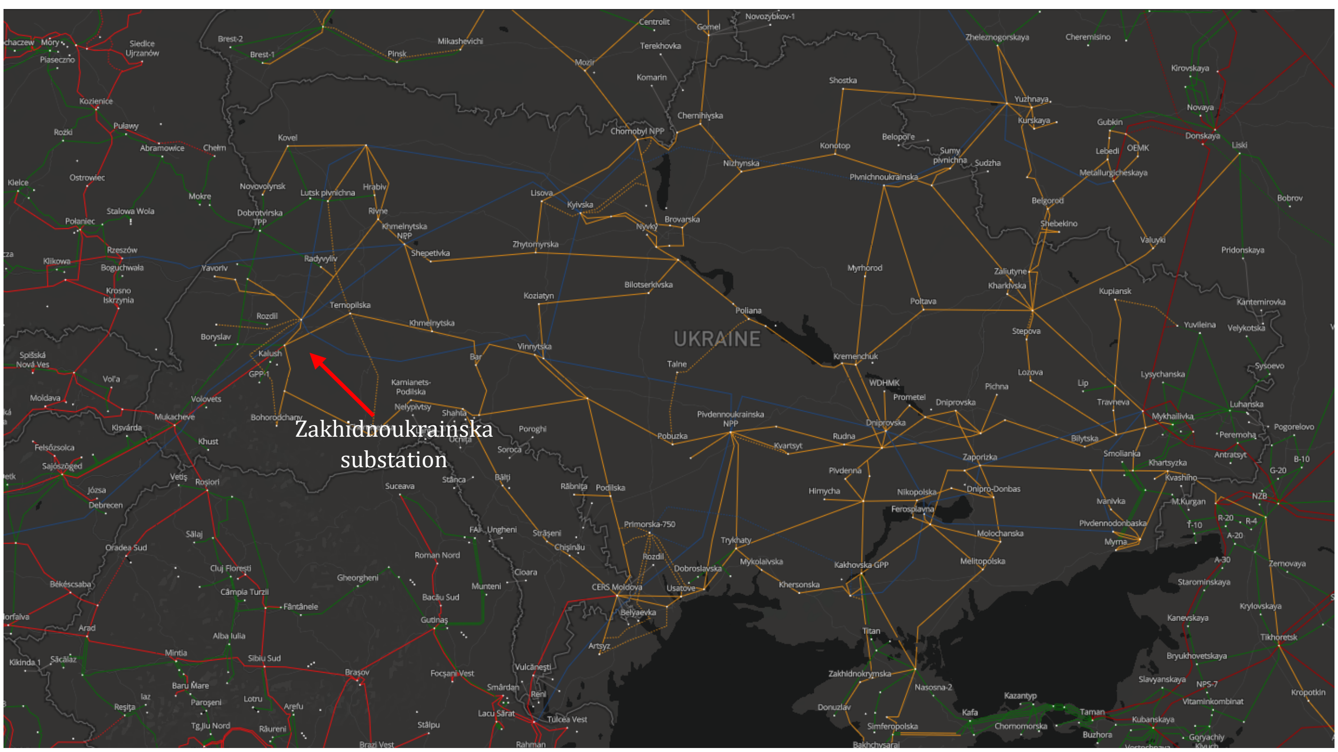


Figure 6: Snippet of Pan-European grid map in 2020

As seen from the results of the analysis of the status of generating facilities in Ukraine and their operating conditions, the IPS of Ukraine can be described as currently having sufficient generating capacities (even with some part of generating facilities left in non-government-controlled areas) compared to the total power system load. However, this is mainly a base-load (inflexible) capacity not designed for frequent and rapid changes of operating modes, and some of those facilities, which are able to change their operating modes (mainly concentrated at TPPs) are past their service life. Thus, the IPS of Ukraine has an insufficient flexibility.

1.3 Review of Current Regulatory framework in Ukraine

The rapid development of RES in Ukraine has occurred due to the one of the largest feed-in tariffs in Europe and due to decreasing investment costs. Fixed feed-in tariffs are provided in Ukraine to all RES producers without holding auctions (the first auctions are expected to be held in the coming years), but for producers who already have green tariffs, tariffs will be extended until 2030. As feed-in tariffs significantly exceed the prices in any of the segments of the electricity market, the TSO was obliged to compensate the difference between the market price and the feed-in tariff. At the same time, all electricity produced by RES producers who have received feed-in tariffs should be purchased by the State Enterprise "Guaranteed Buyer", which acts as a trader (not the end consumer). Therefore, the last one is forced in accordance with current legislation to purchase all electricity produced with RES, even if there is no demand for this electricity. In 2019 and 2020, TSO had to curtail the capacity of RES for short-terms (caused by inflexibility and lack of reserves in current portfolio) in order to keep a balance in power system, which led to a shortfall in profits by RES producers for unsold electricity. As a result, in case of RES curtailment, TSO was obliged to compensate RES producers for the cost of unsold electricity at a price equal to the feed-in tariff. In this case, according to current legislation, the RES curtailment is the last of the possible tools to achieve balance (this approach is not market-based because it does not take prices into account). Thus, RES power plants do not provide any ancillary services, and until the beginning of 2021 were not responsible for keeping the balance in the power system and were not responsible for keeping their own schedules of electricity production. Apparently, this did not stimulate RES producers to provide quality forecasts of electricity production.

On the other hand, under market rules according to legislation there are merit-order list. But an exception from merit-order list are RES-producers, which have feed-in tariffs, who, regardless of the offer price, always comes first in this list. Thus, such RES-producers displace producers which provide reserves (primarily TPPs), so there is an increasing deficit of reserves in the IPS of Ukraine (obviously there is a question of providing reserves for further RES growth).

Among other things, in Ukraine, in order to keep electricity prices for the population (is about a third of total consumption, see Figure 7) at a low level, since the launch of the updated model of the electricity market in 2019, there is a public special obligations (PSO) mechanism, which obliges to sell electricity to the public at non-market, non-competitive tariffs (approved by the regulator at the request of the Cabinet of Ministers and are periodically reviewed) produced by:

1) State enterprise Energoatom up to 50-55% of the own total production (in the structure of production nuclear power plants now make up a little more than half);
2) State enterprise Ukrhydroenergo up to 30% of own total production;
3) Several small state-owned CHPPs.

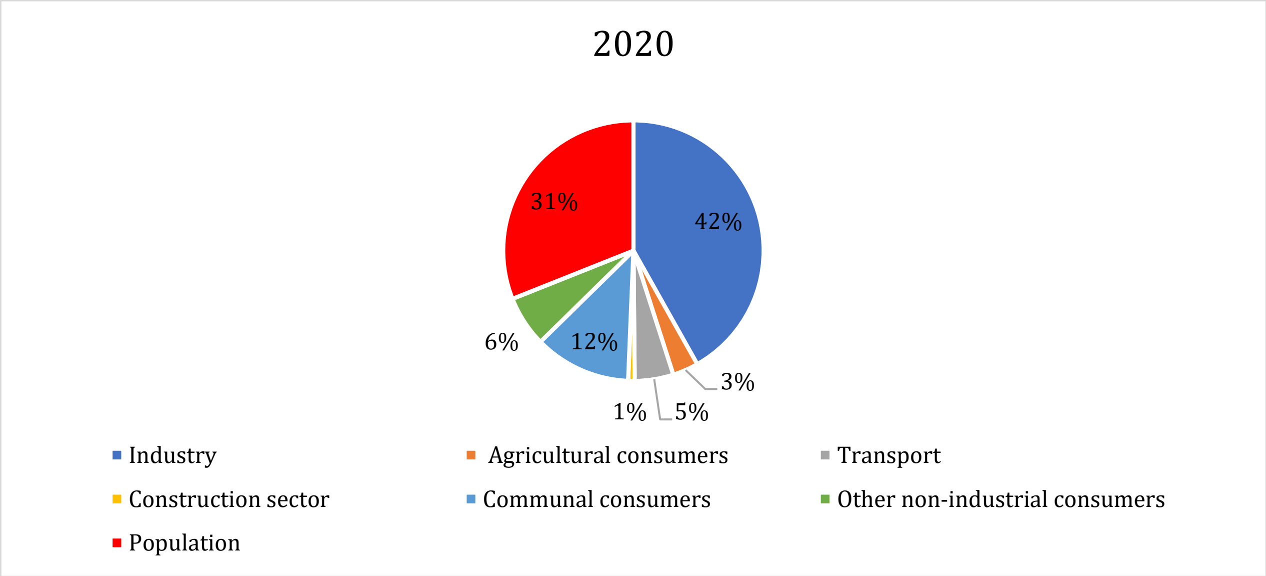


Figure 7: Electricity consumption structure in the IPS of Ukraine in 2020

The role of a trader is played by the State Enterprise "Guaranteed Buyer", which buys electricity from the above-mentioned producers (based on its own consumption forecasts) and sells this energy to the population. It so happened that the Guaranteed Buyer often buys much more electricity than the population needs (not only because of poor forecasts), which leads to significant imbalances. This in turn is a challenge for the energy system, as most of this electricity for the population is produced by inflexible NPPs, which requires flexibility and balancing costs (first of all for TSO) increasing.

Ukraine also has a number of regulatory price restrictions (ie price-caps) in all market sectors (including the ancillary services market), with the exception of the forward market. Such price-caps negatively affect the operation of natural gas-fired power plants (i.e. TPPs and CHPPs), as the cost of electricity exceeds the price-caps. In the market of ancillary services, in turn, there are also unreasonable price-caps, which negatively affects the reserves provision in the energy system (see Table 6).

Table 6. Current price-caps on ancillary services in the IPS of Ukraine in 2020 (UAH/MW)

	FCR	**aFRR**	**mFRR**	**RR**
Upward	512.27	512.27	512.27	512.27
Downward	289.27	289.27	289.27	289.27

On the one hand the application of such price-caps in the market of ancillary services does not stimulate the development of automatic reserves, and on the other hand does not create preconditions for the application of proactive balancing philosophy.

In addition to the above, one of the restraining factors in the development of RES in Ukraine is the excessive settlement period for market operations, which is currently 60 minutes (as in many other European countries) during which it is difficult to adhere to electricity production / consumption schedules, which increases the number of dispatcher commands and balancing energy volumes. That's why more and more countries (including Denmark and Belgium) are trying to move to shorter settlement period.

2 Simulation assumptions and results

2.1 Assumptions for the IPS of Ukraine

Based on the assumptions about the development of the transmission system in Ukraine, set out in the Ukrainian Ten-Year Network Development Plan (TYNDP), we should expect the following transformation of the generation portfolio, consumption, and grid (Table 7).

Table 7. Actual (for 2020) and expected (for 2025 and 2030) generation portfolio, demand and interconnectors

Year	Yearly demand, TWh	WPPs, GW	SPPs, GW	NPPs, GW	TPPs, GW	CHPPs, GW	HPPs, GW	PSHPPs, GW	NTC, GW
2020	130.4	1.11	5.36	13.835	21.8	6.1	4.8	1.993	4.685
2025	151.5	4.5	7.675	13.835	8.227	4.9	4.9	1.993	1.7
2030	159.75	6.5	9.8	13.835	3.685	3.4	4.9	1.993	1.7

It should be noted that the increase in capacity compared to 2020 is expected only for RES and interconnectors, and the decrease in capacity of TPPs and CHPs is caused by the implementation of the National Emission Reduction Plan (developed in accordance with the Paris Climate Agreement).

Interconnection between different modelled countries are managed though Net Transfer Capacity (NTC) modelling. Such modelling is common in many generation adequacies, amongst others the ENTSO-E Mid-term Adequacy Forecast. NTC modelling considers the exchange on each border as an independent variable.

NTC modelling was chosen for this analysis, since it is the most common market coupling mechanism which is present in the region. Within the Continental European Synchronous Area, currently only the Central Western European region (Belgium, The Netherlands, France, Germany, Austria) area using flow-based modelling in practice.

The NTC assumptions which are used for the interconnections for this analysis are based on information received from Ukrenergo as well as data from the ENTSO-E Mid-term Adequacy Forecast (MAF) report, and are shown in Figure 8. The figure shows as well which links are activated:

- The link with Poland, assuming the 750 kV connection "Khmelnitska NPP - Substation Rzeszow" is switched off (in 2020, the Polish side refused to develop this link, although this link could increase the NTC between Ukraine and Poland to 2235MW);
- The link between the Burshtynska TPP island and the rest of the IPS of Ukraine with an NTC of 750MW.

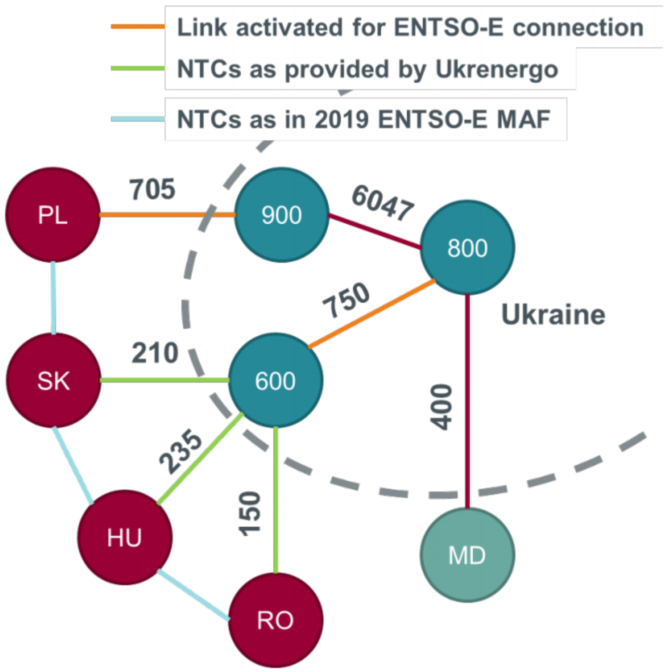


Figure 8: Interconnection assumptions for the connection of Ukraine to ENTSO-E Member States

The Ukrainian system is modelled with seven different areas, and the exchanges which can occur between them are shown in Figure 9 (numbers in the circles indicate the code of the subsystem, while numbers near the lines indicate the NTC of the links) . At all times, the Moldavian system is assumed connected to the Ukrainian system with a total capacity of 800MW.

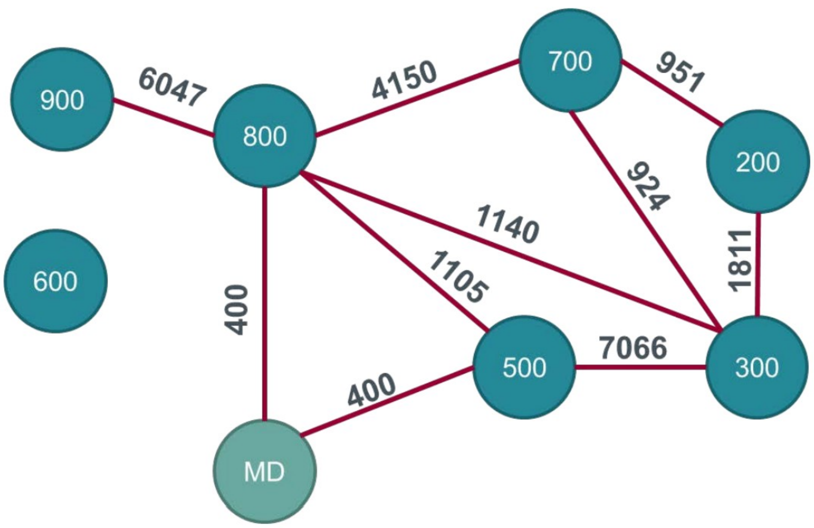


Figure 9: Transmission limits applied between different Ukrainian zones

2.2 Assumptions for other countries

As was already shown in Figure 8, the neighboring ENTSO-E Member States have also been modelled in detail for this analysis. The assumptions used for this modelling are in line with those used for the Mid-term Adequacy Forecast. However, since for this project no use could be made of the ENTSO-E Pan-European Market Modelling Database, public information and in-house experience contributed significantly to the development of these assumptions as well. An overview of the dispatchable generation assumptions and the peak load for these neighboring ENTSO-E Member States is provided in Figure 10.

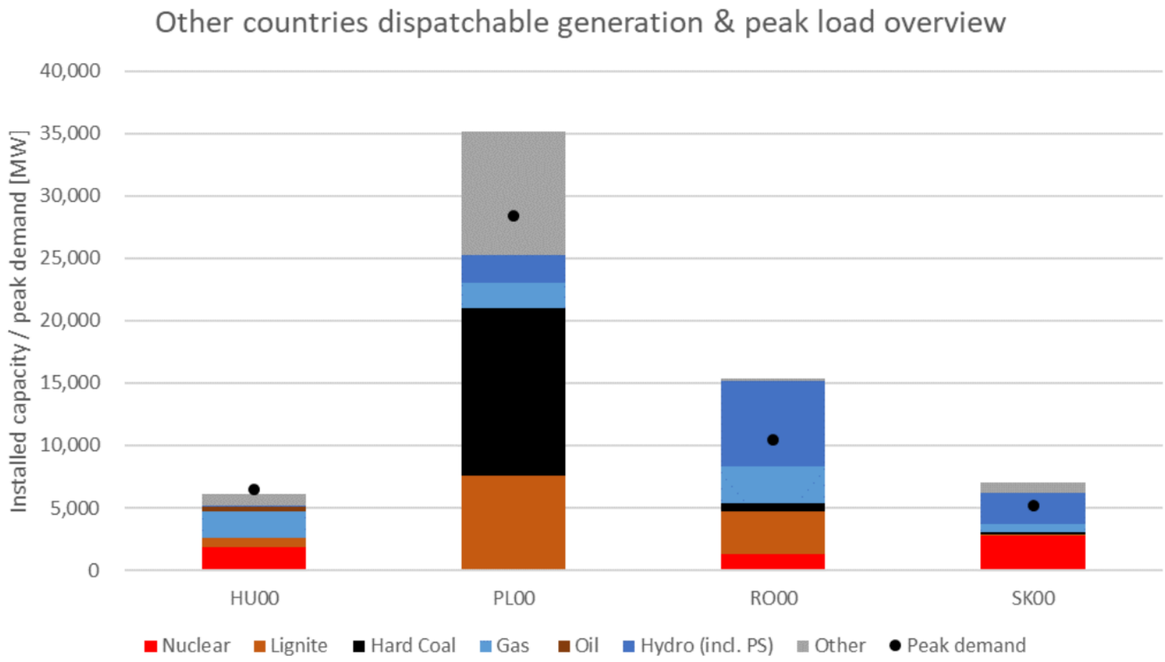


Figure 10: Dispatchable generation and peak load overview for the neighboring ENTSO-E Member States of Ukraine

2.3 Adequacy Methodology

The methodology used in this analysis is very similar to that used for generation adequacy studies in most ENTSO-E Member States and in the ENTSO-E Mid-term Adequacy Forecast (soon to be renamed European Resource Adequacy Assessment). Currently, this methodology is being formalized as well in the context of the Clean Energy Package. This Section describes firstly the generation adequacy modeling using the Monte Carlo (MC) approach, next the used reliability standard is briefly touched upon. Finally, the method for determining the necessary capacity to comply with the reliability standard is described.

2.4 Generation adequacy modelling

The modelling of the generation adequacy for the Ukrainian power system is done using Monte Carlo techniques. The principle of the used Monte Carlo technique is shown in Figure 11:

1. First, the distribution of the uncertain input parameters is described. Two different ways of doing this are used:

a. Through the development of time-series (e.g. for variable renewable energy sources or demand), often based on historical meteorological conditions.

b. Through the description of a probability distribution (e.g. for outage characteristics). This probability distribution is next sampled to generate different time-series.

2. Next, draws are performed on the uncertain input parameters, allowing to generate multiple deterministic problems.

3. The generated deterministic problems, in this case deterministic generation scheduling problems (see further), are subsequently solved to identify any moments of scarcity.

4. The distribution of the solutions for the multitude of deterministic problems is finally analysed to deduct statistically significant conclusions

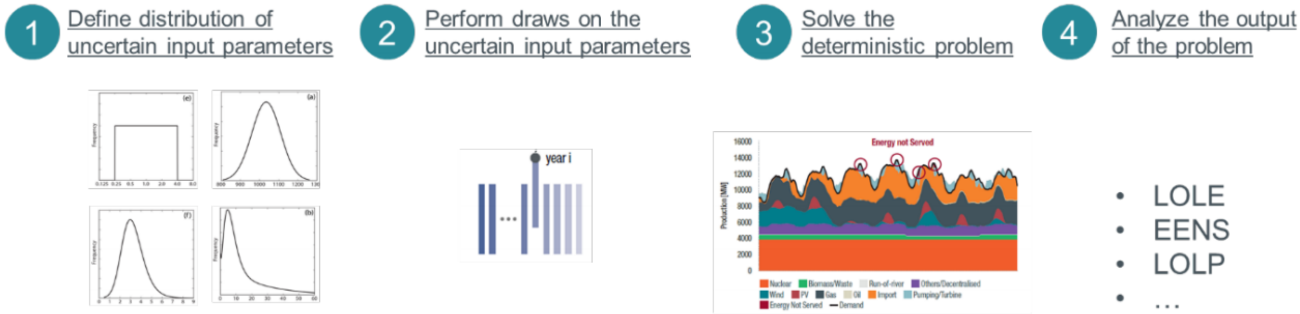


Figure 11: Illustration of the Monte Carlo approach used for generation adequacy modelling

Within the Monte Carlo approach, a multitude of deterministic problems are solved. Each of these problems constitutes a generation scheduling problem which is in this case solved on an hourly basis. Figure 12 shows an illustration of the result for one week for some power system. From the figure, it can be seen that baseload (e.g. nuclear), flexible generation (e.g. gas), variable renewable resources (e.g. PV & wind) are balanced on an hourly basis to meet demand. Additional means for balancing are storages and imports. However, for some hours the demand cannot be served (e.g. if not enough imports are available) and unserved energy (also referred to as Energy Not Served – ENS – is identified).

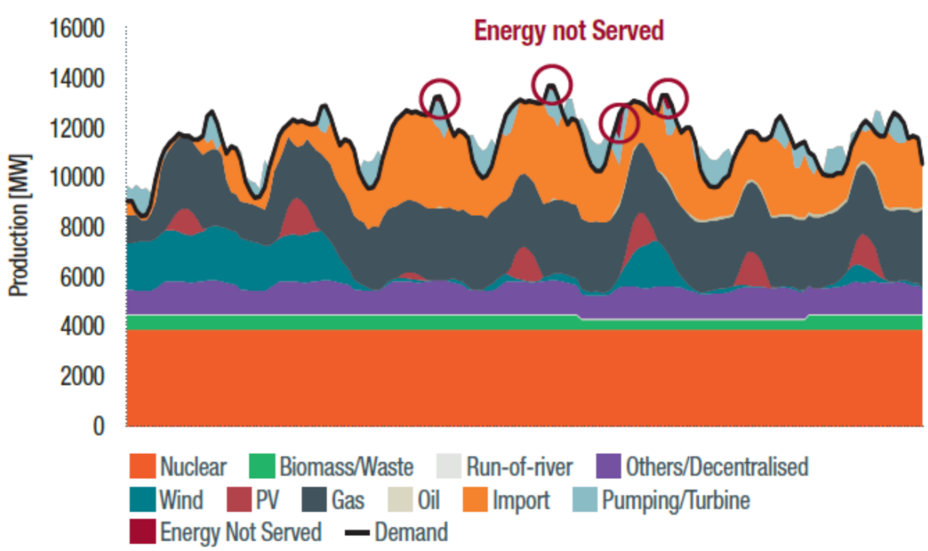


Figure 12: Illustration of the hourly generation dispatch methodology with an illustration of situations where unserved energy is present

For the construction of the above-mentioned deterministic generation scheduling problems, sampling is performed on the probabilistic distribution of the different uncertain variables. The advantage of the Monte Carlo approach is that correlations between these probabilistic distributions can easily be taken into account as well. Indeed, there is for example a large correlation between the demand and the available PV production: for European countries demand peaks often occur between 18:00 and 20:00, a time during which PV production is very limited.

The principle of taking this correlation into account is shown in Figure 14. Variables which are correlated amongst each other are renewable production (PV, wind, hydro) and load (highly related to temperature). Therefore, time series for these variables are constructed based on historical meteorological conditions (e.g. temperature, wind speed, irradiance) and the same historical year is always used for all these correlated variables when developing the different deterministic problems (also referred to as 'Monte Carlo years').

It should be noted that all variables profiles (including bad meteorological conditions for electricity production by RES ie with very capacity factor as it shown in Figure 13) formulate the data for Monte Carlo years.

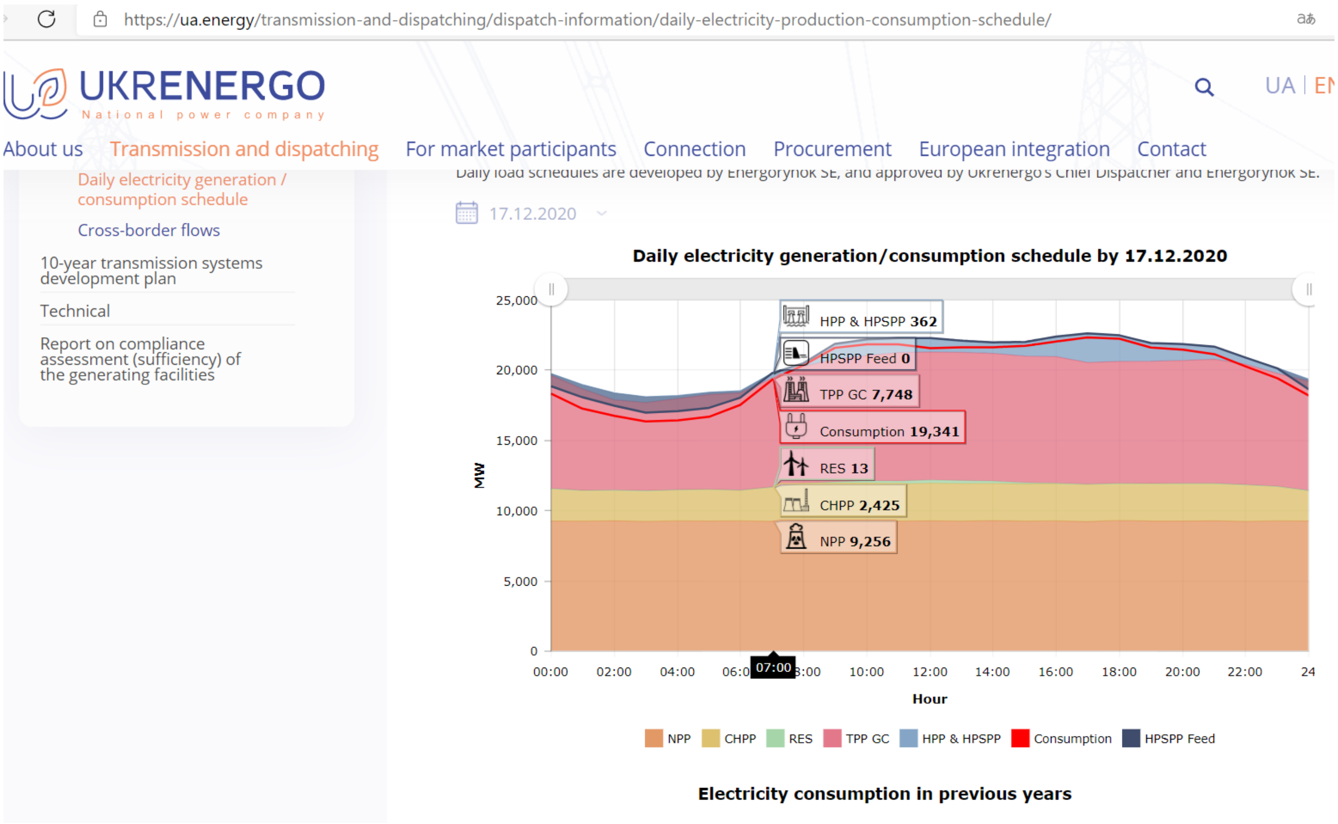


Figure 13: Some historical data for creating different 'Monte-Carlo' years.

Forced outages on conventional generation or grid infrastructure (e.g. HVDC links) are however not correlated among each other, and they are also not significantly correlated with meteorological conditions. Therefore, these variables can be combined in a random way with the meteorologically correlated variables as shown in the figure.

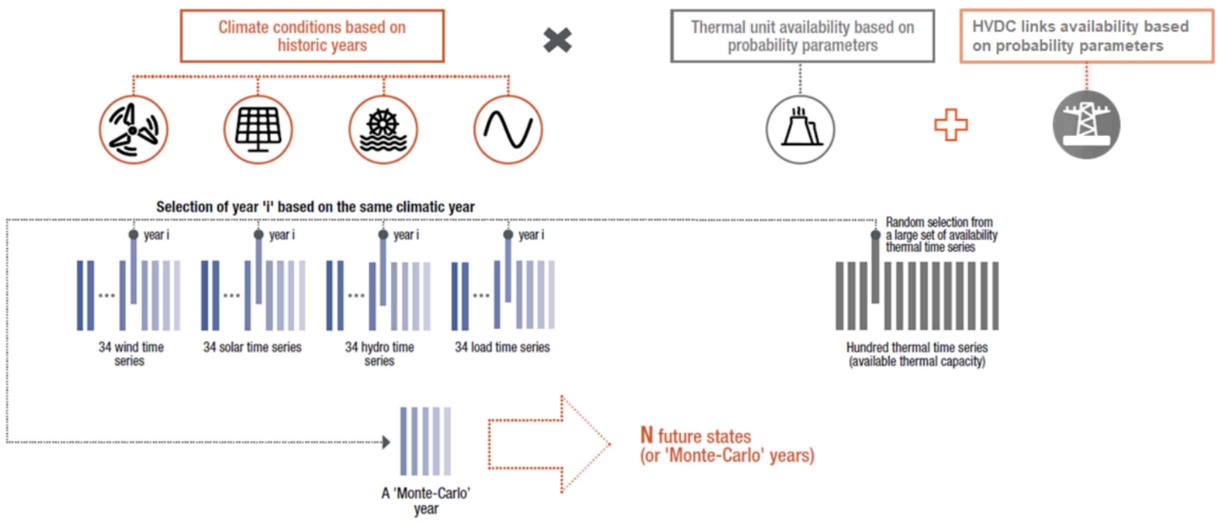


Figure 14: Illustration of the principle for creating different 'Monte-Carlo' years.

The generation dispatch problems are solved using the Plexos software. In Figure 15 an overview of the input data and model output is provided. For this study, only adequacy indicators such as Loss Of Load Expectation (LOLE) and Energy Not Served (ENS) will however be studied. A total of 1000 Monte Carlo years has been simulated to achieve sufficient convergence of the results. On top of that, the convergence of the adequacy indicators has been validated.

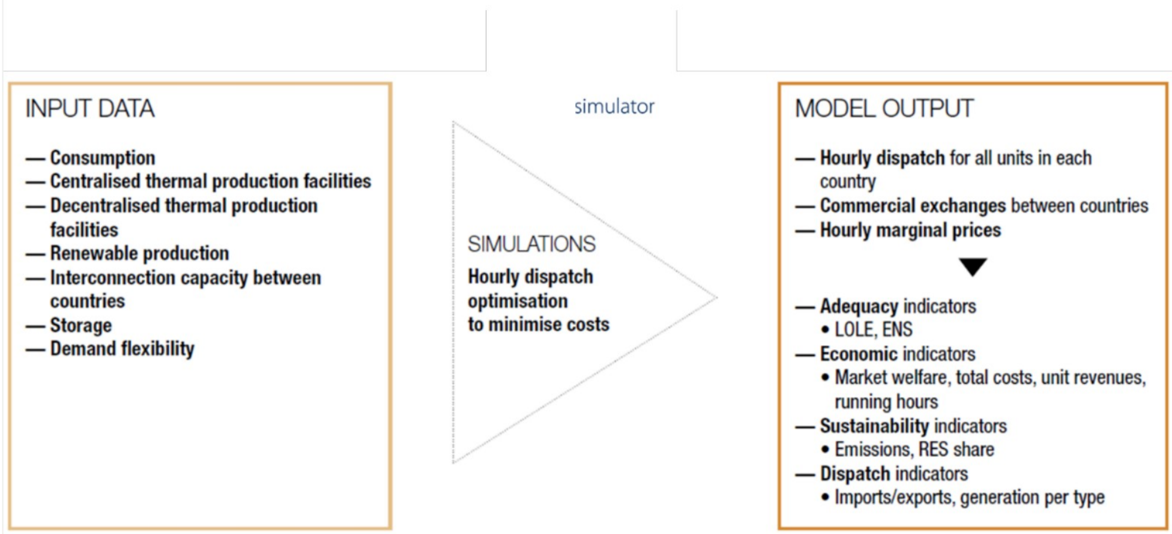


Figure 15: Overview of the input and output of the generation adequacy model.

2.5 Reliability standard

This study will look at the following reliability indicators:

- Loss Of Load Expectation (LOLE): the average number of hours per year when the system will be experiencing some energy which cannot be met by generation and imports.

- Energy Not Served (ENS), sometimes also referred to as Expected Energy Not Served (EENS): the average energy per year which will not be able to be met by generation and imports.

Many other generation adequacy indicators exist, as shown for reference in Figure 16. However, the above-mentioned indicators are most used for this purpose, and have been defined in the Clean Energy Package regulation as the indicators European Member States should use in their generation adequacy assessments.

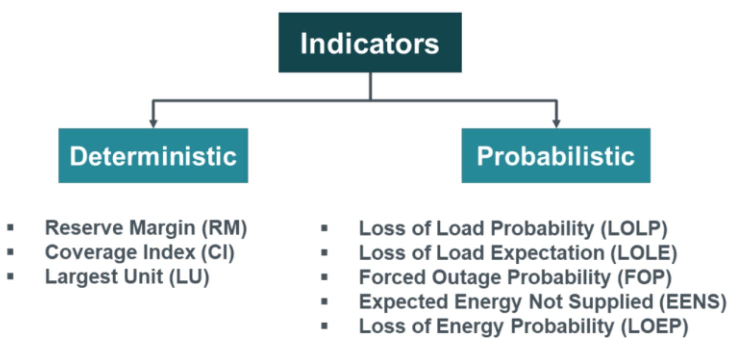


Figure 16: Illustration of different generation adequacy indicators which are used.

At the moment there is no legally binding generation adequacy reliability standard defined for the Ukrainian power system. The latest Ukrainian generation adequacy report uses as reliability standard a LOLE below three hours per year. This reliability standard is quite common in Europe and is similar to that used in France, Belgium and Great Britain. In the current analysis therefore the same generation adequacy criterion will be used.

2.6 Adequacy assessment results

The adequacy indicators for the studied interconnected situation are shown in Figure 17. A LOLE of 2.2 hours per year for an expected ENS of 1.1GWh is identified. This result does not comply with the chosen reliability standard of a LOLE below 3 hours per year. In Figure 17 the evolution with increasing number of simulated Monte Carlo years is shown for the LOLE and ENS indicators. It can be seen that for an increasing number of Monte Carlo years convergence of the indicators is achieved.

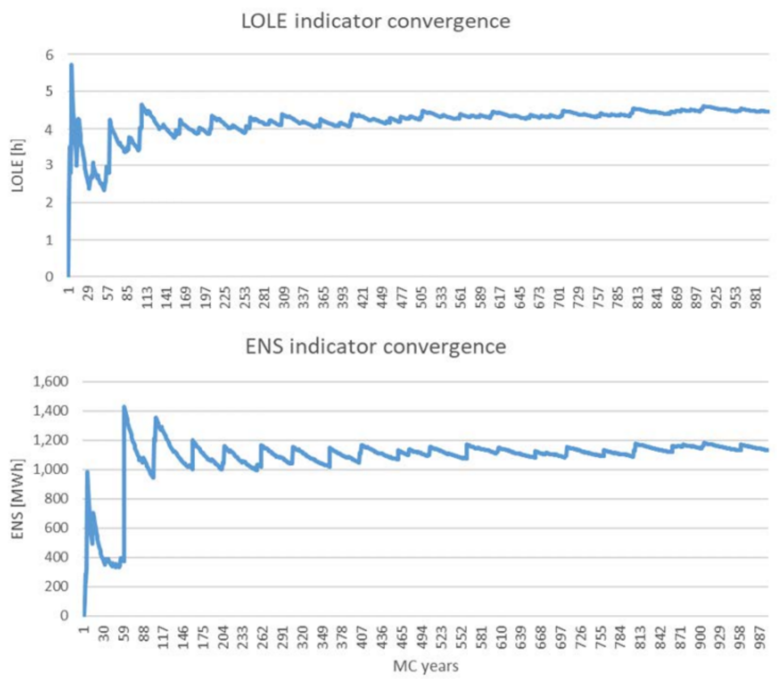


Figure 17: Monitoring of the convergence of LOLE and ENS for 2025

As for any generation adequacy analysis of an interconnected system, the modelling of the neighboring countries is extremely important. For this analysis, the assumptions as used in the ENTSO-E 2019 MAF were used. This results in no significant adequacy issues for the neighboring ENTSO-E Member States, as also found in the MAF results. However, Poland estimates that issues will arise due to the Clean Energy Package regulation prohibiting the participation of polluting generation in the capacity market. Producers indicate that 4.8GW of coal-fired generation might be decommissioned or mothballed up to 2025.

2.7 Analysis of the contribution of interconnection to generation adequacy

As already discussed, the contribution of interconnection to Ukrainian generation adequacy is very significant. This means that the availability of energy in the neighboring ENTSO-E Member States is high for moments in which scarcity situations occur in Ukraine. This observation can be quantified by looking at the Pearson correlation of the unserved energy between the different countries (see Figure 18). From the figure it shows that only for Moldova a significant correlation with Ukrainian unserved energy can be identified.

Another metric to monitor this same effect is shown in Figure 19. The figure shows the probability of all neighboring ENTSO-E Member States (+ Moldova) experiencing scarcity issues when unserved energy occurs in Ukraine. It can be seen that this probability is below 1.6% for all countries except Moldova, indicating high possibility of adequacy support. These above metrics can also give an idea to which extent foreign capacity could participate to a capacity market. However, as proposed in the “ENTSO-E proposal for Cross-border participation in capacity mechanisms" it will probably be based on the average imports observed in the generation adequacy modelling from each country in hours of scarcity. This methodology is however not yet approved and not performed in this study.

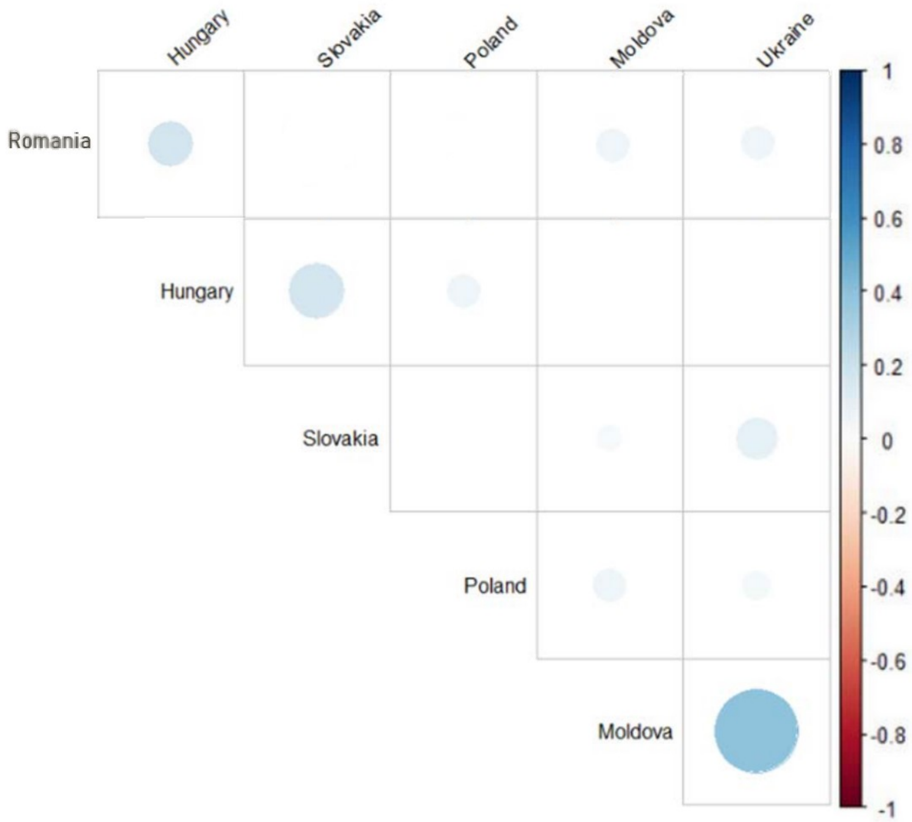


Figure 18: Pearson correlation of unserved energy for 2025

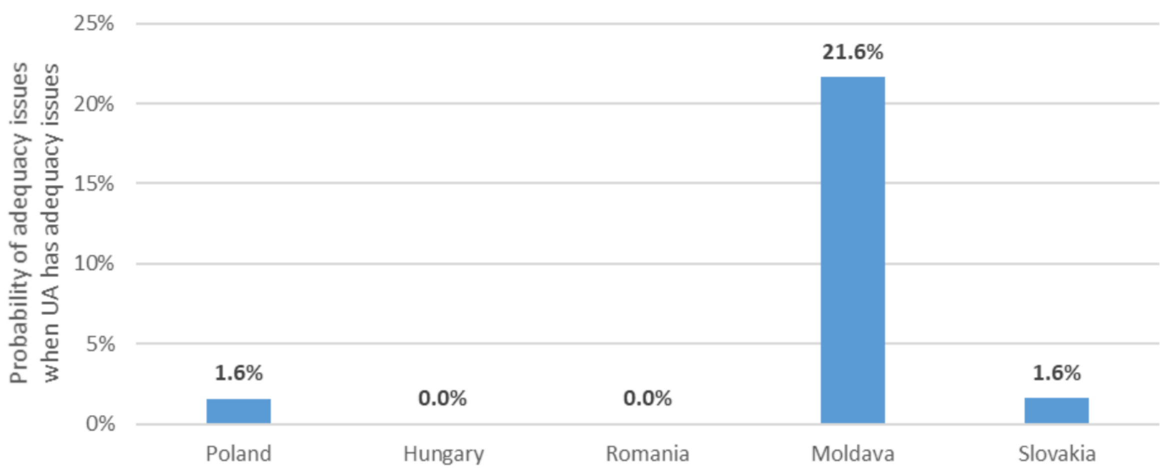


Figure 19: Probability of scarcity issues when Ukraine is experiencing scarcity issues in 2025

Using Plexos software, the operation of the IPS of Ukraine (interconnected with ENTSO-E) was simulated under the accepted assumptions. A detailed market model was created of the Ukrainian power system together with that of its neighboring ENTSO-E member states. Figure 20 gives a schematic overview of the developed model, whilst the geographical interpretation of the areas is shown in Figure 20.

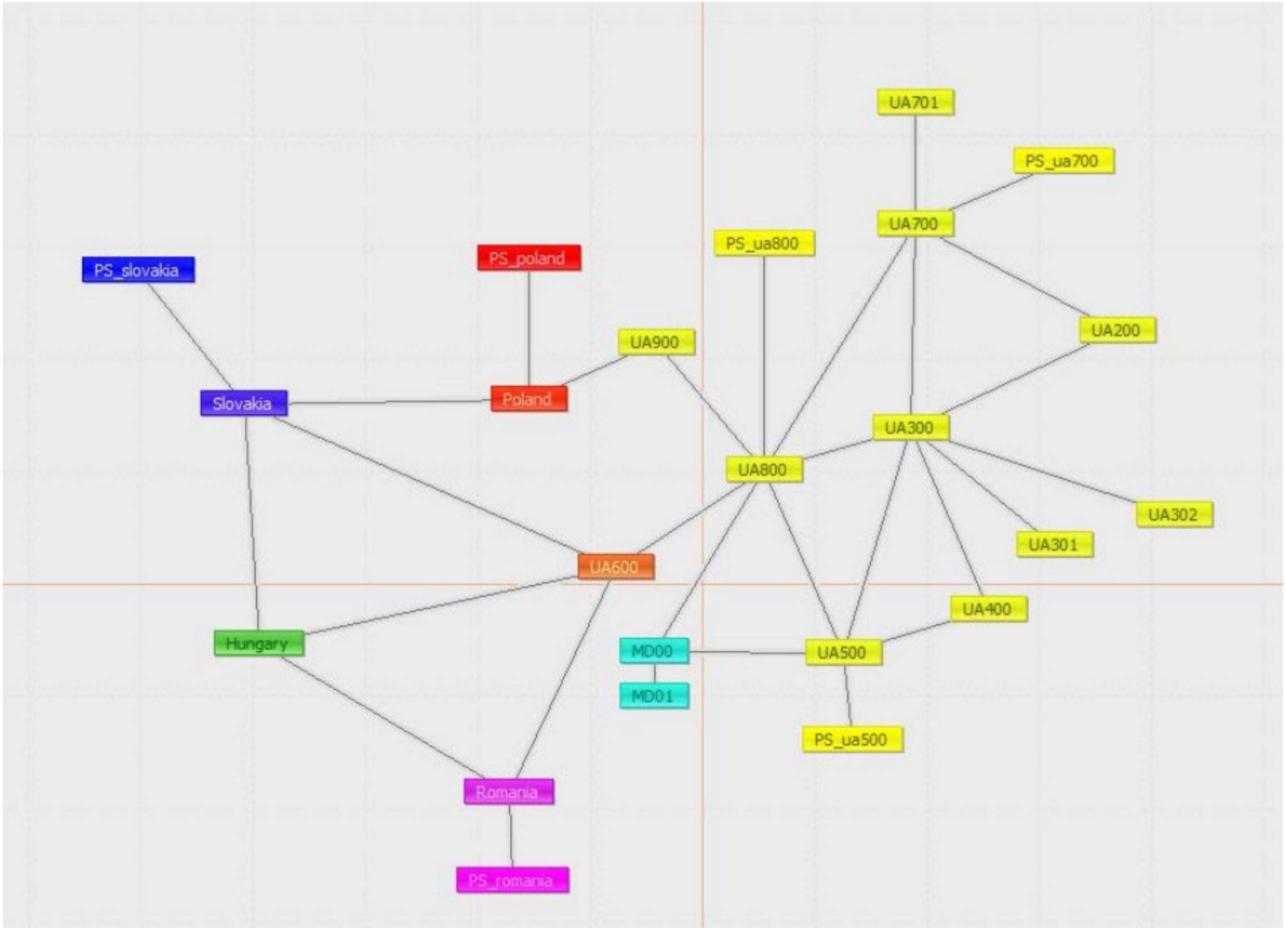


Figure 20: Schematic overview of the market model developed in Plexos software

However, the simulation results indicate problems with adequacy in both 2025 and 2030 (see Table 8).

Table 8. Adequacy assessment results

Year	LOLE (hrs)	LOLP (%)
2025	4.61	1.15
2030	13.02	5.28

At the same time, it should be noted that even with increasing the capacity of interconnectors, it is difficult to achieve the accepted level of adequacy, because in periods of deficit in the IPS of Ukraine similar situation can occur in some neighboring energy systems (see Figure 18 and Figure 19). It should be noted that most of the neighboring countries are unclean importers (see Figure 10). Therefore, such countries should increase the power reserve along the lines in the event of a significant increase in Ukraine's electricity imports.

2.8 Determination of the necessary capacity for generation adequacy

Although the most common generation adequacy criterions are indeed LOLE and ENS, results of these indicators are not suitable for the definition of appropriate policy actions. Therefore, it is common to in addition communicate on the necessary additional volume (in terms of capacity) in order to achieve generation adequacy. Analogously, one could also identify any surplus capacity in the system from a generation adequacy point of view.

The process which is used in the current analysis is shown in Figure 21. After a first simulation, it is verified whether the reliability standard is met or not. Should the standard not be met, a synthetic additional capacity of 100MW is added to the system and another simulation is ran. This process is repeated until the reliability standard is met. It should be noted that this synthetic capacity is considered to be fully flexible generation capacity which is available 100% of the year. Therefore, when considering policy actions, for example the commissioning of new capacities, the availability of these capacities has to be properly accounted for through deratings. In a similar way, one could identify the surplus capacity which is present in the system from a generation adequacy point of view.

Considering that the Ukrainian system is modelled with different areas it is not trivial to decide where the synthetic 100MW of capacity should be located within the Ukrainian system. For this analysis the following procedure is used in order to assure the additional capacity is located there where it is needed the most:

1. The LOLE indicator is calculated for each separate Ukrainian area instead of on a country level.

2. The additional synthetic capacity is added to the system in the area which has the highest LOLE value

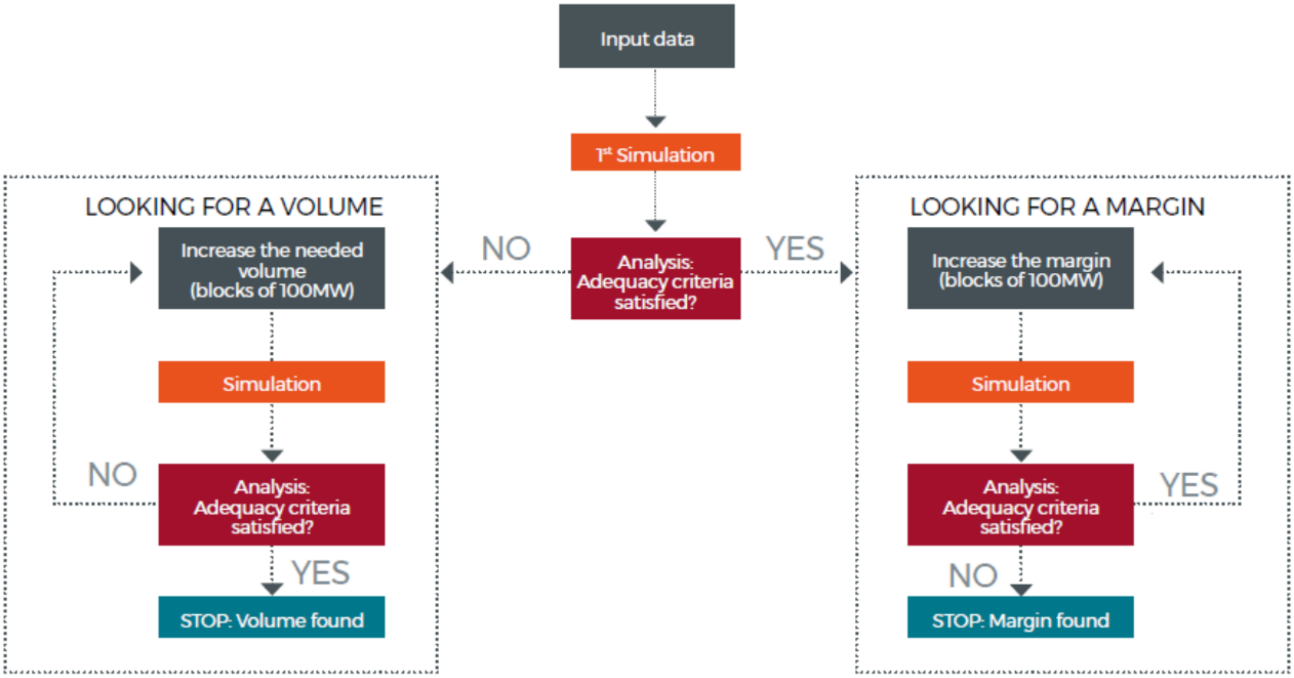


Figure 21: Illustration of the process used for the determination of the needed capacity to satisfy the reliability standard.

2.9 Analysis of additional new facilities operation

This requires the construction of additional new capacity. And taking into account that the energy system is inflexible, flexible generating capacity should be built. However, the role of interconnectors in keeping balance is only growing.

In order to be able to advise policy makers in their decisions on what technology could be employed as additional, different indicators can be studied. One of the most common such indicators is the running hours for this capacity, which is shown in Figure 22 by blocks of 500MW. It can be seen that the first 500MW of new additional capacity is running on average 120 hours per year, whereas for the last 100MW this only is 24 hours per year. For the whole new additional capacity, the running hours are quite low suggesting peaking capacity, demand side management or storage could be appropriate technologies to fill the gap.

Additional new capacity (MW)	Average running hours
2500-2600	24
2000-2500	25
1500-2000	52
1000-1500	72
500-1000	95
0-500	120

Figure 22: Average running hours of the additional new capacity

The detailed statistical distribution of the running hours for the additional capacity is shown in Figure 23. The distribution shows the large variation among the studied Monte Carlo years, indicating as well high volatility in generation asset owner revenues.

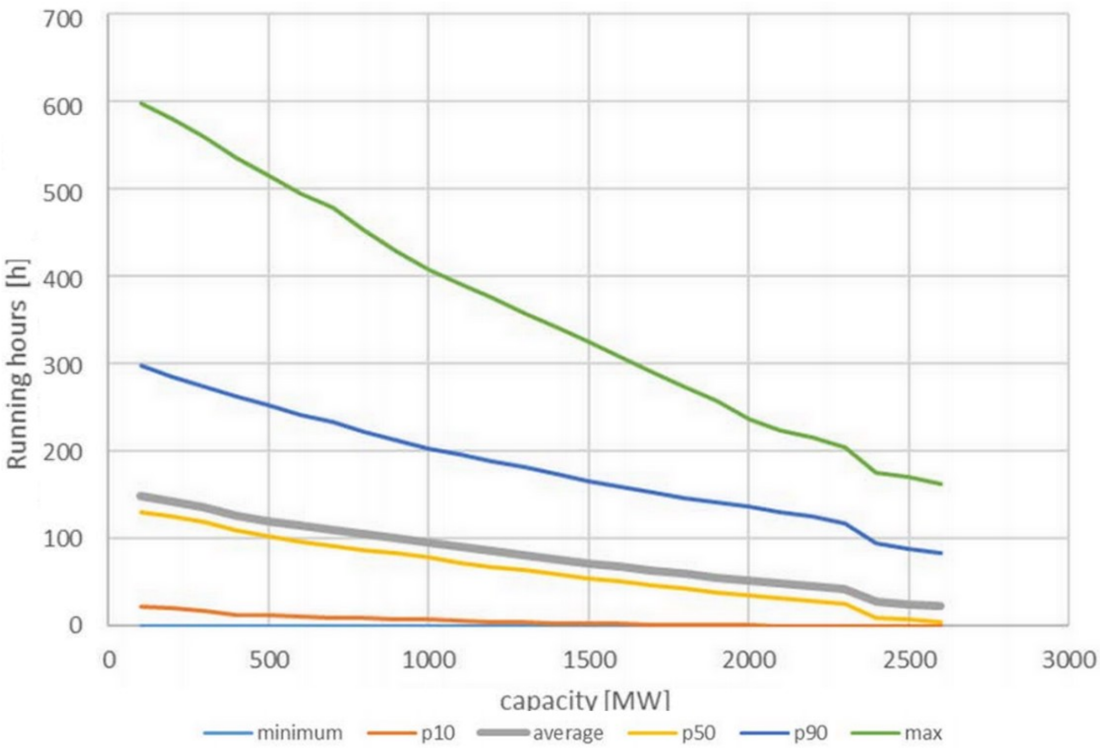


Figure 23: Statistical distribution of the running hours for the additional new capacity

Based on the mode of operation of the new additional capacity, these should be flexible gas TPPs units with the possibility of start-up in up to 15 minutes and with 75% regulation range. Or it can be combination of flexible gas TPP units and energy storage.

Recommendations

As a result of the exchange of experience with colleagues from Denmark and based on the results of this research, in the future (in order to increase the RES penetration) it is proposed:

1) Increase the flexibility of the IPS of Ukraine building new additional capacity with an installed capacity up to 2.1GW;
2) Improve the RES forecasts and load forecasts providing professional forecasting tools based on neural networks, that will make it possible to forecast for longer-term horizons and with less forecast errors;
3) Develop grids not only in the direction of ENTSO-E (the highest priority is Poland), but also to rebuild internal grids (first of all the Zakhidnoukrainska Substation and its surrounding infrastructure that is currently bottleneck);
4) Remove regulatory restrictions that hinder the RES development and the introduction of means of their integration (especially those that prevent the construction and further operation of new flexible generation);
5) Actively involve RES producers in the provision of ancillary services (first of all FRR) introducing appropriate regulatory changes;
6) Achieve the appropriate level of price differentiation in all market segments (including the market of ancillary services);
7) Avoid cross-subsidization (especially with the use of PSO for which it is necessary to gradually reduce the share of obligations under this mechanism);
8) Avoid the use of non-market approaches (especially participation in the electricity production by RES producers with not according to the general market rules, ie merit-order list) introducing appropriate regulatory changes;
9) Review further concepts of RES development in Ukraine without the imposition of feed-in tariffs (for example, with the use of auctions, etc.) introducing appropriate changes in Ukrainian legislation;
10) Ensure the construction and operation of new flexible technologies for the production/storage of electricity with a capacity of up to 2.1GW (either new flexible gas TPP units or combination of new flexible gas TPP units and energy storage) , that can provide ancillary services, reserved and additional balancing energy.