Flexibility to future-proof the Ukrainian power system

Solving the Ukrainian Green-Coal paradox

1. Overview of Ukrainian energy

Ukraine's Energy Strategy-2035, adopted in 2017, has set ambitious targets to achieve energy efficiency and security through the implementation of market mechanisms and integration to the European energy markets. In power generation, the Energy Strategy envisages accelerated use of renewable energy sources: 5 GW of renewable generation (excluding hydro) would be added by 2025. However, during this period the power system will still rely on the nuclear and coal-fired power generation.

1.1. SYSTEM INFLEXIBILITY

Nuclear power plants produce more than 50% of electricity, thermal power plants – more than 30%, with the rest being hydro, pumped storage and renewables. Thermal generation is coal-fired, apart from a few gas-fired combined heat and power (CHP) plants that supply hot water to urban district heating systems.

Due to the limited capacity of hydropower plants (HPP) and the amount of water reserves, HPPs cannot provide sufficient level of regulating capacity for the grid. In times of high and low water levels, HPPs do not participate in regulation at all.

The daily load regulation must, therefore, be done mainly by the condensing (i.e. not CHP) coal plants. More than 70% of the coal plant's installed capacity has passed the 250,000 hours of operation threshold. Provision of regulating reserves by the old coal blocks is generally inefficient due to the sub-optimal mode of operation (part-load and cycling) and ineffective because of the slow response and low ramping rates. Additionally, partly loaded coal blocks produce higher emissions.

As such, the power system in Ukraine is one of the most inflexible national power systems in the world.

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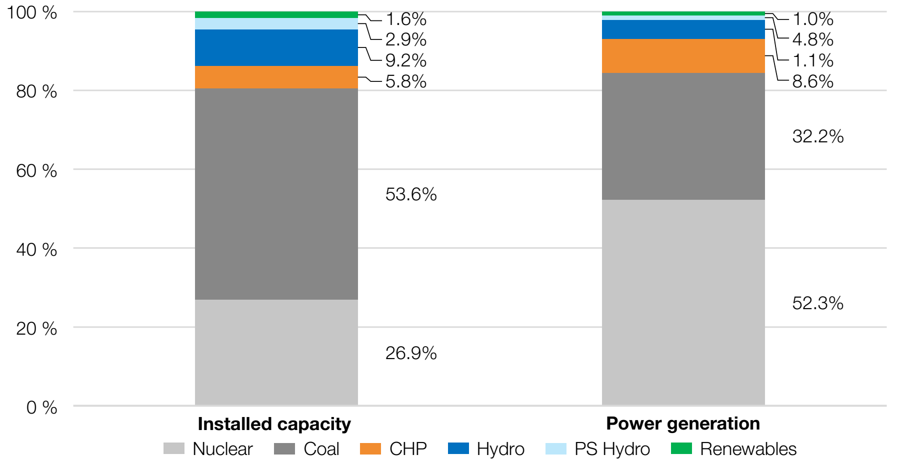

Figure 1. Capacity and energy mix in 2016.

1.2. SYNCHRONISATION WITH ENTSO-E

Currently the integrated power system of Ukraine is synchronised with the power systems of Russia and Belarus. The large size of the combined system provides the benefits of frequency support and back up even without the actual cross-border power trade. In line with the strategic direction towards association with the EU and integration of energy markets, Ukraine has started the program of preparation for synchronisation with the European grid (ENTSO-E) by 2025. The plan assumes the availability of own reserve capacities that would ensure successful "isolated" mode tests approximately in 2023. According to the calculations of Ukrenergo, the Transmission System Operator (TSO), the system does not have sufficient reserves to pass the tests.

The amount of reserves required for frequency regulation and the restoration of capacity in the "isolated mode" depends on the generation mix, including the amount of wind and solar installations in the system. On the other hand, fast reserves provide the flexibility to the system that allows integration of intermittent renewable energy sources (RES).

1.3. "THE CHALLENGE"

In March 2018, the CEO of Ukrenergo publicly announced the TSO's concerns regarding the power system stability if the share of RES continues to grow at the current pace. The installed capacity of wind and solar power plants is expected to rise from 1,200 MW in early 2018 to 3,000 MW by end of 2019. This will bring the system to the limit of its flexibility. According to the TSO, investors have already received grid connection agreements for 7,426 MW of wind and solar, and in order to manage this amount of intermittent generation the TSO will require flexible balancing capacity.

Given the Take-or-Pay type of the renewables feed-in tariff in Ukraine, the alternative could be to curtail the cheap nuclear energy and increase the "dirty" coal generation in order to balance the RES. This scenario contradicts with the country's commitments and is not viable.

The TSO suggests making prompt changes to the generation mix. Highly flexible generating capacity should be added to the system, staring already in 2019 in order to enable integration of the new RES capacities according to the strategy and Ukraine's obligations under the EU association agreement.

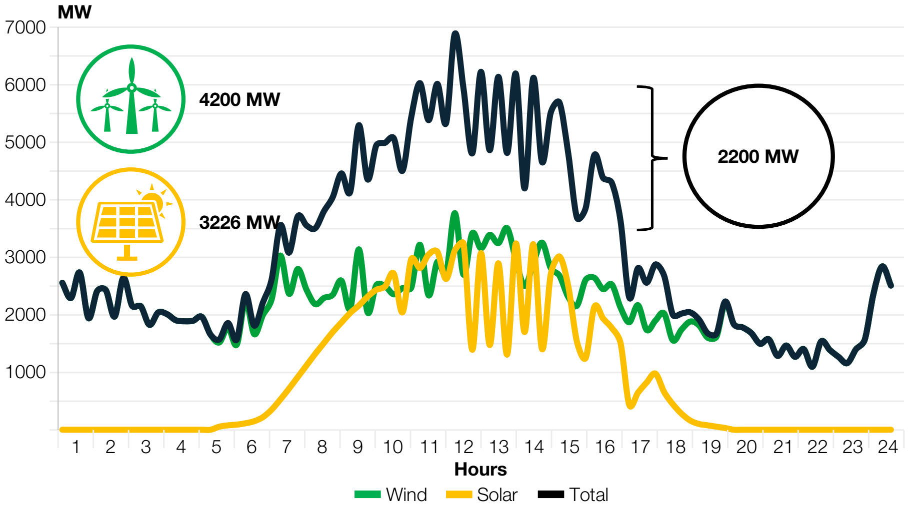

Figure 2. The TSO requires balancing capacity (1).

BACKGROUND INFORMATION

Intermittent renewables need complementary flexibility

Wind turbines and PV panels produce intermittent output, depending on the prevailing weather conditions. This creates a mismatch against the levels of electricity that consumers need at any one time. This effect is now very well understood and accepted as a feature that needs to be managed as levels of intermittent generation grow. Ukraine's electricity system currently manages this mismatch by flexing the output of controllable sources of electricity generation (such as coal and hydro).

Without flexibility, increasing intermittency could make the system unstable and insecure. It requires action in order to maintain system security, and in an extreme scenario it could also lead to black-outs.

In this context, flexibility can be defined as the ability to change the level of electricity output (or consumption) in response to an instruction or a signal, such as fluctuations in the output of RES. The response time is also an important aspect of flexible resources. In order to efficiently manage fluctuations in RES output, flexibility resources need to be able to respond quickly, ramping up or down.

Retaining the nuclear energy share means that the level of flexibility will reduce

As the amount of required flexibility is set to grow with increasing volumes of renewables, the share of Ukraine's nuclear energy is expected to remain. Thermal generation, represented by coal plants that are currently providing system balancing, will therefore be gradually phased out by the increasing share of RES. However poor and inefficient, this source of flexibility will be getting even smaller.

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(1) https://ua.energy/wp-content/uploads/20 18/04/ENG-Zaluchennya-VDE.pdf

Different types of flexibility are needed

To ensure that renewables can be deployed efficiently at the lowest cost to consumers, it is important first that the flexibility is made available, and second, that it is provided in the most efficient way. Using a variety of flexibility sources is a sensible approach, but the mix of technologies must also be able to deliver. While it is likely that Demand-Side Response (DSR), interconnection with ENTSO-E and storage will all have important roles to play, generation flexibility will remain essential. Compared to other flexibility sources, flexible generation has the advantage of being fully controllable and capable of rapid response.

Providing flexibility from generation

Flexibility provision can be thought of as having two dimensions – the response time (within seconds, minutes or hours), and the time over which the response can be sustained (minutes, hours or days).

Different generating technologies have different ways of providing flexible electricity. Some generating technologies are able to start up from zero output and then increase their output (‘ramp up’) within a matter of seconds. Other technologies may take a number of hours to start up, but once they are generating above a stable level they can quickly flex their output to meet the system needs (typical of large units such as combined cycle gas turbines (CCGTs), and large coal plant).

Part-loading power plants is inefficient

While providing flexibility from conventional technologies (called ‘part-loading’) may have been efficient in the past, it is not likely to be the most efficient way to provide the increased amount of flexibility that Ukraine will need in the future. The extra costs created through part-loading include:

- Reduced fuel efficiency,
- Increased carbon costs,
- Increased numbers of generators needed on the system, and
- The cost of curtailing wind generation to maintain the security of the system.

Given these costs, if conventional sources of flexibility are used in a system with higher levels of renewables, we may not be able to achieve the full benefits of decarbonisation, and consumers will end up paying higher prices.

2. Engine technology

The most feasible technology for the integration of large amounts of RES and provision of fast non-spinning reserves is the internal combustion engine (ICE) technology. "ICEs can execute a cold start in under 15 minutes and ramp from 80% to 100% within seconds, features that make natural gas engine-based electricity plants a strong flexibility resource" (Energy Technology Perspectives. International Energy Agency (IEA) 2014). Modern engines can start even within 2 minutes.

Ukrenergo considers ICE as a source of flexibility that can provide fast and efficient reserves to balance renewables and ensure system stability. Up to 2,000 MW of engines can be required by 2025 under the RES growth scenario.

Modern gas engine power plants can provide very flexible generation capacity, avoiding the costs associated with part-loading but bringing the following benefits:

- **Speed** – A quick response from zero output, and the ability to respond almost instantaneously to fluctuations in the supply and demand balance of electricity;
- **Sustainability of output** – Unlike other fast start technologies, ICE can start up quickly and maintain its output without needing to be quickly relieved afterwards;
- **Efficiency** – ICE incurs minimal costs for being on standby as a reserve but can deliver much needed electricity in the same (or in some cases quicker) times as conventional flexible technologies.

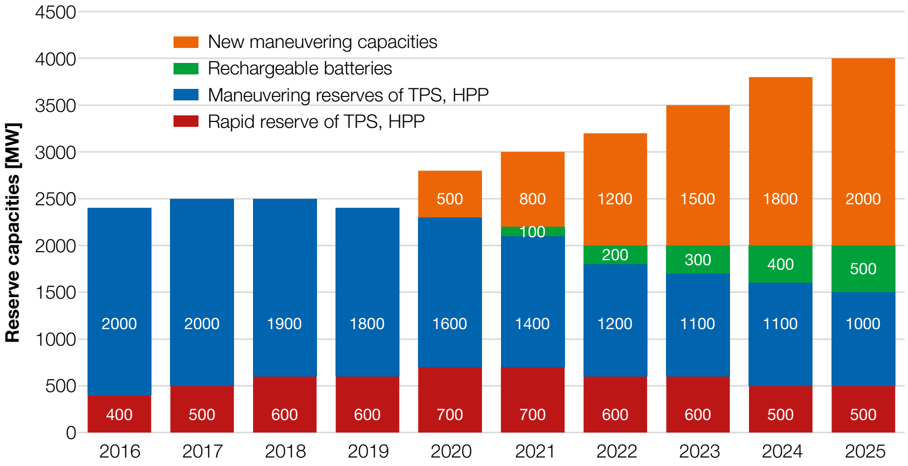

Figure 3. Up to 2,000 MW of engines and 500 of batteries can be required (1).

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(1) https://ua.energy/wp-content/uploads/20 18/04/ENG-Zaluchennya-VDE.pdf

3. The Ukrainian power system model

3.1. OBJECTIVE

Wärtsilä is the global leader in Smart Power Generation solutions that enable transition to more sustainable societies. Wärtsilä has done analysis of more than 50 power systems globally to identify the optimal system design that would support integration of renewables and reduce the system operational cost and emissions.

We became committed to the Ukrainian power system study with the objective of providing our expert view on the optimal configuration of the country generating mix, the optimal amount of flexible generation, and aimed at defining the economic and environmental effect of the proposed solution.

The outcome of the study was the country-level value proposition expressed in

- Euros of savings of the total system cost
- Tons of CO_2 emission reduction.

The tool used for the study was PLEXOS®.

3.2. POWER SYSTEM MODELLING WITH PLEXOS®

The optimisation software PLEXOS® is developed by the Australian software company Energy Exemplar™. PLEXOS® is widely used by Transmission System Operators (TSO), consultants, utilities among others to optimise the dispatch of power plants, the utilisation of transmission systems, long-term development planning, etc.

In PLEXOS® it is possible to build detailed models of power plants, transmission systems, power system reserves, power markets, etc. By running different scenarios based on the model, one can assess what happens in the system in various situations. The outcome being, for example, optimised dispatch or plans for future capacity additions.

The target for the solver is to find a solution with the lowest cost while fulfilling all boundary constraints, such as dynamic parameters of plants, load profile, etc., i.e. to minimise the target function. The optimisation process used in this study is based on Mixed Integer Programming (MIP) and chronological optimisation, namely, each hour is optimised.

The level of detail in the input data is of high importance as input accuracy is directly related to output accuracy. Profiles that are used in the model should be 1-hour resolution and higher in order to depict variations in, for example, solar and wind generation. Figure 4 shows an overview of input parameters for the model.

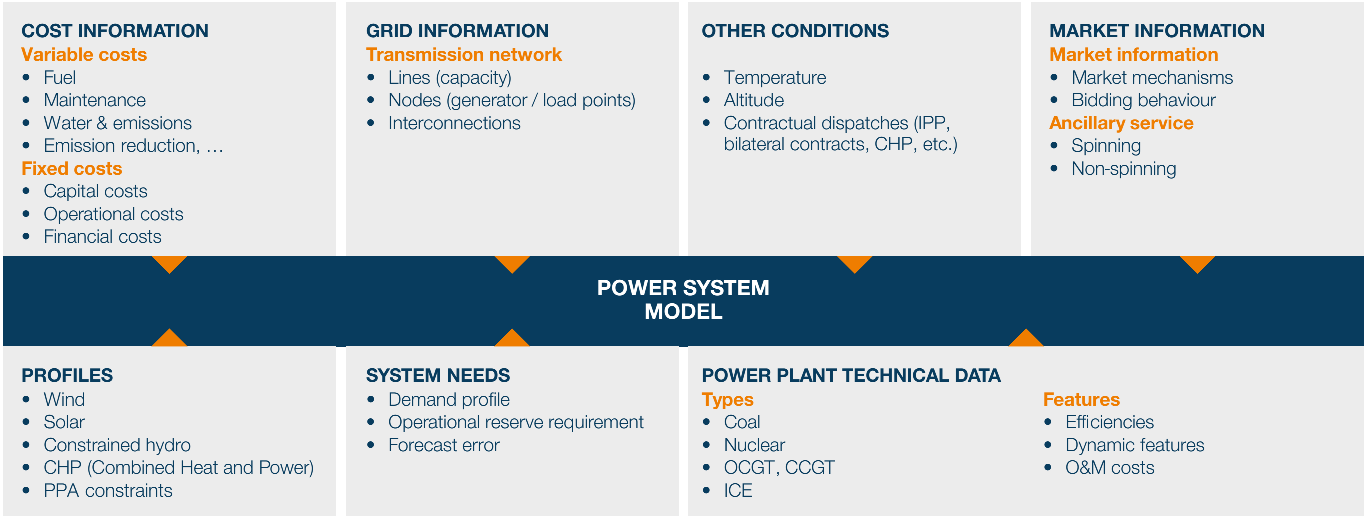


Figure 4. Overview of PLEXOS® inputs.

The primary objective of this study is to determine the optimal share of flexible capacity in the Ukrainian power system that is required to balance the increasing amount of renewable energy.

The details and assumptions for the development of the Ukrainian power system model are presented in the following sections. Input data has been verified by, among others, the Ukrainian TSO Ukrenergo and local utilities.

3.3. ASSUMPTIONS

POWER SYSTEM RESERVES

Power system reserves are defined as a fixed percentage of actual load and hence changes from hour to hour. The following values have been used:

Description	Percentage of system load
Primary reserve	4%
Secondary reserve	9%

Table 1. Power system reserve definitions.

FUELS

Fuel prices are, naturally, important factors in this kind of study. In this study fixed fuel prices have been assumed in order to keep the number of scenarios manageable, but sensitivity analysis with fuel prices are advisable if this study is advanced. The second important parameter, from an environmental point of view, is the CO_2 production rate from different fuels. In the model, CO_2 is accounted for but does not bear any additional cost. Table 2 outlines the different parameters depending on fuel.

Description	Price	CO_2 production
Uranium	0.60 EUR/GJ	0 kg/GJ
Coal	2.71 EUR/GJ	96.1 kg/GJ
Gas	8.79 EUR/GJ	56.1 kg/GJ
Biofuel	4.00 EUR/GJ	85.0 kg/GJ

Table 2. Fuel prices and CO_2 production rates for different fuels.

HYDRO POWER

Hydro power is a major contributor within the Ukrainian power system and the hydro plants have been modelled to reflect the seasonal variations in water flow. As the water flow changes from year to year depending on precipitation, the hydro plants are modelled to correspond to a statistically average year. The hydro plants do not have fixed profiles, but PLEXOS® can freely optimise the generation within the given limits and constraints.

FINANCIAL PARAMETERS

One part of this study is to evaluate the feasibility of different investments into the system. For these feasibility calculations, the figures in Table 3 have been used.

Description	Value
Equity/debt	30%/70%
Return on equity	12%
Interest rate	8%
Economical lifetime	15 years

Table 3. Feasibility parameters.

3.4. MODELLING POWER PLANTS

One of the cornerstones in power system modelling is the modelling of the generation assets in the system. Especially when assessing the value of flexibility in a system, it is important to include the dynamic parameters of different generation technologies. Otherwise, the result might not show any value of flexibility in the system, even though this is not true. Therefore, the power plants have been modelled to depict reality as closely as possible, taking into account the dynamic properties of the plants.

Properties of modelled power plants.

- Capacity
- Number of units
- Minimum stable factor
- Heat rate at 100% load
- Heat rate at 50% load
- Variable O&M charge
- Start cost
- Run-up rate
- Run-down rate
- Maximum ramp up rate
- Maximum ramp down rate
- Minimum uptime
- Minimum downtime
- Maintenance rate
- Forced outage rate
- Fuel offtake at start
- Fixed O&M charge

3.5. DEVELOPMENT OF RENEWABLE ENERGY SOURCES

At present in Ukraine there is a feed-in tariff program for solar and wind power projects in force. The feed-in tariffs are fixed in euros until 2030, but the regulator quarterly converts the tariffs into local currency. The eligibility for the feed-in tariffs is depending on the commissioning date of the plant and the tariffs are outlined in Table 4. The feed-in tariffs are set up as a Take-or-Pay scheme, i.e. the tariffs are paid in full regardless of whether the energy is utilised or curtailed.

Year commissioned	Wind	Solar
2016	-	160 EUR/MWh
2017 – 2019	101.8 EUR/MWh	150 EUR/MWh
2020 – 2024	90.5 EUR/MWh	135 EUR/MWh
2025 – 2029	79.2 EUR/MWh	120 EUR/MWh

Table 4. Ukrainian feed-in tariffs currently in force.

With the current feed-in tariff system, it is projected that the installed capacity of wind and solar will raise to 7.5 GW by 2025. Figure 5 shows the capacity development of wind and solar until 2025. Capacities have been signed up until year 2022 and the capacity development for the consecutive years has been extrapolated, assuming similar growth.

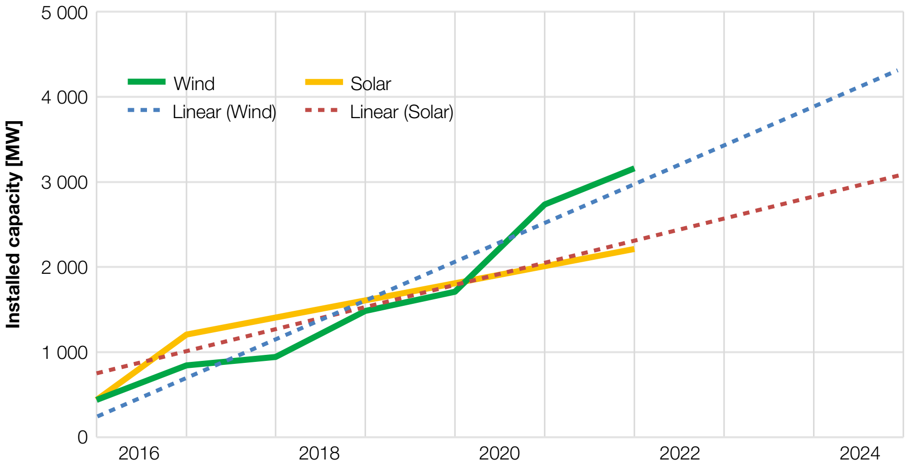


Figure 5. Development of renewable energy capacity until 2025.

3.6. RENEWABLE FEED-IN TARIFFS VS. RENEWABLE AUCTION SYSTEM

Feed-in tariff schemes have for a long time been an important way for authorities to incentivise the development of renewable energy sources, especially when renewable energy was new, expensive and unproven. During recent years, great improvements and cost reductions have been achieved both for wind and solar. This rapid decreasing of prices is foreseen to continue in the future as well. The issue with feed-in tariffs is that they depend on legislative action, which by its nature can be a slow process. Therefore, revisions of the feed-in tariffs lag behind the technical development and end up being every expensive for the state.

This fact has prompted many authorities around the world to abandon feed-in tariff schemes and replace them with a subsidy scheme based on auctions in which developers can compete for the subsidies. The auction system ensures the continuous growth of renewables while keeping costs down. An example is the solar auctions in Dubai and Abu Dhabi where the lowest bids were below 30 USD/MWh. The same trend can be seen around the world as well with prices for both solar and wind clearing between 30 and 60 EUR/MWh.

Based on experience from other countries, we believe that Ukraine would benefit from changing from the feed-in tariff system to an auction system for renewables. The calculation in Table 5 gives an idea about the price levels that could be expected in Ukraine for such an auction.

Description	Solar	Wind
Specific investment cost	700 EUR/kW	1,800 USD/kW
Economical lifetime	15 years	
Equity/debt	30%/70%	
Return on equity	8%	
Interest rate	12%	
Risk factor	10%	
Capacity factor	18%	33%
Lowest clearing price	**45 – 50 EUR/MWh**	**63 – 68 EUR/MWh**

Table 5. Calculation of possible clearing price if a renewable auction were held in Ukraine.

3.7. FORECAST ERROR OF RENEWABLE ENERGY

Due to the unpredictable nature of renewable generation, it is inevitable that the forecasted renewable generation will not completely match the actual generation. Even though forecasting technology and methods are improving, this is a new addition to the day-to-day balancing of the system. This phenomenon is not a fault in the system, but rather a consequence of renewables that the system must handle. Figure 6 provides an example week of how the day ahead forecast and generation of renewables differ. What can be seen from the graph is that the forecast and generation match relatively well on a high level, but there are always discrepancies that must be corrected with other generation assets. Small and short duration mismatches are not a big problem. The major issues arise when the mismatch is large and persists over longer timeframes.

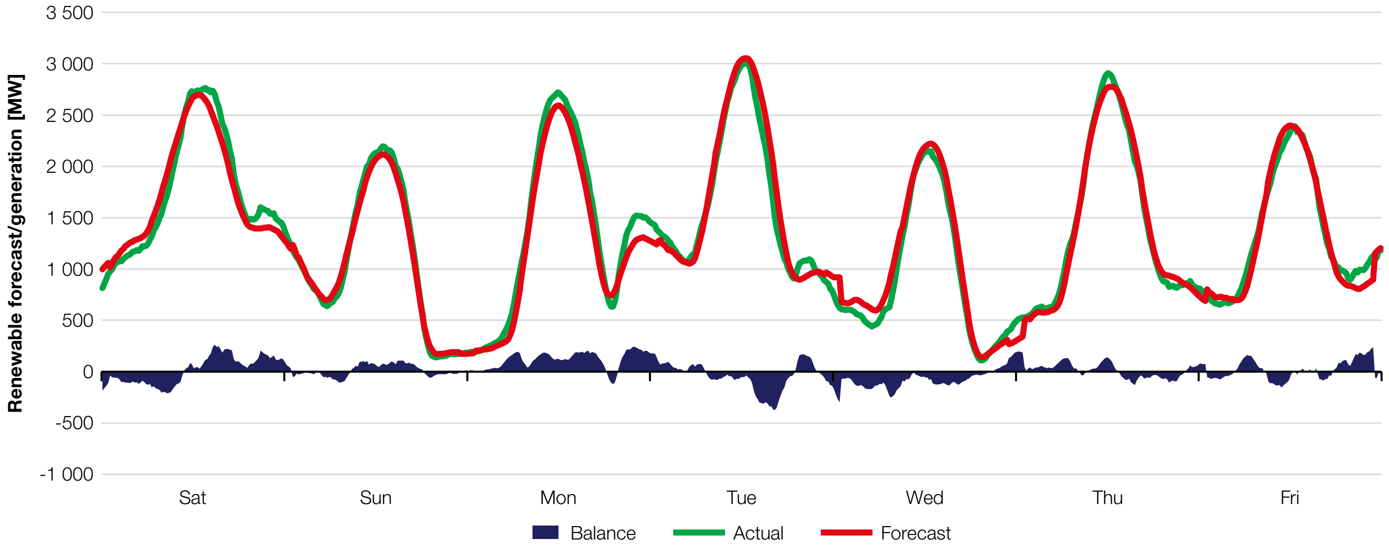


Figure 6. Renewable forecast and generation profiles for one week. The profiles are scaled to match 7.5 GW of wind and solar.

By doing a statistical analysis on the forecast and generation data, one can draw conclusions about how much balancing capacity is needed to cope with the situation. Figure 7 outlines the balancing capacity requirement due to forecast errors expressed as percentage of actual wind and solar generation. Up balance means that the renewables are generating less than forecasted, i.e. the system must activate raise reserves. Likewise, down balance means that the renewables are generating more than forecasted and the system must activate down reserves.

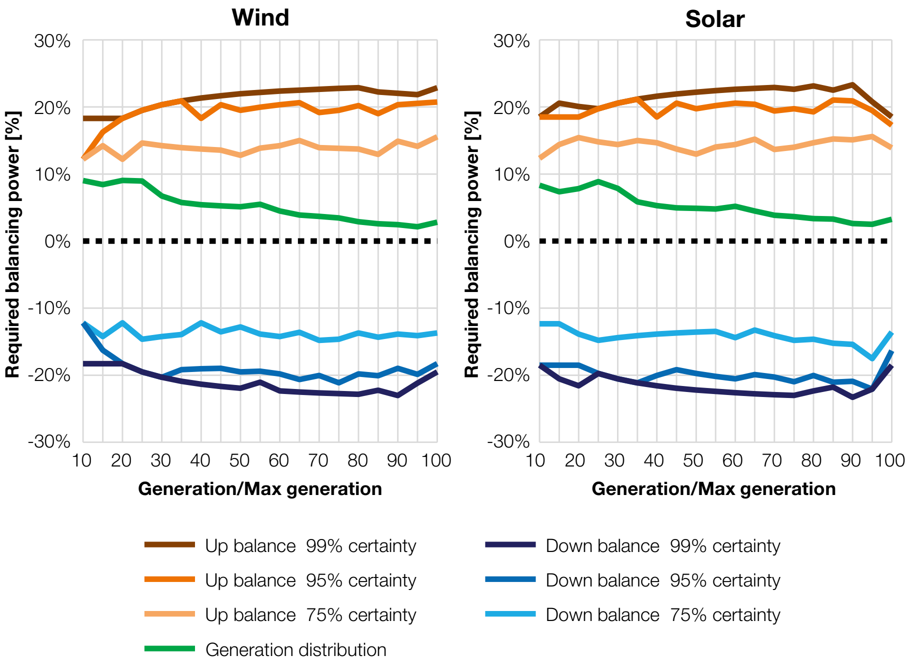


Figure 7. Dynamic balancing requirement for wind and solar expressed as percentage of actual generation for the whole range from no generation to full generation.

As an explanatory example, let's consider solar generation at 50% of max generation. The max generation of solar in 2025 is approximately 3,000 MW, as described in Section 3.5, hence 50% of max generation is 1,500 MW. Now the graph tells us that to be able to balance the solar generation with 99% certainty, due to forecast errors, the system needs to have:

$$Raise\ reserves = 50\% \times 3{,}000\ MW \times 22.0\% = 330\ MW$$

$$Down\ reserves = 50\% \times 3{,}000\ MW \times 22.2\% = 333\ MW$$

Therefore, with increasing amounts of renewable energy in the system, the balancing requirement increases. Analyzing the generation data, it shows that the additional balancing demand is approximately 20-30% of renewable generation at all times. In this study it has been taken to 30%.

Summarising the imbalance figures over the year, an estimate of how much the forecast error reserves are actually activated.

Description	Activated raise reserved	Activated lower reserve
Solar	71 GWh	74 GWh
Wind	176 GWh	174 GWh

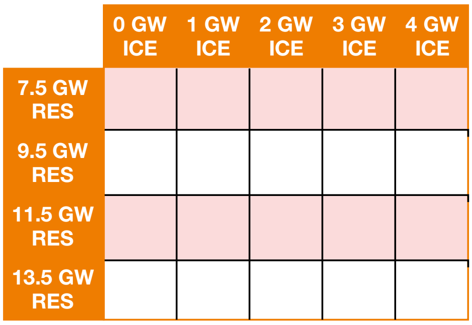
Table 6. Estimation of actual activation of forecast error reserves.

As both wind and solar generation are independent of each other, there will be situations where the forecast errors work against each other, e.g. solar generates less than forecast but wind generates more than forecast, meaning that the actual activated reserves might be lower.

3.8. SCENARIOS

In order to find the optimal amount of flexible capacity, 25 different scenarios were optimised. The two variables are the capacity of renewable energy sources and the capacity of flexible generation. The amount of renewable generation capacity was varied between 7.5 GW, representing the predicted amount in 2025, and 13.5 GW, which assumes a rapidly increasing growth of renewables. Likewise, the amount of flexible generation was varied between 0 GW, being the "Business-as-Usual" case, and 4 GW.

For all cases the operational cost of the system was coupled with the capital costs of each scenario in order to assess the feasibility. For the modelling and feasibility calculations of the scenarios in this study, it has been assumed that 7.5 GW of renewables are paid according to the existing feed-in tariff system, while the renewable capacity exceeding 7.5 GW are paid according to the renewable auction prices described in Section 3.6.



	0 GW ICE	1 GW ICE	2 GW ICE	3 GW ICE	4 GW ICE
7.5 GW RES					
9.5 GW RES					
11.5 GW RES					
13.5 GW RES					

Figure 8. Scenarios modelled to find the optimal amount of flexible generation for increasing renewable energy penetration.

4. Findings

4.1. CURTAILMENT OF RENEWABLE ENERGY

As the feed-in tariffs for renewable energy are paid regardless of whether the energy is utilised or curtailed, it is a direct cost benefit for the system to utilise the renewable energy to an as large extent as possible. Figure 9 outlines the utilised versus curtailed renewable energy for each case. The first important finding is that adding flexible engine capacity reduces the curtailment. The same trend is visible for all the different amounts of renewables in the system. In the 7.5 GW RES case, the amount of curtailment can be reduced from 30% to around 5% by adding 2 GW of flexible engine capacity.

The second observation is that the underlying inflexibility of the system causes excessive curtailment in cases of large renewable capacity. In the 13.5 GW RES case, around 20% of the energy is curtailed even though 3 or 4 GW of flexibility is added.

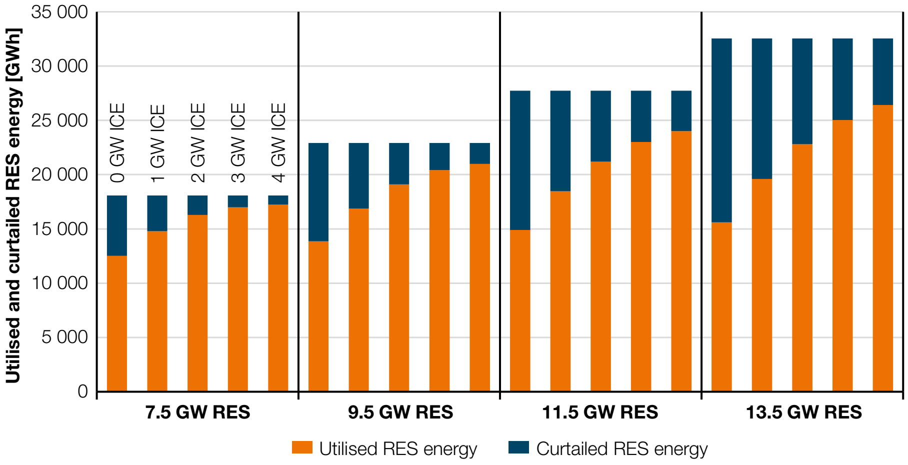


Figure 9. Utilised and curtailed renewable energy under different scenarios.

4.2. POWER SYSTEM RESERVES

The primary reserve in Ukraine has traditionally been provided by the coal blocks around the country. Hydro dams do not provide the primary reserve as they are not telemetrically connected to receive activation signals from the TSO and cannot therefore react quickly enough.

The modelling result does not show any major change to the way the primary reserves are provided. Only in cases with a high amount of engines, a portion is provided by engines primarily due to their capability to be spinning at very low load with very fast ramping capabilities.

The secondary reserve has also traditionally been provided, to a large extent, by coal blocks with a minor part provided by hydro. Here the results show a very different picture, especially in the cases with engines. Firstly, with more renewable energy in the system, the need for secondary reserve is increasing due to the forecast errors of renewables, as explained in more detail in Section 3.7. Secondly, when engines are added, they provide secondary reserve as non-spinning and the reserve provision increases with the amount of engines in the system. It is primarily the provision by coal that is displaced. For the coal plants, this means that they can run at a higher load with higher efficiency and hence some of the coal units can be switched off completely. This is one of the great values of having fast and flexible generation capacity in the system. Engines are extremely well suited to perform this task due to their dynamic properties.

By providing secondary reserve as non-spinning, a significant amount of fuel can be saved, and equally the amount of CO_2 emissions is reduced. This translates directly into saved costs as well, and is one of the main contributors to the decreased operational costs of the system as a whole.

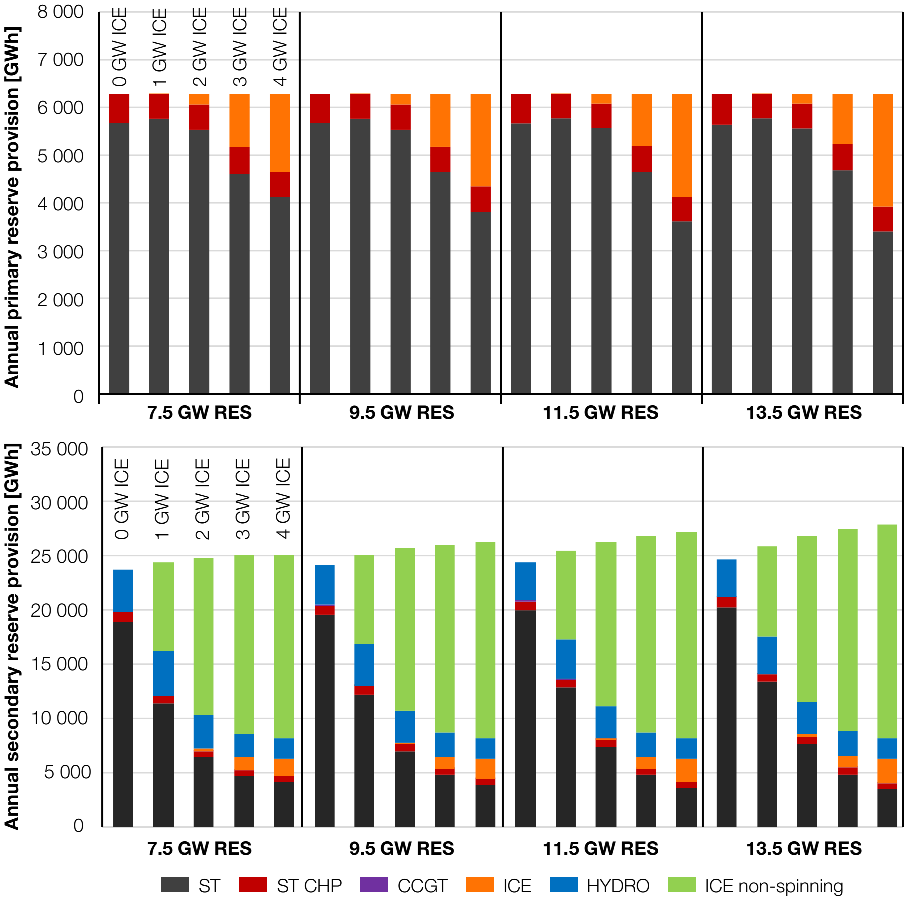


Figure 10. Provision of primary and secondary reserves.

4.3. OPTIMISED UTILISATION OF PLANTS IN THE SYSTEM

One of the results of the PLEXOS® modelling is the optimised dispatch of the entire Ukrainian system. Figure 11 to Figure 13 show the annual generation of nuclear, coal and engine plants in the system, and some important conclusions can be made.

It has been expressed by the authorities and the TSO that nuclear, which forms the backbone of the Ukrainian energy supply, should be utilised as much as possible. This stems from the fact that nuclear is practically CO_2 free, the plants already exist in the system and the investment costs have been paid off, i.e. cheap electricity. Therefore, the major concern when assessing future scenarios with an increasing share of renewables is that nuclear would be "pushed out" and replaced by coal generation that is more flexible than nuclear. Our study shows that this concern is valid for the cases without flexible engines. The number appearing in Figure 11 shows that nuclear generation without flexible engines in the system is reduced from 84 TWh to 83.6 TWh, which is not very much. However, one should keep in mind that the model curtails renewables, as described in Section 4.1, rather than reduces nuclear generation. This is directly due to costs; even though curtailing renewables is expensive, it would be more expensive to shut down a nuclear reactor. On the other hand, when introducing more flexible generation into the system, the nuclear generation is kept at a high level regardless of the capacity of renewables.

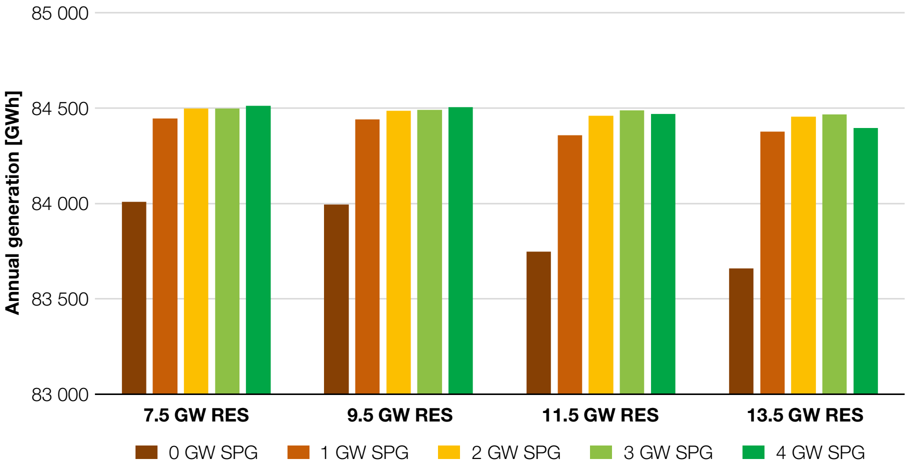


Figure 11. Optimised nuclear generation.

The modelling shows that the role of coal is changing markedly with the increasing renewable capacity and even more so with the amount of flexible engines in the system. It can be clearly seen that the coal generation decreases when more renewable energy is utilised. This behaviour is also directly linked to the provision of system reserves. As the secondary reserves can be provided by engines, which is discussed in Section 4.2, coal generation can be better optimised when it do not need to run on part load in order to provide spinning reserves. This leads to the situation that some coal blocks can be switched off completely, the currently running blocks can run at higher loads and efficiency, and older units could even be decommissioned.

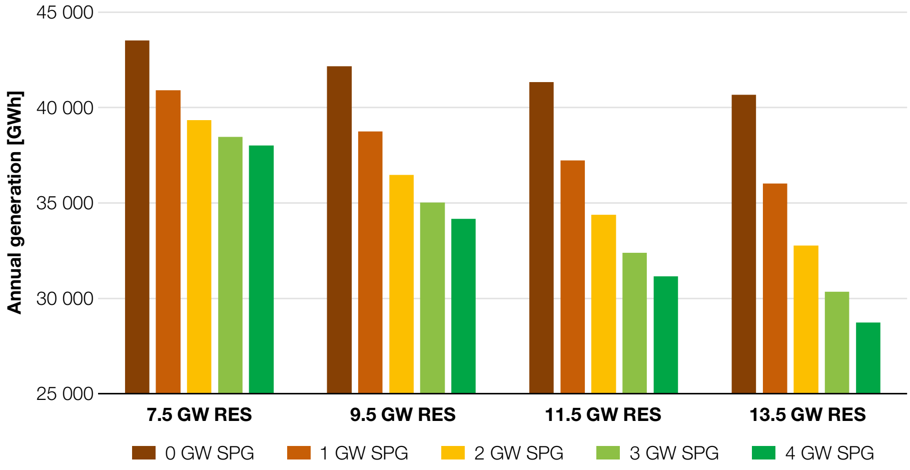


Figure 12. Optimised coal generation.

The generation of the engine plants is also very much linked to the secondary reserve provision. In the cases with 1 and 2 GW of engines in the system the engines are providing almost no energy to the system. The reason being that the engines almost exlusively provide non-spinning secondary reserves. In the cases with more than 2 GW of engines some energy is provided to the system. Here it is the marginal cost of generation that is the deciding factor. As the engines run on gas, the cost of generation for the engines is much higher than for coal and nuclear, namely, it is most of the time cheaper to ramp up a coal plant from part load rather than starting the engines. The engines are started during the times when fast ramp ups or short generation pulses are needed.

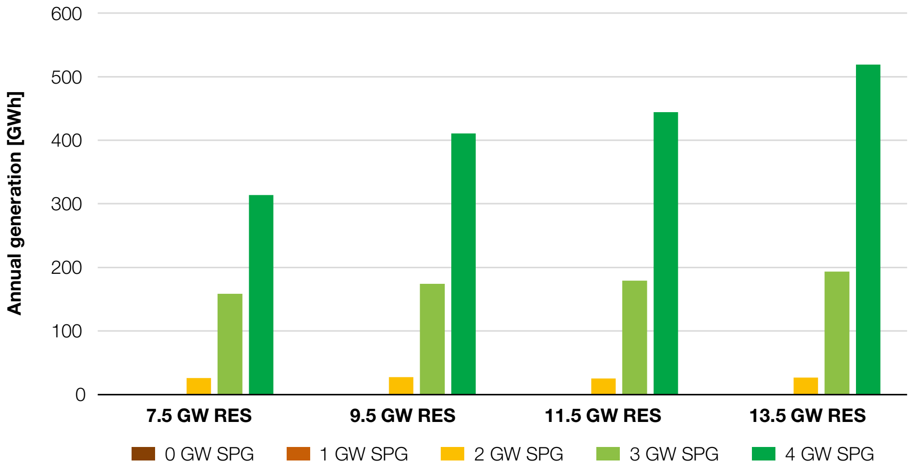


Figure 13. Optimised generation from engines.

The gas consumption of the engines is in the range of 300-1,200 GWh or 28-113 million m^3 depending on the case. Furthermore, the actual generation from engines would increase when the demand that stems from forecasting errors of renewables is taken into account.

The gas consumption is not large, but the engines will be used more to cover the forecast errors of renewables. As shown in Section 3.7, the total estimate of activated raise reserves due to forecast errors amounts to 247 GWh. Assuming the same ratio of activation between the plants as the reserve provision in Figure 10, the engines would provide an additional 149 GWh to the system. Calculating this into gas consumption, the additional offtake amounts to 329 GWh. The total assumed gas consumption will be in the range of 600-1,600 GWh or 56-150 million m^3.

4.4. DECREASING OPERATIONAL COSTS WITH RENEWABLES AND FLEXIBLE GENERATION

Taking all the benefits into account the question becomes: how does this impact on the operation cost and total system cost? Figure 14 shows the annual operational cost of the Ukrainian system. These values include variable costs such as fuel and variable O&M costs.

There are three important observations that can be drawn from the chart. Firstly, the general trend for all cases is that the cost is decreasing, i.e. adding renewables and/or flexibility reduces the variable operational cost. Secondly, adding more renewables without flexibility only slightly reduces the cost. The reason can directly be linked to the curtailment of renewable energy. As discussed in Section 4.1, adding renewables without flexibility leads to large amount of curtailment, i.e. the energy is instead mostly generated by coal and nuclear. The third observation is that adding already a small amount of flexible engine capacity has a significant impact on the operational costs. The reason is mainly found in the way the reserves are provided, as detailed in Section 4.2. and, of course, the fact that more renewable energy is utilised.

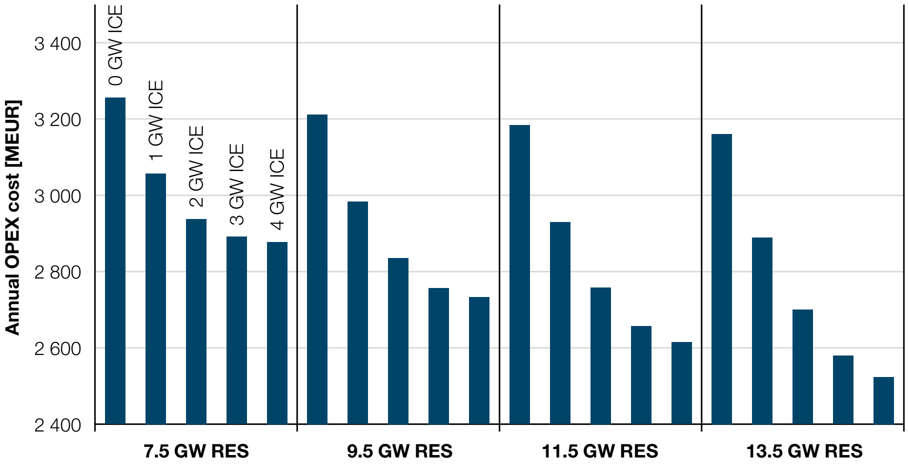


Figure 14. Annual variable operation cost of the Ukrainian power system.

The reduced operational costs are in the range of 200 to 600 MEUR annually, depending on the scenario, which is a significant saving on the system cost. This is, however, only one side of the results. In order to obtain a more correct view, the fixed costs, feed-in tariffs, renewable auction tariffs and investment costs have to be included. The fixed costs of the power plants are given in the input parameters and the feed-in and renewable auction tariffs are discussed in detail in Section 3.6. For the investment in the engine power plants, an investment cost of 700 EUR/kW was used for the calculation. This investment cost considers a full turn-key delivery of the power plants. By doing the financial calculations for the engine plant investment using the parameters in Section 3.3 and deriving a total, we arrive at the results shown in Figure 15.

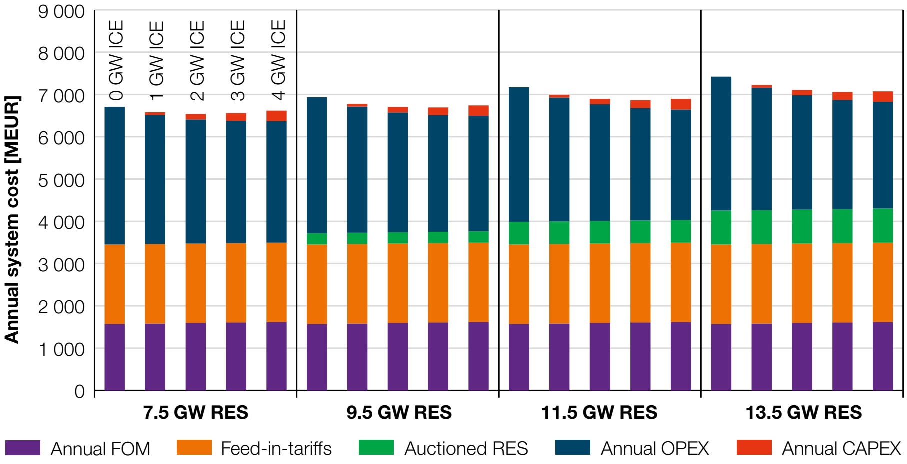


Figure 15. Total generation cost of the Ukrainian power system.

There are a couple of important things to note. First, after adding all the costs together there is still a significant benefit of introducing flexible engines into the system. The total system cost reduction amounts to 2-5%, depending on scenario. Furthermore, as discussed in Section 4.3, with more flexibility and renewable energy in the system, some of the existing generation assets could be mothballed and decommissioned, which would lead to a direct reduction of fixed costs. This has not been assessed in detail and has not been accounted for in the results.

Second, comparing the cost of the feed-in tariffs with the auctioned RES it is obvious that the feed-in tariffs are becoming very expensive for the system. Hence, it is important to increase the utilisation of renewable energy and make use of this already paid for energy.

4.5. OPTIMAL RATIO OF FLEXIBLE GENERATION

The total system cost including investment cost also shows the optimal capacity of engines for different capacities of RES. Figure 16 presents the same information as in Figure 15, but in a slightly different way. As can be seen, there is an optimal point at which the engines provide the most value to the system. This optimal capacity increases with the capacity of renewables and stretches from 1.5-2.5 GW for 7.5 GW of RES up to 2.5-3.5 GW for 13.5 GW of RES.

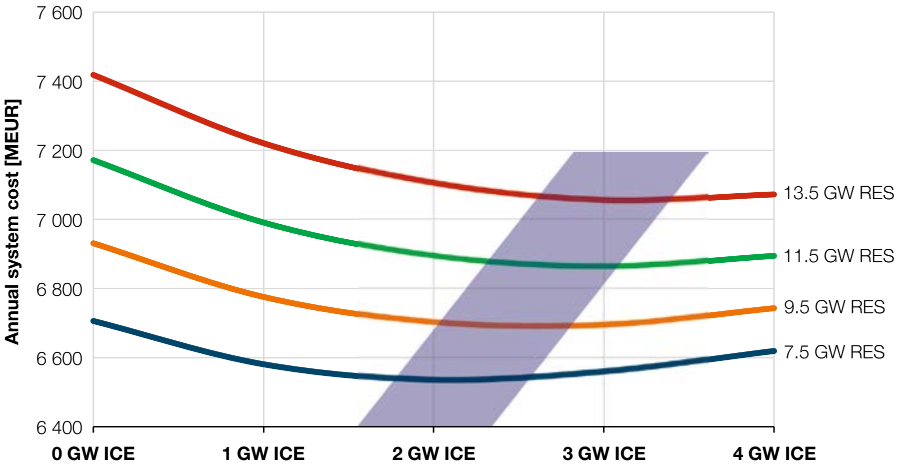


Figure 16. Optimal capacity of engines for different RES capacity.

4.6. REDUCED CO_2 EMISSIONS

The CO_2 emissions of the system are closely following the trend of reduced curtailment when adding flexibility to the system. The main contributor is the reduced consumption of coal. The CO_2 emission reduction is substantial, and ranging from 8% to as high as 30% in the most optimistic case. From an environmental point of view, it is a big contributor for reaching the reduction targets that have been set for Ukraine.

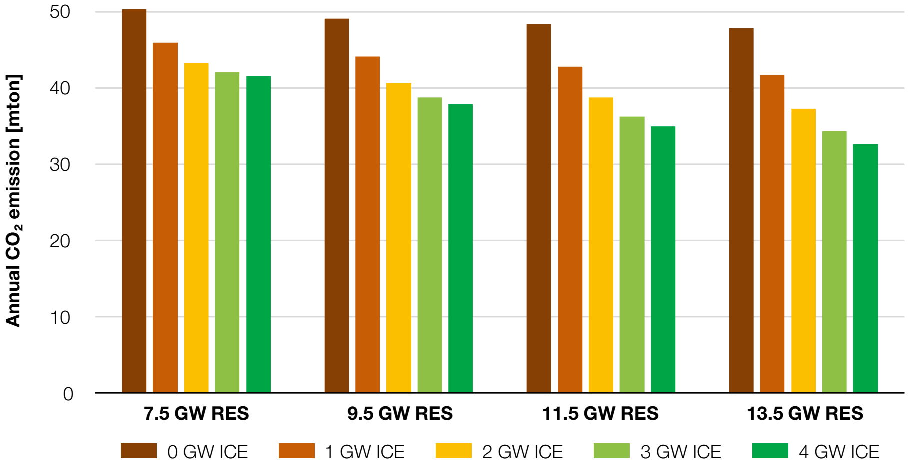


Figure 17. Reduced CO_2 emission with increased flexibility.

5. Conclusions

The energy sector in Ukraine is on the brink of a major change. The plans outlined in the Strategy-2035 document by the government take the first steps towards a new energy market, increased use of renewable energy and integration with the European energy system. These changes are made to provide the citizens with sustainable, reliable and affordable electricity in years to come. However, there are challenges that need to be addressed to make this transition to a market-based energy system as smooth as possible.

1. System inflexibility

The generation assets in the Ukrainian power system consists to large extent of large, inflexible, centralised nuclear and coal blocks that have been designed to operate in a steady baseload mode. Roughly half of the energy generated in Ukraine comes from nuclear and one third from coal, while the rest comes mainly from hydro and renewables. This capacity mix together with an accelerated plan to utilise more renewable energy is leading to a situation where the renewable energy is curtailed as the rest of the system cannot adjust sufficiently quickly.

2. Increased utilisation of renewable energy requires more power system reserves

Due to the intermittent nature of renewable energy the requirement for reserves or back-up power is increased. This increased requirement for reserves stems mainly from forecasting error of renewable generation. This situation will become the new normal and the Transmission System Operator should be prepared. If no more flexibility is added to the system, it might lead to a situation where nuclear plants are taken offline in favour for coal plants that can provide reserves, i.e. more renewable energy may lead to more coal.

3. Feed-in-tariffs vs. renewable auctions

The present feed-in-tariff scheme for renewables is very lucrative for investors, but in the long run this will become expensive for the state. The feed-in-tariffs have played their role in bringing the first renewables to the market. However, going forward, a more competitive scheme should be assessed. Renewable auctions are becoming more and more popular around the globe, as they are bringing a steady increase of renewables while keeping the cost down.

4. Synchronisation with ENTSO-E

At present, there is a plan to synchronise the whole Ukrainian grid with Western Europe and disconnect from the Russian grid. However, before synchronising with Europe, Ukraine must show that its grid is capable of operating in an island mode. This is a task that needs to be carefully planned and requires the TSO to have sufficient reserves at hand.

All these challenges have, to a certain extent, a common theme: the demand for more flexibility. As has been shown in this white paper, bringing more flexibility to the system would solve a significant share of these issues. The results from modelling of the Ukrainian system shows that adding 2-3 GW of flexibility by 2025 would:

- Allow nuclear plants to continue to operate at the present high load 80-90 TWh/year
- Allow renewable energy sources to be better integrated into the system
- Reduce the curtailment of renewable energy from 30% to almost 0% in the case of 7.5 GW installed renewable energy sources
- Reduce the electricity generation from coal by 13-30%
- Reduce CO_2 emission by 10-20%
- Reduce the overall system cost to serve load by 200-450 MUSD/year, which is corresponding to a 2-5% cost reduction
- Give the TSO access to modern fast starting and ramping capacity for balancing the grid and provision of reserves

This will lead to a future where Ukraine is less dependent on coal and significantly reduce its CO_2 emissions. It would allow Ukraine to create a future-proof system that is ready to adopt more renewables and reach its emission reduction targets.

NOTES

WÄRTSILÄ ENERGY SOLUTIONS
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— Wärtsilä Energy Solutions is leading the transition towards a 100% renewable energy future. As an Energy System Integrator, we understand, design, build and serve optimal power systems for future generations. Our offering includes ultra-flexible internal combustion engine-based power plants, hybridised solar power plants, energy storage & integration solutions, as well as gas to power systems. Wärtsilä's solutions provide the needed flexibility to integrate renewables and secure power system reliability. Wärtsilä has 68 GW of installed power plant capacity in 177 countries around the world.

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