

# Decreasing the need for fossil capacity with flexibility

The role of flexibility in future energy market

2022

# Executive summary

This analysis follows on from the study by the independent energy think tank Ember on a pathway to a coal-free Czech Republic by 2030. This study aimed to show how coal power plants could be replaced with renewable energy without having a negative impact on the European electricity system. Coal power plants do not only produce electricity, which can be easily replaced by renewable sources; they also produce “guaranteed capacity” and “regulation energy” (i.e., ancillary services), which must also be replaced if coal power plants are to be phased out.

We have evaluated the present situation with respect to the role of coal-fired plants and evaluated/extrapolated the flexibility requirements anticipated by the Ember study. Further, we have analysed the potential of flexibility capacity in the Czech Republic in the industry, residential, electric vehicle, storage, and heat sectors. Based on these inputs, we have assessed the potential of flexibility to reduce the need for additional capacities (e.g., natural gas as a transitional fuel) and increase the share of renewables.

## Highlights

- **Flexibility decreases the need for traditional dispatchable sources:** Using this flexibility can decrease the need for dispatchable power capacities from 0,9 to 1,3 GW.
- **Flexibility enables RES integration into the grid:** Using this flexibility enables the full accommodation of short-term gradients from RES production that would otherwise keep RES penetration below the desired level.
- **Flexibility enables higher utilization of renewable energy**
  - o An additional 1 000 to 1 500 GWh of RES production is integrated into the grid that would otherwise need to be curtailed or exported (from total RES production of cca 20 000 GWh).
  - o The amount of surplus electricity decreases by 2-5 times from the 9% in the reference scenario.

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# 1. Introduction

This analysis follows on from the Ember study on a pathway to a coal-free Czechia by 2030 (Ember, 2020). It aims at calculating, with hourly granularity, how to replace coal power plants with renewable energy without having a negative impact on the European electricity system. Coal power plants do not only produce electricity, which can be easily replaced by renewable sources; they also produce “guaranteed capacity” and “regulated energy” (i.e., ancillary services), which must also be replaced if coal power plants are to be phased out.

Renewables do not typically provide a baseload supply of electricity, as opposed to the coal-fired power plants that renewables should replace. Intermittent sources such as wind and solar, are difficult to predict and require partial accumulation for times when there is no wind nor sunlight. The technical possibilities to make up for the projected reduction in generation capacity of conventional sources are still limited.

With the growing market share of intermittent renewable sources assumed in the Ember study, we expect the short-term imbalances to grow in volume. Thus, the need for flexibility (either at the BRP level, in order to manage imbalances in prices, or at the TSO level, in the form of reserved capacity) will necessarily increase as a consequence. We are therefore evaluating the present situation with respect to the role of coal-fired plants and evaluating/extrapolating the flexibility requirements anticipated by the Ember study.

To unleash the full potential of renewables, not only will the supply side need to be adjusted, but so will real-time demand. There is significant potential to manage flexibility (regulation down or up) of industry as well as the residential sector, which are similar in magnitude, but very different in the number and complexity of energy assets to be controlled. The primary goal of this analysis is to assess the potential of flexibility for an increased share of renewables and a reduced need for additional sources (e.g., natural gas as a transitional fuel).



# Analysis

We have divided our analysis into two phases. First, we have extrapolated the future electricity generation based on the composition of renewable sources estimated by the Ember study. Second, we evaluate the potential of flexibility in the Czech Republic and its potential to reduce the need for additional sources and to utilize a higher proportion of renewables.

## Phase I

We have evaluated the current electricity generation and consumption profile with hourly granularity. Based on this analysis, we have extrapolated the data for an increase in PV and wind production based on the Ember study's forecast for 2030. In the projection, we have disregarded all fossil power plants and explored the profile of over- and under-production should electricity be produced only by RES and nuclear. This approach helped us identify the frequency and time distribution of under- and over-production. This analysis thus suggests the minimum level of additional capacity necessary and its utilization. The primary purpose of the phase I analysis is to identify time and frequency distributions of over- and under-production, so we can elaborate on the potential role of flexible electricity consumption/production in phase II. A summary of our analysis is provided in Section 2.

This is the first step in compensating for the current role of fossil power plants in the electricity system balance (including the provision of ancillary services).

## Phase II

We have evaluated the potential of flexibility in 2030 in the Czech Republic in two scenarios and with respect to their technical and operational limitations (Section 4) and defined relevant representative scenarios. We have analysed the following areas from the perspective of demand-side management:

- Industry
- Residential
- Electric vehicles
- Storage
- Large-scale heating

Based on the estimated volumes and technical or operational limitations we have analysed the potential of flexibility to reduce peak demand for additional sources. Further, we have evaluated the potential to utilize renewables during hours when there is a surplus of electricity predicted and estimated volumes of probable RES curtailments (Section 5). Based on these results, we have evaluated the need for additional installed capacity and its utilization profile.

We note that we have not explicitly evaluated the potential of production flexibility (i.e., the capacity of sources to increase the volume of production at specific times). These sources are typically fossil-based and thus are included in the residual category of additional sources needed. Further, we have not evaluated the option for demand curtailment. We assume these measures to be of a last resort and as such we are not including them in the defined scenarios.

## Data

All input data points used within phase I of our analysis (unless explicitly stated otherwise) are based on publicly available data from the ENTSOE transparency platform. This approach enables us to use data that can be in principle also compared with different countries using similar methodology. However, this should be kept in mind when reconciling our data points with other studies using different data sources, mainly publicly available data from ERÚ, ČEPS or OTE, as their data reporting methodology might differ (mainly with respect to own use of power plants, electricity losses, etc.).

Input data for phase II, i.e., the estimation of flexibility potential, are based on a mixture of sources, mainly:

- Publicly available statistical data
- Reviews of studies and literature
- Estimates from internal data and expert opinions

For specific categories, we aim to describe the methodology used and the respective sources. However, it must be noted that we have estimated the majority of specific data points and future predictions based on combinations of these sources.

Analysis of the potential of flexibility provided in Section 5 is based on the custom optimization code. We explain the underlying logic in Section 3.



## 2. Summary of input data - Phase I

To analyse the current role of coal power plants mainly with respect to flexible production of electricity, we are using 2019 as the base year. The year 2020 (and 2021 to a certain extent) was highly influenced by reduced demand for electricity in connection with the global pandemic and we consider earlier years as less representative due to relatively rapid changes in the electricity markets with respect to ongoing energy transformation. To ensure the robustness of the analysis, we also consider sensitivity analyses based on the years 2017, 2018, 2020 and 2021.

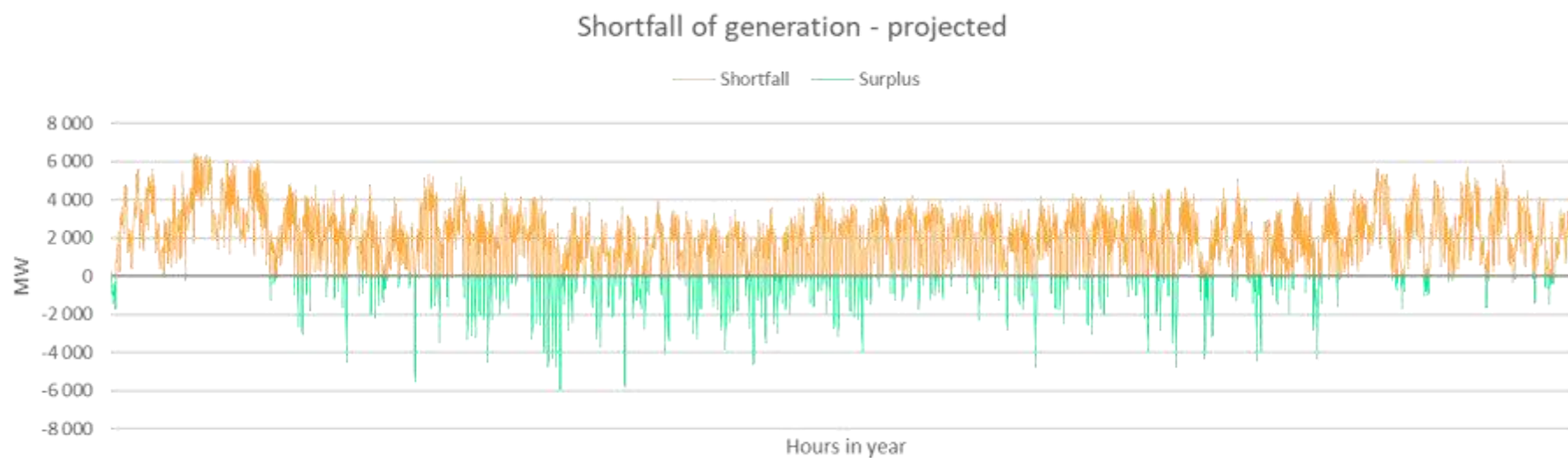
From base year data, we assume three main changes. In accordance with the Ember study, we assume that overall PV production will increase to 10.538 GWh while wind production will increase to 9.776 GWh. We do not extrapolate other sources such as gas CCGT and CHP. Our goal is rather to determine the minimum necessary amount that other sources would need to produce in order to see how much of it could be covered through flexible consumption/generation.

In accordance with the Ember study, we also extrapolate the consumption in the Czech Republic to match the projected year (2030), i.e., to 70.175 GWh.

Based on extrapolated hourly production, we further analyse the residual load in the projected year. We thus show a shortfall of generation based on nuclear and extrapolated RES generation alongside the extrapolated consumption. We note that we have excluded pump storage from the data. Pump storage optimization is included in the analysis as part of other storage solutions.

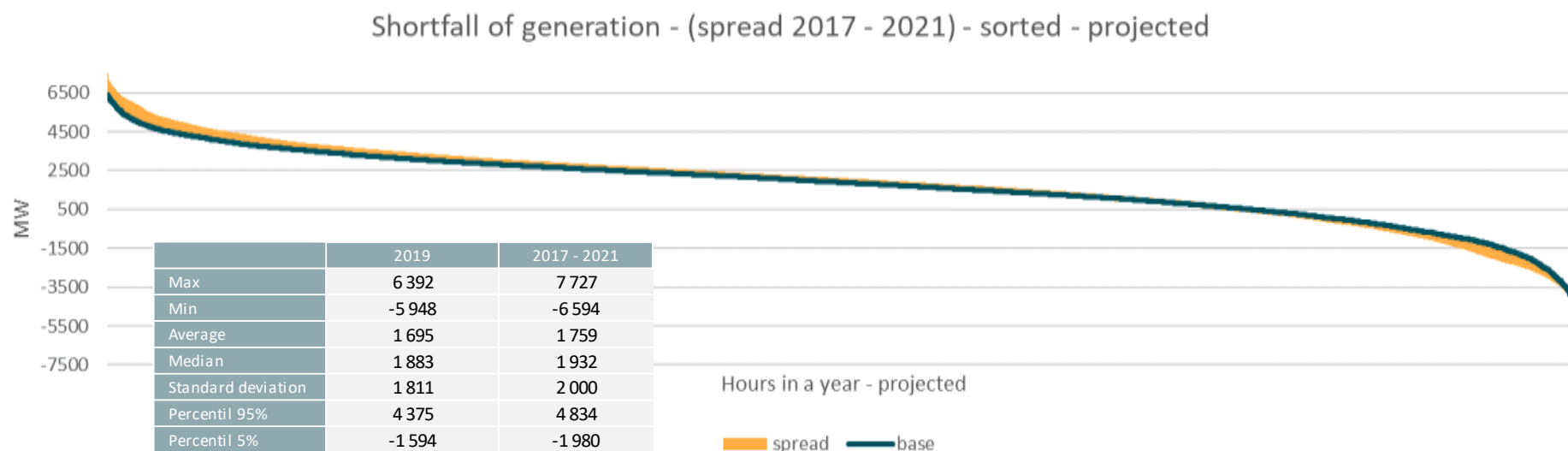
Figure 1 shows the generation shortfall (a surplus is depicted in negative values) in the projected year with hourly granularity.

Figure 1: Projected generation shortfall



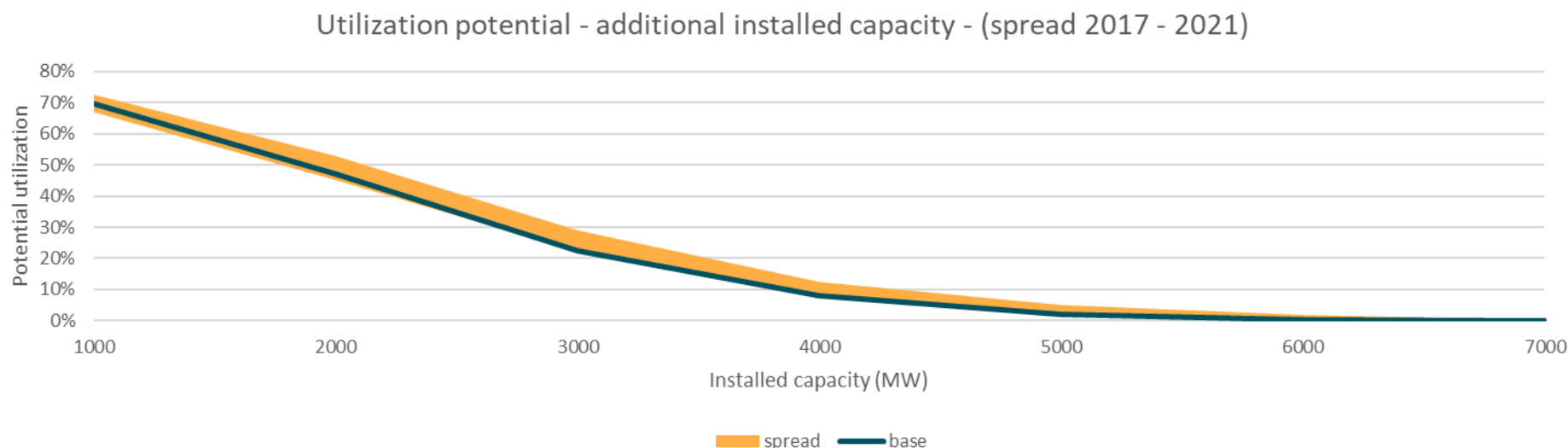
In Figure 2 we show the shortfall in a sorted manner. The resulting curve shows the frequency of the shortfall/surplus. We also provide sensitivity, should a year other than 2019 be chosen as the base year, as a spread between maximum and minimum during these years. The results show notable but not significant differences between the years used for the analysis. In the lower left corner, we also show statistical differences between the base year and the years 2017–2021.

Figure 2: Sorted shortfall of projected generation with maximum and minimum spread based on different base years (2017–2021)



Assuming a production shortfall, we model potential utilization of additional sources based on installed capacity. Utilization decreases with increased installed capacity, as the source would be required to operate only during shortfall hours, which, with increased capacity, becomes less likely. Again, we model the scenario with sensitivity on the base year and maximum and minimum values between 2017 and 2021. Figure 3 shows the utilization potential of such added capacity.

Figure 3: Utilization potential of additional installed capacity with max and min spread based on different base years (2017–2021)



We show that only the first few GW would be utilized often, and any additional increase in capacity would be used rather infrequently. This enhances the need to determine how much of this additional capacity can be in fact replaced by a smart use of flexibility.

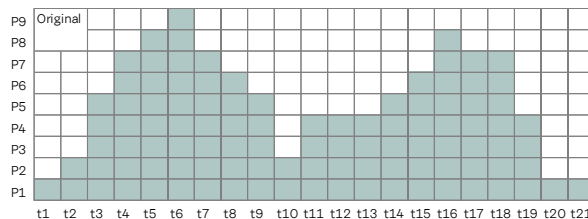
# 3. Theoretical optimization

In this section, we present the underlying logic of the optimization algorithm (this will later be used to optimize the input shortfall data presented in Section 2). Further, we elaborate on the theoretical potential and limitations of such load optimization.

## The optimization algorithm

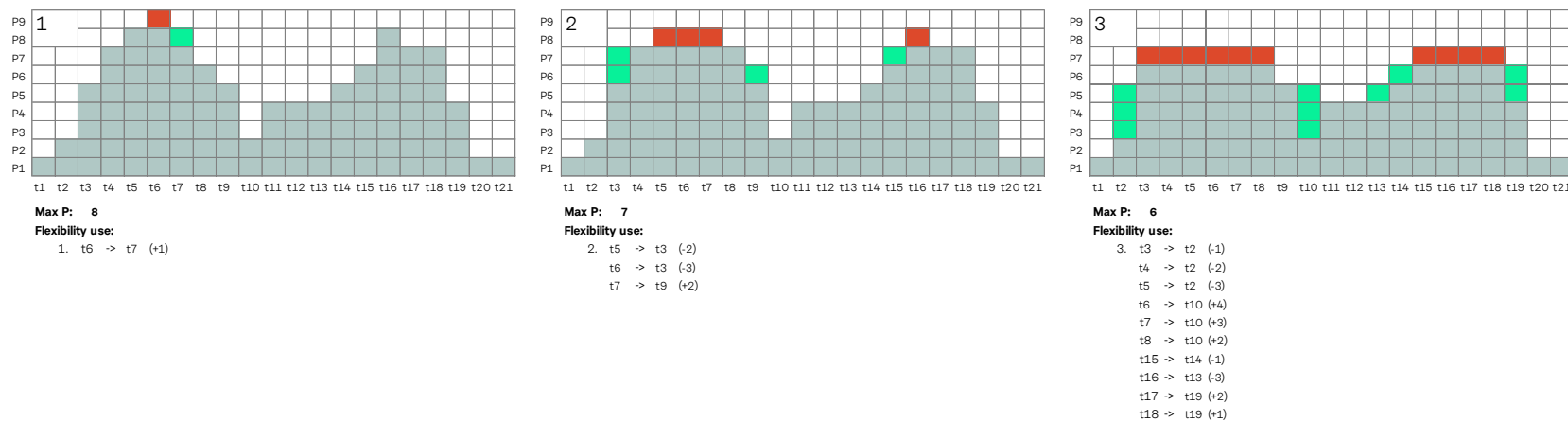
The input for the algorithm is the residual load (or generation shortfall) profile. In Figure 4 we show an example of the profile, where time is shown on the x axis (from  $t1$  to  $t21$ ) and power is depicted on the y axis (from  $P1$  to  $P9$ ).

Figure 4: Original residual load profile



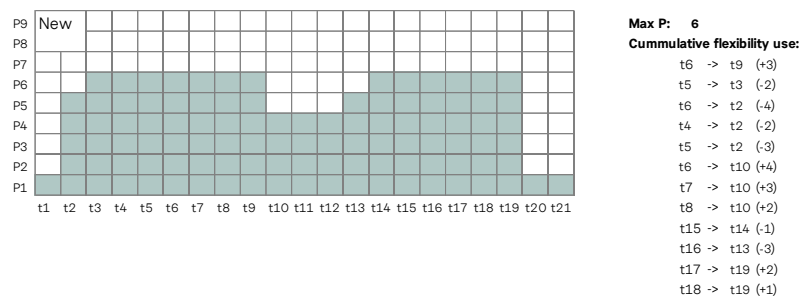
The optimization algorithm selects the highest value, here at  $t6$  and moves it to the closest lower time, here at  $t7$ . The original position, new position as well as the distance of the move are stored, and a new load profile is created. This process repeats. The highest values are gradually selected, and respective load adjusted. In the case that highest value is at position which has already been moved (e.g.,  $t6$  was moved to  $t7$  and that is in the next iteration the highest value and should be moved again), the distance of the move is also stored cumulatively. We show an example of the algorithm in Figure 5, where each move is shown underneath the picture with the respective distance in brackets. Further, the new maximum value is shown as  $Max P$ .

Figure 5: Optimization of residual load profile



After the optimization ends, i.e., either the desired reduction of the maximum load is reached or the parameters of flexible units do not allow for further optimization, a new profile is created. We show the example of the profile after 3 rounds of optimization in Figure 6.

Figure 6: New residual load profile after optimization



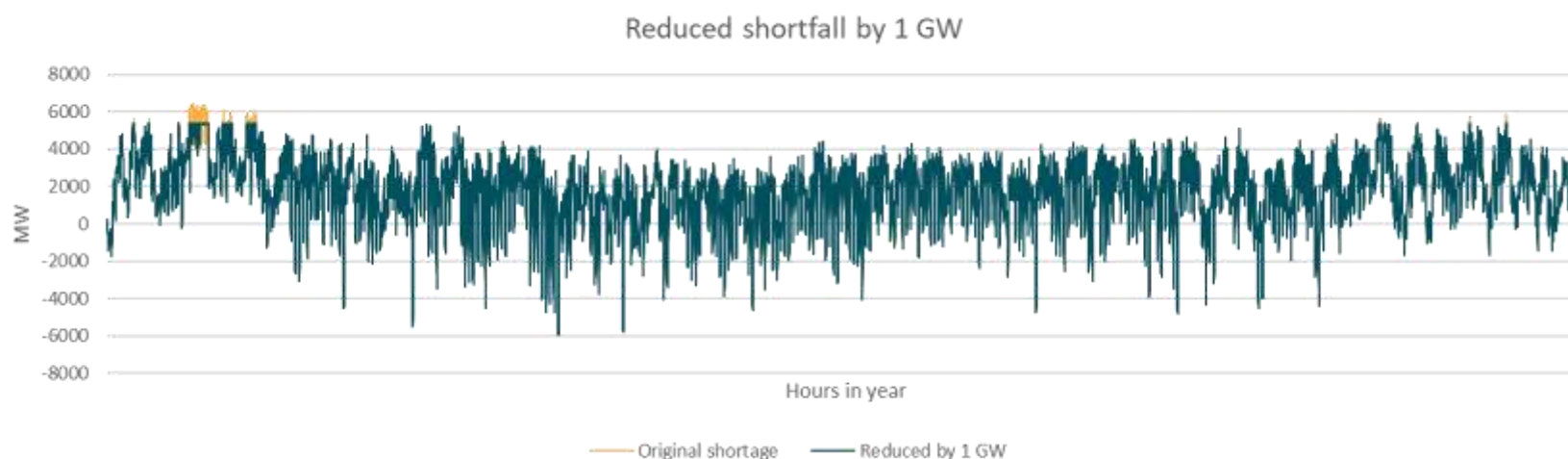


## Example – maximum generation shortfall reduction

Based on the algorithm described above, we further show a simplified example and theoretical analysis of the shortfall input data presented in Section 2. To estimate the potential of flexibility to reduce peak demand for additional sources, we first examine the reverse logic, i.e., what type of flexibility would be needed to reduce the peak shortfall hours.

To illustrate the underlying process, in Figure 7, we show the input shortfall (as presented in Section 2) and profile which have been optimized so that the maximum peak shortfall is reduced by 1 GW.

Figure 7: Base year 2019 – projected 1 GW maximum shortfall reduction



As shown in Figure 7, reducing the maximum shortfall by 1 GW concentrates the needed flexibility to only several specific hours of a year, specifically in January. The figure shows that even a significant maximum shortfall reduction can be achieved with relatively low utilization of flexibility at specific times.

However, reducing the maximum shortfall further is relatively difficult, as significant moves within a short period of time would be required. Demand-side management is expected to be used to shift consumption within a short window of time, and not to reduce it for significantly longer periods.

To illustrate the required time window for flexible load shifts, in Figure 8 we show the respective distance of shifts in hours and their frequency for 1 and 2 GW reductions of maximum shortfall. The y axis (number of occurrences) is in logarithmical scale, so that long shifts, which are low in frequency, are also clearly visible. We therefore show how far the load needs to be shifted, so that it leads to a maximum shortfall in reduction of 1 and respectively 2 GW.

Figure 8: Occurrence frequency of distance of shifts; maximum shortfall reduction (1GW – 2 GW)

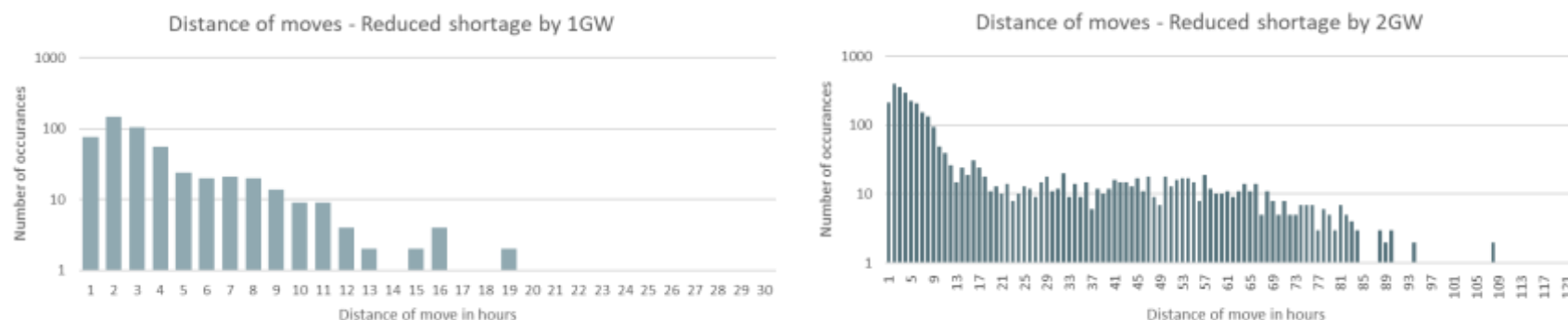


Figure 8 thus illustrates that significant maximum load reduction would lead to shifts which would be a matter of days and thus not suitable for short-term optimization. On the other hand, shorter local peaks can be substantially reduced even with shorter load moves shifts.

The function of maximum generation shortfall reduction decreases quickly at first, when few flexible units are introduced. However, to reduce maximum peak further, an exponential increase of flexibility potential is required. We show the maximum shortfall reduction as a function of the number of required flexibility shifts in Figure 9.

Figure 9: Maximum shortfall reduction as a function of number of shifts



However, increasing the number of shifts is not the only thing that is required. Similarly shifted capacity increases significantly. In Figure 10 and Figure 11 we show the yearly distribution of cumulative shifted capacity within specific periods of time for 1 and 2 GW peak shortfall reductions, respectively. While the figures show quite similar patterns, the required volumes differ significantly. In the case of a 1 GW reduction, the shifted capacity is focused predominantly in January and reaches a maximum of around 7 GWh (i.e., seven times higher than achieved peak reduction). In the case of a 2 GW reduction, the shifts are slightly more dispersed throughout the year, however the maximum capacity shifted within a specific period of time reaches approximately 50 GWh (i.e., 25 times higher than achieved peak reduction).

Figure 10: Cumulative shift of capacity in specific time periods - 1 GW maximum shortfall reduction

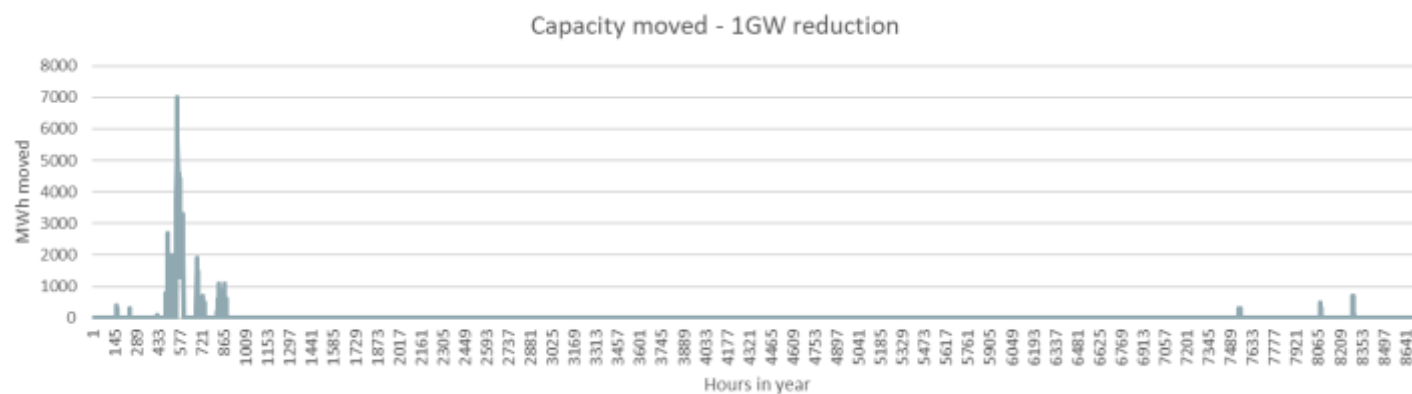
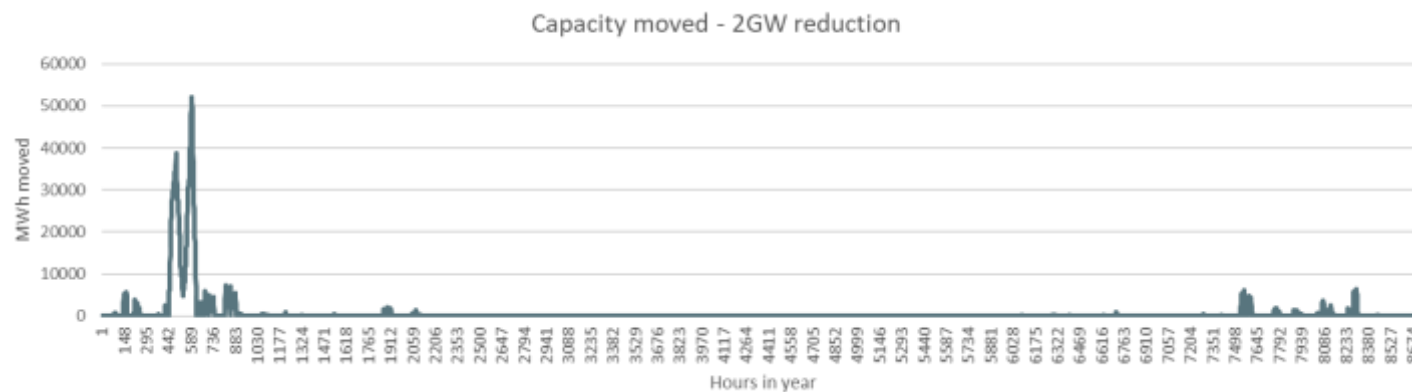


Figure 11: Cumulative shift of capacity in specific time periods - 2 GW maximum shortfall reduction



# Implications for specific scenarios

We have examined the theoretical maximum shortfall reduction and respective requirements of load flexibility. The analysis serves as a starting point for specific optimization based on technical and operational characteristics of specific scenarios based on potential in the Czech Republic. The specific analysis will be based on reverse logic, i.e., based on defined limitations, we will estimate the potential reduction for maximum shortfall, utilization of specific flexible units, capacity of flexibility shifting and the impact on the utilization potential of additional sources and gradient distributions. In the following sections we will also consider the possibility to flatten the shortfall curve, i.e., we will not focus only on the reduction of the maximum shortfall values. Here, we rather illustrate the approach to better explain the function of the model.

## 4. Flexibility potential in CZ

We are estimating flexibility potential in CZ in 2030 in two scenarios, medium and high. We have analysed 5 categories of flexibility:

- Industry
- Residential
- Electric vehicles
- Storage
- Heat

We are modelling specific scenarios based on operational and technical limitations including:

- Power of specific flexible units (in MW)
- Capacity of the flexible units (in MWh)
- Efficiency of the unit
- Time limitations (in hours of a day and months within a year)
- Maximum possible move (in hours)
- Minimum possible pause between cycles (in hours)

Combining these input data, we derive a flexibility matrix that we apply in a similar manner as presented in Section 3. For all relevant technologies we provide this simplified matrix with a traffic light indication of suitability and limitations. FCR, aFRR and mFRR are indicators (derived from the current grid-regulation codex) showing whether the technology can be activated in the short/medium/long term (short term: less than an hour, long term: several hours in a row). FCR and aFRR-suitable technologies may help address higher power gradients induced by the scaled-up RES portfolio but cannot reduce the high load for several hours in a row, thus they are not part of the optimization algorithm. mFRR-suitable technologies are included in the optimization since they can address a high load – low-RES production for several hours in a row. We would like to note that we are showing flexibility potential figures per one full cycle of flexibility. This means that the figures provided cannot be cumulatively added to one point in time but are rather subject to spatial and time limitations. We project the flexibility potential based on representative consumer behavior, observed technological possibilities and key industrial processes.



# Industry

To estimate the industrial flexibility potential in the Czech Republic we first estimate the flexibility of core manufacturing processes within industries with the highest electricity consumption. Consumption proportions of the specific industry sectors are provided in Figure 12. The study starts with an estimation of flexibility within the group of industrial sectors which represents 70% of all electrical energy consumption.

Figure 12: Overview of industries with largest electricity outtake

NACE	NCV GJ of electricity outtake in 2018	% on all outtake	Aggregated % on sum of outtake
23 - Manufacture of other non-metallic mineral products	8 529 873	12,4%	69,95%
29 - Manufacture of motor vehicles, trailers and semi-trailers	7 891 016	11,5%	
20 - Manufacture of chemicals and chemical products	6 168 821	9,0%	
22 - Manufacture of rubber and plastic products	5 954 561	8,7%	
25 - Manufacture of fabricated metal products, except machinery and equipment	5 889 556	8,6%	
10 - Manufacture of food products	5 216 574	7,6%	
28 - Manufacture of machinery and equipment n.e.c.	4 267 731	6,2%	
24 - Manufacture of basic metals	4 015 655	5,9%	30,05%
Other Industries	20 589 037	30,0%	

Due to a lack of data and problems identifying processes and their intensity within NACE 25, we replaced NACE 25 with the well documented paper industry process NACE 17 (NACE 25 – 8,60% of all consumption, NACE 17 – 3,21% of all consumption). By estimating the potential within selected NACE processes, we extrapolate the overall potential (as these provide the largest impact on the grid balancing).

Further, we analyse representative processes within chosen sectors (key processes illustrate energy intensity and operational characteristics of specific industries). From the analysis of specific processes, we extrapolate the flexibility as well as shifting of processes in time. The selected processes are listed in Figure 13.

Figure 13: Most intensive processes and sources

NACE	Most intensive process	Source (proportion on all processes)
23	Glass container production	SynErgie (melting 50 - 80%)
29	Painting booth	SynErgie: (52 %) Giampieri et al. (59%)
20	Chlorine-alkaline electrolysis	SynErgie
22	Common mixing	Ali et al. (40%)
10	Cooling	Ladha-Sabur et al. (40 - 60 %)
28	General additive process	Yoon et al.
2	Electric arc furnace	SynErgie
17	Pumping	MPO (50%)

The processes for Glass container production (NACE 23), Chlorine-alkaline electrolysis (NACE 20), Electric arc furnace (NACE 24), and Drying (NACE 17), were sourced from the SynErgie study, part of the Kopernikus project which estimated industry flexibility in Germany. We have adjusted the results by the appropriate industry specific consumption ratios (reflecting the intercountry sector specific consumption differences). To calculate intercountry ratios, we used the 2019 Eurostat energy balances.

The estimation of all presented processes and respective values are derived from assumed key processes in the largest companies of a given sector. To assess the most intensive representative processes, the following methodology was used:

1. Identification of all companies in a given sector (based on Business Register issued by the CZSO)
2. Grouping the companies by NACE
3. Identification of large companies. The Czech Republic identifies large companies as entities with more than 250 workers
4. Grouping companies that match NACE identified in step 3; the most common NACE with the most workers are identified
5. The most electricity-intensive processes within the most frequent NACE group are identified and defined as the representative ones
6. Representative processes are analysed, and the input matrix estimated (flexibility, efficiency, cycles, time moves, and seasonality)
7. We extrapolated to the entire industrial sector and carried out a sanity check via related studies

The figures provided should be nevertheless taken cautiously, as industry sectors are rather difficult to assess. The interconnectedness of the manufacturing processes and production quota pressures (as well as other technical and economic factors) play a crucial role and are relatively difficult to estimate. The potential for flexibility in industry may be high, however, it is related to changing patterns of

production. We tried to estimate the flexibility values without significant impact on the production in the medium scenario. However, values presented in the high scenario may interfere with optimal production requirements.

### Non-metallic minerals

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	85	134	
Capacity (MWh)	165	261	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	short/long		
Seasonality	none		

The most common subcategories of the non-metallic minerals industry are the glass and cement industries. The non-metallic minerals industry has the highest electricity outtake of all industries – 12,5 %. The glass processing industry has a long tradition in the Czech lands and maintains a strong position on international markets. We identified 46 companies with 50+ employees and 10 with more than 250 in this industry segment.

The representative process is container glass production. The process was thoroughly reviewed in the SynErgie project, which estimated 25 MW of positive flexibility in Germany for the glass industry. By comparing intercountry ratios of electricity consumption in the sector we extrapolated

the values for the Czech Republic. Using Eurostat data, the respective ratio is 0,19:1 (Czech: German), thus the estimated potential for the glass industry (a subsector of the non-metallic minerals sector) was estimated at 5 MW. We are extrapolating the result to whole industry (NACE 32130 represents roughly 1/6 of the industry). The second most common process – manufacturing of concrete products, was again sourced and edited from the SynErgie project (the potential for Germany was + 172 MW and adjusted by the same ratio). As cement and glass represent 75% of all processes in large companies for the industry, the resulting flexible potential in the Czech Republic is estimated at 85 MW. Specifically, the glass industry has a short reaction time and around 15 – 30 minutes load change, while cement grinding can change load up to 12 hours with 1 day ahead notification. There is almost no seasonality in the industry except for cement grinding, which is linked to the intensity of construction.

## Automotive Industry

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	35	113	
Capacity (MWh)	35	113	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	short		
Seasonality	none		

The NACE 29 is led by ŠKODA AUTO. Other significant companies are Toyota Motor Manufacturing Czech Republic and Hyundai Motor Manufacturing Czech. The majority of large companies in NACE 29 are focused on the manufacture of other parts and accessories for motor vehicles – we identified 32 of these. However, the automotive production process is complex and highly dependent. The values for specific plants should be specified for longer periods of observation and process optimization, and the general difficulties of making such estimations are discussed in other studies as well (SynErgie 2019). We are thus using data for the electrical intensiveness of the industry from Tennet and adjusting the values by intercountry ratios. This led us to a result of 35 MW flexibility in the medium scenario and 113 MW for the high scenario.

## Chemical Industry

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	33	169	
Capacity (MWh)	8	42	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	short/long		
Seasonality	none		

The chemical industry represents 9% of the overall electricity outtake by industry.

As in case of the non-metallic minerals industry, we estimate the flexibility potential using German data from the SynErgie project. The core process by the SynErgie project was established chlor-alkali electrolysis, which is used to produce chlorine and sodium hydroxide. The process has a high energy consumption – ca. 10 000 MJ per tonne of sodium hydroxide produced.

Chlor-alkaline electrolysis with storable intermediates has a high flexibility profile, allowing the technology to work as part of a short-term compensation of load. The reaction time for the load change period is up to 15 minutes and the advance notice interval is in the range of just several minutes.

The SynErgie study estimated potential in Germany with approximately 21 units and 95% availability on negative flexibility of -15 MW and positive flexibility of 421 MW. However, Germany's chemical industry is disproportionately compared to the Czech one, resulting in an industry outtake ratio of 0,06:1 (Czech: German). The Czech chemical industry should offer ca. 25 MW of positive flexibility with high frequency recall and good reaction for short and mid-range load operations. A comparison with the meta study *Energieflexibilität in der Industrie* led us to re-estimate the potential of positive flexibility to 33 MW for the medium scenario and 169 MW for the high scenario.

### Rubber and Plastic Industry

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	45	163	
Capacity (MWh)	11	41	
Efficiency	efficient		
Min pause - cycles	none		
Max move	medium		
Seasonality	none		

The largest companies include Continental Barum s.r.o., Trelleborg Wheel Systems Czech Republic a.s., Nexen Tire Europe s.r.o. and Devro s.r.o. all operating in NACE classification 22110 – manufacture of rubber tires and tubes, tire retreading. Our focus is thus on the rubber tire manufacturing processes. Among these, the general mixing of raw materials consumes most of the electricity, approximately 40 % of the total (Ali and Jaiswal 2019, Stankevičiūtė 2000).

This mixing is the first process in tire manufacturing, which gives the tire industry a high level of flexibility. The Banbury mixer is a representative mixer and at full load it has an outtake of 1200 kW, produces 250 kilos of mixture, and is run approximately 25 times per man-day. Given the number of tire production lines in Czechia, we estimate consumption of 45 MW for the whole industry in the medium scenario and 163 MW in the high scenario.

## Food Industry

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	28	89	
Capacity (MWh)	28	89	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	medium		
Seasonality	none		

inside the freezer. Depending on the food inside the freezer and temperature boundaries, option A is medium-term in nature, with a shutdown of up to 3 hours, while ventilators should be thought of as a short-term solution (SynErgie 2019).

## Machinery

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	4	40	
Capacity (MWh)	1	10	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	short		
Seasonality	none		

The food manufacturing industry has the highest number of selected companies in subgroups of NACE 101 – processing and preserving of meat and production of meat products, while the second-most important companies focus on NACE 107 – production of bakery, confectionery, and other flour products. There are 8 large companies in Czechia focusing on meat processing. Poultry slaughtering consumes more energy than that for other meats due to hair and feather removal, and singeing operations. According Ramírez (2008) and Ladha-Sabur et al. (2019), cooling is the most electricity-intensive process in meat processing. There are two possibilities for flexibility in cooling systems A) Switching on/off the entire freezer or B) Switching on/off ventilators which redistributes the cold air

The largest companies in the Czech Republic operate in NACE 282, namely DENSO MANUFACTURING CZECH s.r.o, with more than 2,500 employees and a focus on the manufacture of industrial refrigeration and air conditioning equipment, Daikin Industries Czech Republic s.r.o. with more than 1,500 employees, which focuses on the manufacture of general-purpose machinery (specifically air conditioning units), and VOP CZ s.p., which has more than 500 employees and focuses on the manufacture of general-purpose machinery (specifically military equipment). In machinery, the most intensive process is the general additive process. According to the SynErgie project, in Germany, each hour a load shift of 15% up or down can be carried out in the machinery processes, which has outtake of approximately 200 MW (for Germany). The inter-country ratio of 0,13:1



(Czech: German) means Czech potential of approximately 26 MW, of which 15% is 4 MW of flexible units. The ability to readjust the process every hour gives us a frequency of 6 recalls per standard man-day.

### Industry of basic metals

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	70	266	
Capacity (MWh)	210	798	
Efficiency	efficient		
Min pause - cycles	long		
Max move	long		
Seasonality	none		

The potential in industry of basic metals is extrapolated using the research from the SynErgie project, which estimated the potential in Germany for positive flexibility at 766 MW. The ratio for intercountry comparison is 0,09:1 using Eurostat data, resulting in approximately 70 MW of positive flexibility in the Czech metal industry, specifically the iron and steel industry. The most energy-intensive process is the electric arc furnace, which is well known for operating in off-peak hours due to the high electricity consumption. Although there is no particular seasonality for electric arc furnace usage, the process should be, with respect to its high electricity consumption, well planned. The typical melting time ranges from 1 to 4 hours.

## Paper Industry

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	40	126	
Capacity (MWh)	40	126	
Efficiency	efficient		
Min pause - cycles	long		
Max move	long		
Seasonality	none		

Large paper companies in the Czech Republic are mostly focused on NACE 17120 and 17210 - production of paper and cardboard packaging. Bleached sulphate pulp processing has high outtake in the drying process, which accounts for up to 25% of electricity consumption, while pumping has the highest outtake, at up to 50% of the total.

According to meta study by Sauer et al. the paper industry has median of load incrementation of 94 MW and maximal potential of 1700 MW. In case of load reduction, the potential for Germany is estimated to 251 MW of median value and maximum in 1700 MW. Maximal move can shift from as less as 2 hours to maximum of 48 hours. Using ratios for intercountry comparison and adjusting values for Max/Median variance, we estimated the potential for Czech Republic for medium scenario to 40 MW and high scenario provides 126 MW with anticipated 24 hours of maximal move in both scenarios.

## Other Industries

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	186	603	
Capacity (MWh)	186	603	
Efficiency	efficient		
Min pause - cycles	various		
Max move	various		
Seasonality	none		

We have not analysed remaining industries in-depth. These represent approximately 30% of the electricity consumption of all industrial sectors as a whole. The combined potential of all the sectors is extrapolated proportionally for the remaining 30% of the potential, resulting in 186 MW of power potential in the medium scenario and 603 MW in the high scenario. We expect to find in these industries various processes, mainly additive and subtractive processes, however we cannot further elaborate on production cycles, load shifting or seasonality.

# Residential

We have identified batteries, boilers, heat pumps and other appliances for residential flexibility. Unlike in industry, residential flexibility is highly fragmented. Although the overall potential is substantial, its utilization is highly dependent on technical availability, which means aggregating a very high number of different appliances into usable blocks. Although the flexibility does not necessarily hinder normal daily life, motivating users to allow for respective shifts may be quite difficult (as the value of single KWh shifts may not provide sufficient motivation). In the respective scenarios we therefore operate with different user participation rates (ranging from 10 to 50%). These estimations are difficult to predict as they are strongly dependent on the financial incentive for participation in flexibility services. Further, any use of residential flexibility will require continuous measurements of electricity consumption at the offtake point. Smart metering is currently mostly not available, though its deployment for residential use should start in 2026 (MPO, 2019).

## Batteries

	FCR	aFRR	mFRR
Suitability			
Power (MW)	Medium	High	
Capacity (MWh)	140	360	
Efficiency	medium		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

Residential batteries are mostly used for to store excess local production of PV. As such, only partial capacity can be dedicated to potential flexibility services. Although batteries can in principle be used to store energy for long periods of time, in practical and economic terms, they are better suited for short-period services (such as FCR or aFRR). We assume a limited usable capacity and only partial willingness to participate in such services.

In line with the predictions of OTE (2020), we assume large deployment of residential batteries in connection with increased capacity of solar rooftop installations. The medium scenario is derived from OTE predictions of installed battery capacity, while the high scenario is derived from scenarios of PV deployment and the related estimation of suitable battery capacity.

## Boilers

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	629	1 165	
Capacity (MWh)	1 257	2 330	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	medium		
Seasonality	winter		

Based on CZSO (2017) data, there are currently roughly 1,3 million electric boilers in use in the residential segment. The potential for flexibility use (i.e., preheating) is thus substantial. Nevertheless, most of the appliances would need to be technically adjusted, which could be challenging.

We have extrapolated the flexibility potential based on the estimation of the number of boilers, typical boiler parameters and profiles of heat demand (also considering the seasonality of consumption). The medium scenario assumes a 25% participation rate while the high scenario assumes 50%. We assume a maximum of 2 hours of shift per day.

## Heat pumps

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	388	1 071	
Capacity (MWh)	776	2 141	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	medium		
Seasonality	winter		

The number of new heat pump installations is gradually rising every year. With the volatile situation for gas supply and prices, this trend is likely to continue. The potential for flexibility from heat pumps may thus rise significantly. There are a significant number of sources assessing the technical parameters of heat pump flexibility (we assume average values).

We have used last year's numbers on new HP installations and extrapolated it to 2030. The seasonality follows the heat demand structure with the exception of summer cooling with higher utilization. In the medium scenario we assume a 25% participation rate while the high scenario assumes 50%. We assume a maximum of 2 hours of shift per day.

## Time of use - other appliances

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	161	806	
Capacity (MWh)	322	1 612	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	medium		
Seasonality	night/evening		

Specific examples have confirmed (e.g., Octopus, 2018) that changing consumer consumption patterns through time of use tariffs (or similar mechanisms) is possible, given the correct incentives.

We have estimated the potential for flexibility based on average shifts that were observed in respective examples and assumed a participation rate of 10% in medium potential and 25% in high potential with various degrees of capacity. Based on the data available, the highest potential for flexibility utilization should be in evening to night shifts. We assume a maximum of 2 hours of shift per day.

# EV

Electric vehicles are expected to grow exponentially in the coming years. MPO's projections (2020) foresee between 220 000 and 500 000 electric vehicles on the road by 2030, providing significant potential for flexible charging. Currently, the capacity for fast and smart charging is limited. However, we assume that with rapid e-mobility expansion these barriers may be quickly removed. We assume two categories for use of flexibility, vehicle charging and the possibility to use the battery capacity in grid-to-vehicle, vehicle-to-grid mode. Similar to residential flexibility, we see a major obstacle to incentivizing customers to allow the use of battery capacity for flexibility purposes as there is a non-negligible possibility of a reduction in convenience of use.

## Charging

	FCR	aFRR	mFRR
Suitability			
Power (MW)	Medium	High	
Capacity (MWh)	219	745	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	medium		
Seasonality	none		

Most EV charging takes place at the home of the car's owner. Given the relatively long period needed to charge the car, the potential for load shifting may be significant. The available capacity for charging (and thus the power for flexibility) is also likely to rise in the near future.

We have extrapolated the potential based on the two boundary estimations of MPO. Further, we have assumed a 15 000 km per year and car, 180 Wh per km and an average 50 KWh battery capacity. The participation levels for smart charging were set at 20% and 30%, respectively, for the medium and high scenarios. We assume flexibility of between 1 and 2 hours once a day.



## G2V/V2G

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	121	1 104	
Capacity (MWh)	275	2 500	
Efficiency	medium		
Min pause - cycles	medium		
Max move	medium		
Seasonality	none		

Grid-to-vehicle, vehicle-to-grid mode is currently mostly not available, however, in principle it is technically possible. The related costs are relatively high, as the battery needs to be in top condition for use in an EV. However, theoretical possibilities for flexibility use are significant

We have used similar inputs for the extrapolation of potential as we did for smart charging, however we assume a lower participation rate of 5-20%. We assume that only 50% of the battery capacity may be available.

# Storage

We have analysed both proven technologies (pumped hydro and utility scale batteries) as well as the potential of other less widespread technologies (compressed air, gravitational storage, flying wheel, Carnot battery and hydrogen electrolysis).

## Pumped Hydro

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	1 170	1 170	
Capacity (MWh)	4 495	4 495	
Efficiency	medium		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

We have included three current pumped hydro storage techniques and their technical dimensions (Dlouhé stráně, Dalešice and Štěchovice). We do not assume additional capacity to be built by 2030, although such plans do exist.

We assume 90% water reservoir capacity.

The efficiency of the power plants was estimated based on existing ENTSOE data as a ratio between production and consumption.

## Utility batteries

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	100	300	
Capacity (MWh)	200	600	
Efficiency	medium		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

Utility batteries are becoming more and more competitive and are a good complement for increasing intermittent renewable production, with a cycle-efficiency above 90%. They are best suited for providing ancillary services like frequency regulation (FCR). These batteries are dedicated to such services, so the only limitation is the speed of deployment and the total capacity installed.

With some already existing large-scale projects in Australia, and in Belgium (10 MW / 20 MWh: <https://estor-lux.be/Estor-Lux-launch-battery-park.pdf>), an environment closer to the Czech context, we can assume a deployment by 2030 of between 100 MW/200 MWh and 300 MW/600 MWh.

## Compressed air

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	290	870	
Capacity (MWh)	580	1 740	
Efficiency	low		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

Energy storage using compressed air technologies at industrial scale have been explored since 1978 in Huntorf (Germany). The main limitation for compressed air technologies is the efficiency of the process. Indeed, compressing a gas generates heat that may be lost. Then, the expanding gas must be heated to keep the plumbing from freezing. Several concepts exist ranging from adiabatic to isothermal, or hybrid. All suffer from low efficiencies (cca 0,5) and might be used mainly to store excess renewable electricity (instead of wasting it with curtailment).

Though the economics do not favour such technologies, we considered 1 such project (similar to Huntorf: 290 MW/580 MWh) up to 3.

## Gravitational

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	40	120	
Capacity (MWh)	40	120	
Efficiency	medium		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

Gravitational storage (excluding pumped hydro storage) suffers from physical limitations. Though some projects using cranes and concrete blocks may exist, the height (cca 100 m) and low density of concrete (2,5 kg/L) gives it an energy density (2,5 MJ/m<sup>3</sup>) much lower than batteries (up to 1500 MJ/m<sup>3</sup>, though the concrete is much cheaper than the electrolyte). However, an interesting concept put forward by gravitricity.com using old mine shafts (deeper than 1 km) may equate to the costs of energy stored by battery-backed methods and provide similar services (FCR).

The Czech Republic could become a pilot site for such a project (see e.g., <https://renews.biz/73143/gravitricity-explores-czech-coal-mine-for-mw-scale-storage>). If successful, this technology could be scaled up to 40 MW/40 MWh or even up to 120 MW/120 MWh.

## Flying wheel

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	20	40	
Capacity (MWh)	5	10	
Efficiency	medium		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

Flying wheels can store kinetic energy that multiplies by the square of the speed. Thus, in order to eliminate the losses (cca 5% per day), a concrete block is accelerated in vacuum tank, and sustained by magnetic bearings. Such a device then has an energy density slightly higher than a battery and could provide similar services (FCR).

Such devices already exist in Germany, Canada, and the USA, but are usually limited to MW with capacities lower than 1 hour (15 min to stop the block at maximum power). We can then assume a deployment of up to 20 MW or even 40 MW to help the grid during high gradients of RES production.

## Carnot batteries

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	50	100	
Capacity (MWh)	200	500	
Efficiency	low		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

A Carnot battery is a thermal energy storage device in which, during the charging process, electricity is converted into heat and kept in heat storage.

The efficiency of the cycle is relatively low and thus such a technology is suitable mostly for storing excessive load from renewable energy sources.

The technology is currently not operational at large scale in the Czech Republic; therefore, we have assumed an experimental deployment with average technical parameters.

## Hydrogen (Methane/ol)

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	50	100	
Capacity (MWh)	33 000	33 000	
Efficiency	low		
Min pause - cycles	none		
Max move	long		
Seasonality	none		

Using the excess of intermittent renewable electricity to produce valuable hydrogen is of course not a new idea. The main limitation of this concept is the cycle-efficiency (all technologies below 50%). Indeed, converting electricity to hydrogen through electrolysis incurs some losses (in tens of %). The best fuel-cell technologies also have efficiencies below 80%. That is why converting electricity to hydrogen should only be used instead of RES curtailment. Besides, hydrogen can then be used as is (in metallurgy, to reduce metal-oxides instead of burning coke) or transformed into more valuable and transportable fuel (methane, methanol) for mobility purposes.

Good subsurface storage in depleted oil and gas fields could have a capacity of several GWh (1000 T or 33 GWh in Teeside, UK, see Wallace et al 2021: Utility-scale subsurface hydrogen storage: UK perspectives and technology). We might find an equivalent form of underground storage in the Czech Republic.

# Heat

Heat can be stored much more easily than electricity (some m3 water tanks have enough capacity to store several hours of heat for a small municipality). Heat and electricity are often linked to each other (heat can be co-produced with cogeneration units, or heat can be produced from industrial heat pumps). In this section, we consider the consumption of electricity by industrial heat pumps that can be shifted over time since the heat is stored, enabling a kind of electricity storage via demand-side management.

## District heating

	FCR	aFRR	mFRR
Suitability			
	Medium	High	
Power (MW)	200	300	
Capacity (MWh)	400	600	
Efficiency	efficient		
Min pause - cycles	medium		
Max move	medium		
Seasonality	heat demand		

Heat pumps are the perfect technology to replace traditional domestic heat plants burning coal for district heating. With the compatible infrastructure, the boilers are replaced by electric pumps with a COP usually above 3,5, which minimizes electricity consumption.

In the Ember study “Coal-free Czechia 2030”, deploying efficiency measures and gas and biomass CHP and boilers led to a residual of 15 TJ of heat to be addressed by heat pumps. With a COP of 3,5, this means 1,2 TWh of electricity used per year, or an average consumption of 136 MW. Due to the seasonality of the heat production, we may safely assume an installed capacity of 200-300 MW that could provide flexibility to the electrical grid.

# Summary

In Figure 14 we provide a summary table of flexibility potential in the Czech Republic. We also show an indicative column of “continuous” flexibility, which illustrates the limitations of the respective technologies and the required minimum pause (in hours) between cycles. The value is calculated as the flexibility power divided by the minimum pause. Utility batteries, gravitational storage and flying wheels are not taken into account for the algorithm calculation.

As explained in the technology details, hydrogen storage provides a huge capacity, associated with very low efficiency, not suitable for electricity storage. Thus, it can be used only to avoid further RES curtailment and be valued in more direct forms of use. That is why we only show and use the total capacity without hydrogen in the algorithm.

*Figure 14: Summary of flexibility potential*



Category	Medium potential MW	Medium - continuous MW	High potential MW	High - continuous MW	Medium per cycle MWh	High per cycle MWh	FCR	aFRR	mFRR	Algorithm
<b>Industry</b>	<b>526</b>	<b>200</b>	<b>1 703</b>	<b>395</b>	<b>685</b>	<b>2 083</b>				
Non-metallic minerals	85	23	134	36	165	261				1
Automotive	35	6	113	19	35	113				1
Chemicals	33	5	169	28	8	42				1
Rubber and plastic	45	45	163	163	11	41				1
Food	28	7	89	22	28	89				1
Machinery	4	1	40	10	1	10				1
Metals	70	3	266	11	210	798				1
Paper	40	2	126	5	40	126				1
Other	186	109	603	101	186	603				1
<b>Residential</b>	<b>1 318</b>	<b>238</b>	<b>3 402</b>	<b>614</b>	<b>2 495</b>	<b>6 444</b>				
Batteries	140	140	360	360	140	360				1
Boilers	629	52	1 165	97	1 257	2 330				1
Heat pumps	388	32	1 071	89	776	2 141				1
Time of use - other	161	13	806	67	322	1 612				1
<b>EV</b>	<b>340</b>	<b>28</b>	<b>1 849</b>	<b>154</b>	<b>568</b>	<b>3 499</b>				
Charging	219	18	745	62	293	999				1
G2V / V2G	121	10	1 104	92	275	2 500				1
<b>Storage</b>	<b>1 720</b>	<b>1 720</b>	<b>2 700</b>	<b>2 700</b>	<b>38 520</b>	<b>40 465</b>				
Pumped Hydro	1 170	1 170	1 170	1 170	4 495	4 495				1
Utility Batteries	100	100	300	300	200	600				0
Compressed air	290	290	870	870	580	1 740				1
Gravitational	40	40	120	120	40	120				0
Flying Wheel	20	20	40	40	5	10				0
Carnot batteries	50	50	100	100	200	500				1
Hydrogen (Methane/ol)	50	50	100	100	33 000	33 000				1
<b>Heat - large scale</b>	<b>200</b>	<b>100</b>	<b>300</b>	<b>150</b>	<b>400</b>	<b>600</b>				
District heating	200	100	300	150	400	600				1
<b>Total</b>	<b>4 103</b>	<b>2 286</b>	<b>9 954</b>	<b>4 012</b>	<b>42 668</b>	<b>53 090</b>				
<b>Total w/o H and CH</b>	<b>4 053</b>	<b>2 236</b>	<b>9 854</b>	<b>3 912</b>	<b>9 668</b>	<b>20 090</b>				

# 5. Analysis

Using the inputs provided in Section 4, we have analysed the potential for residual load optimization in scenarios with high and medium potential. The results of the analysis should serve as a benchmark for theoretical optimization and the role of various technologies in providing flexibility to the system. We have run the optimization algorithm on a week-by-week basis. The scale was chosen as reasonably low, so that the output of the algorithm shows the true potential (even though in real life situations, such optimization detail might not be necessary) and is in line with the precise possible meteorological predictions.

We ran the algorithm first to reduce the maximum generation shortfall and second to utilize the excessive load from RES, which would otherwise need to be curtailed.

## Generation shortfall

Figure 15 and Figure 16 we show the input shortfall (as presented in Section 2) and profile which have been optimized using specified flexibility potentials. The medium potential shows a significant reduction in local shortfall peaks, however there is still a significant surplus from RES (though the peaks were reduced). The extreme values of the shortfall profile are significantly reduced in the high-potential scenario (both for shortfall and surplus).

Figure 15: Base year 2019 – shortfall reduction – medium potential

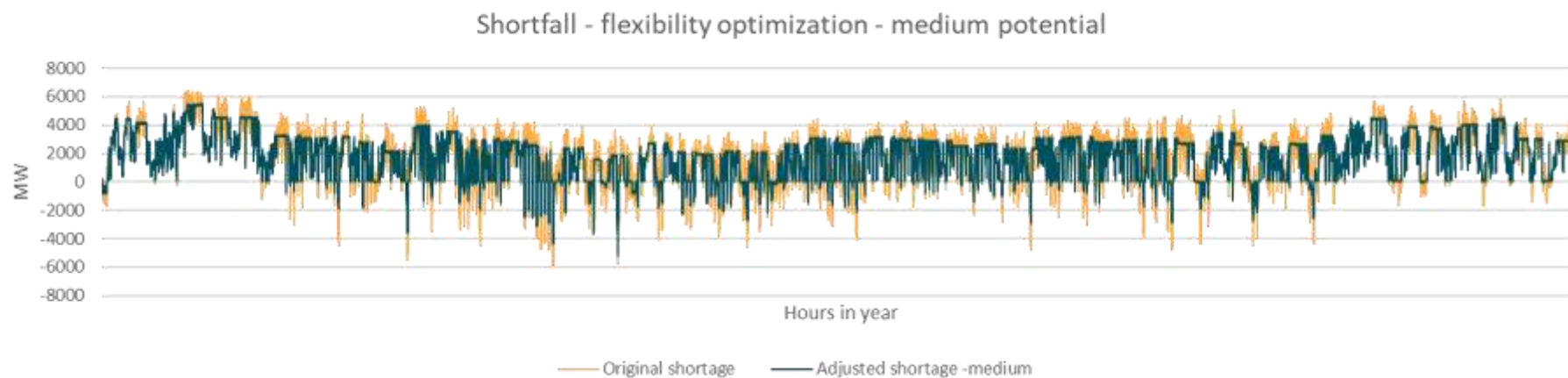
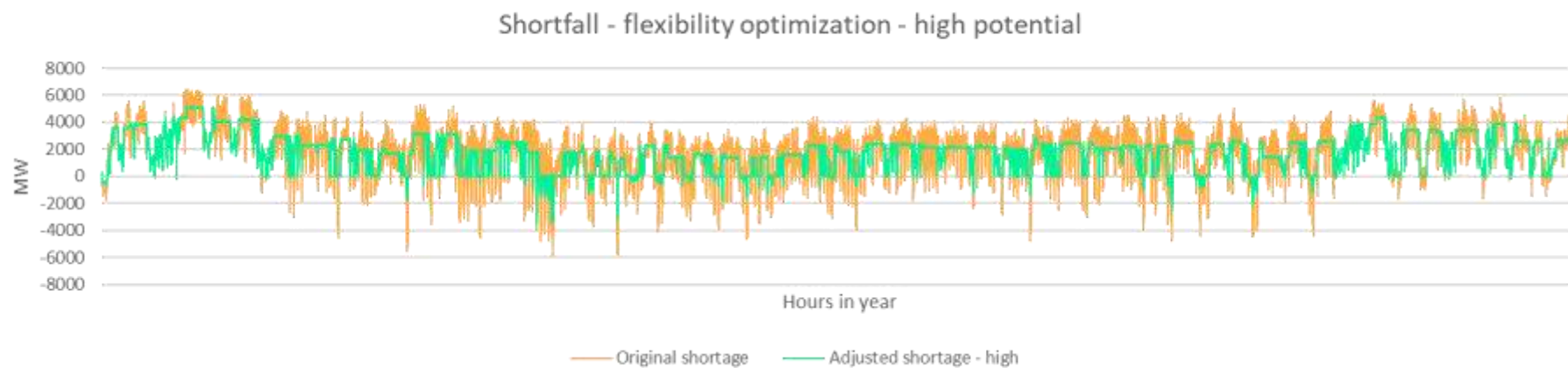
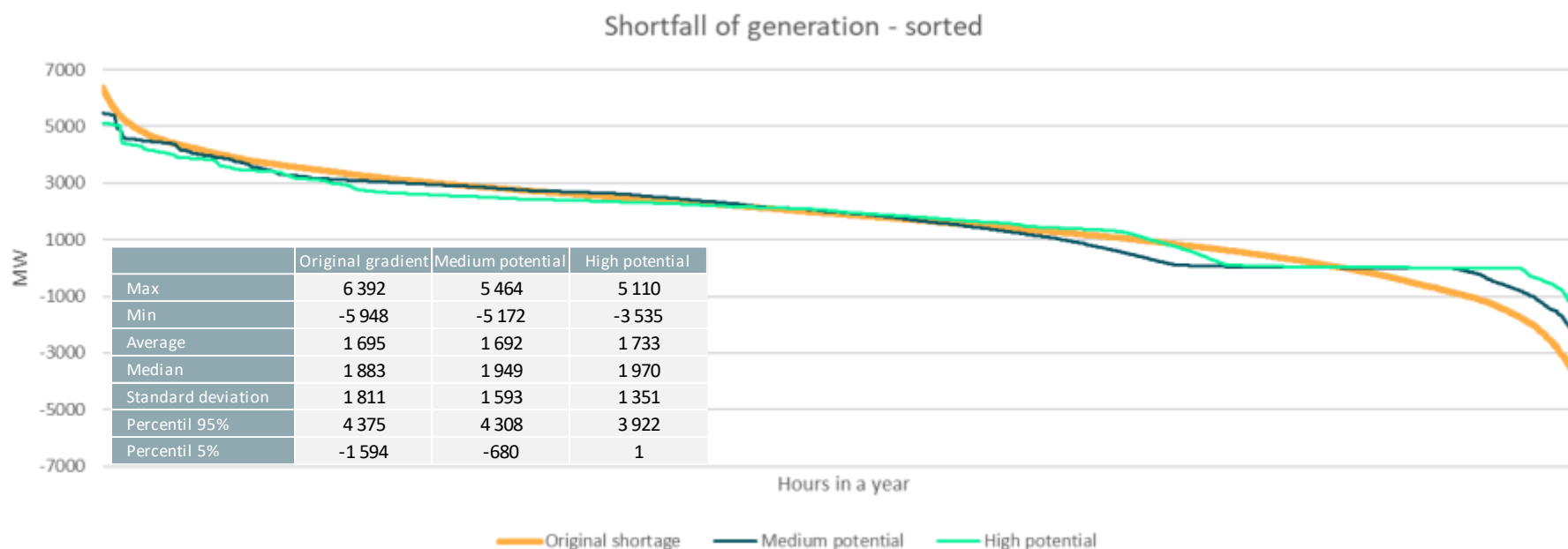


Figure 16: Base year 2019 – shortfall reduction – high potential



In Figure 17 we show the shortfall in a sorted manner. The resulting curve shows the frequency of the shortfall/surplus for original inputs and medium and high potential. Both curves are below the original curve in extreme shortfall cases. The medium scenario reduces the maximum shortfall by almost 1 GW, from roughly 6,4 GW to 5,5GW, while the high potential reduces the maximum shortfall by approx. 1,3 GW. The average values are higher for both scenarios as some of the flexibility operates with less than 100% efficiency. Due to the specific limitations of the flexibility shifts, the curve is rougher but flatter (i.e. there are more shortfall hours in the middle). The minimum value (i.e., surplus) is reduced by around 0,8 GW in the medium scenario. The high scenario provides a significantly higher effect of around 2,4GW.

Figure 17: Sorted shortfall of projected generation (original, medium, high)

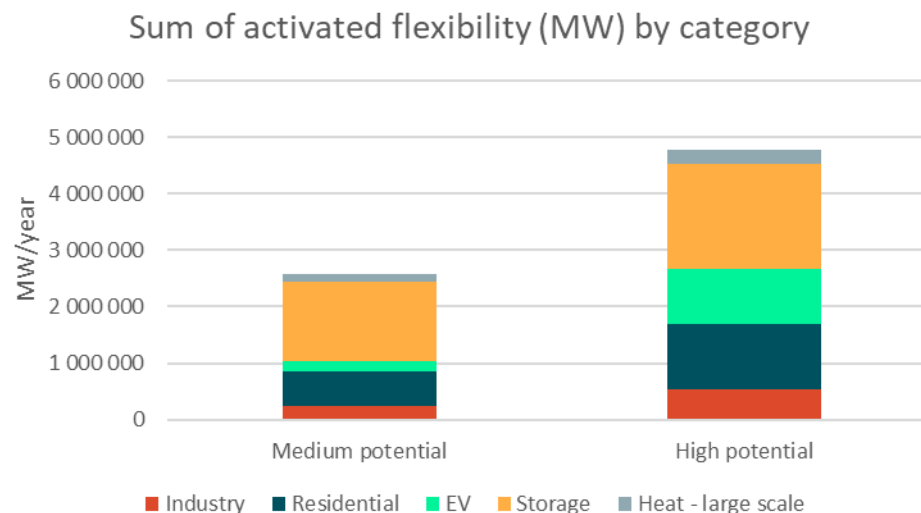


# Activated flexibility

Further, we analyse the composition of activated flexibility and its volume i.e., the power of activated flexibility multiplied by the number of activations (see Figure 18).

The highest proportion of activated flexibility is provided by storage systems (as the capacity is quite high and these do not suffer from significant technical limitations). In the medium scenario this amounts to 1 398GW while in the high scenario it stands at 1 854GW. The second largest proportion is provided by the residential sector, 618 GW in the medium scenario and 1 163 MW in the high scenario. Industry provides around 232 GW and 524 GW, respectively. There is a significant difference in EV flexibility estimations ranging from 195 GW to 986 GW (due to the high range of underlying assumptions). The large-scale heat sector provides between 139 GW and 247 GW. The results suggest that in the medium scenario, slightly less than 50% of the energy flexibility could be provided by demand side response (technologies other than storage), while in the high scenario, the percentage increases to more than 60%.

Figure 18: Sum of activated capacity per year per category



# Moved capacity

The sum of activation does not provide a full picture of the structure of the flexibility used, as it does not differentiate between short and long flexibility shifts. Below in Figure 19 and Figure 20 we show the overall capacity which is utilized by different flexibility categories within the year for the medium- and high-potential scenarios. The figures should illustrate the frequency and scale of the flexible capacity utilization by different categories. In the medium scenario, the maximum capacity values amount to around 6 GWh, while in the high scenario this number more than doubles to almost 15 GWh.

Figure 19: Capacity moved by category – medium potential

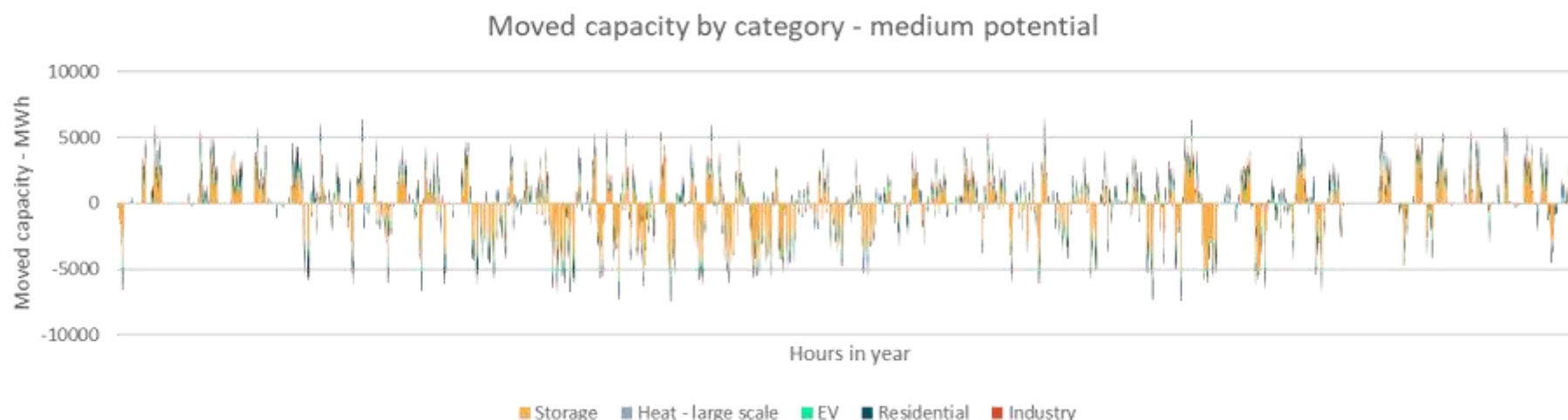
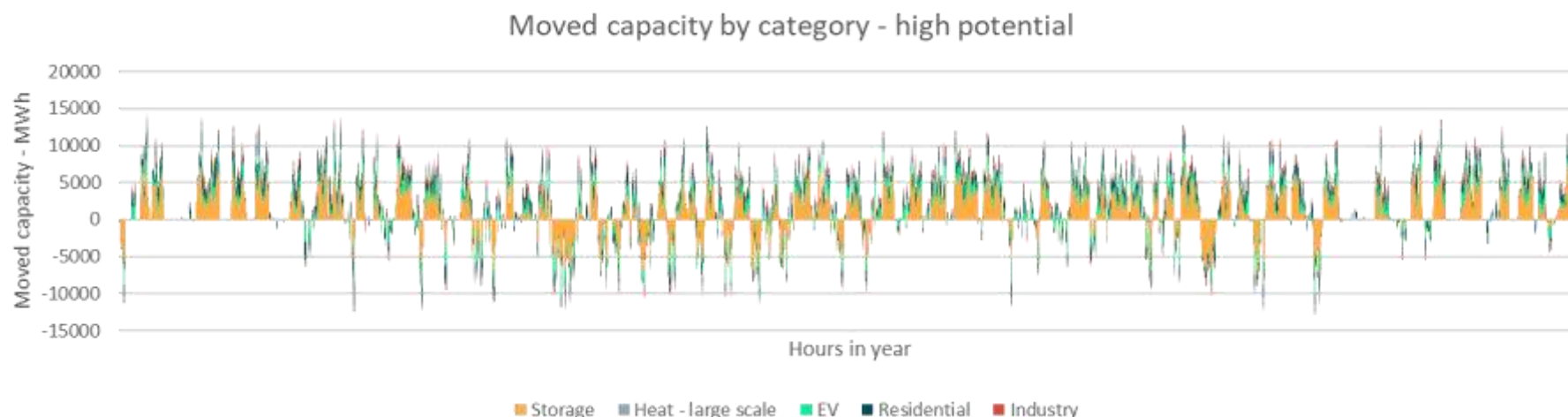


Figure 20: Capacity moved by category – high potential

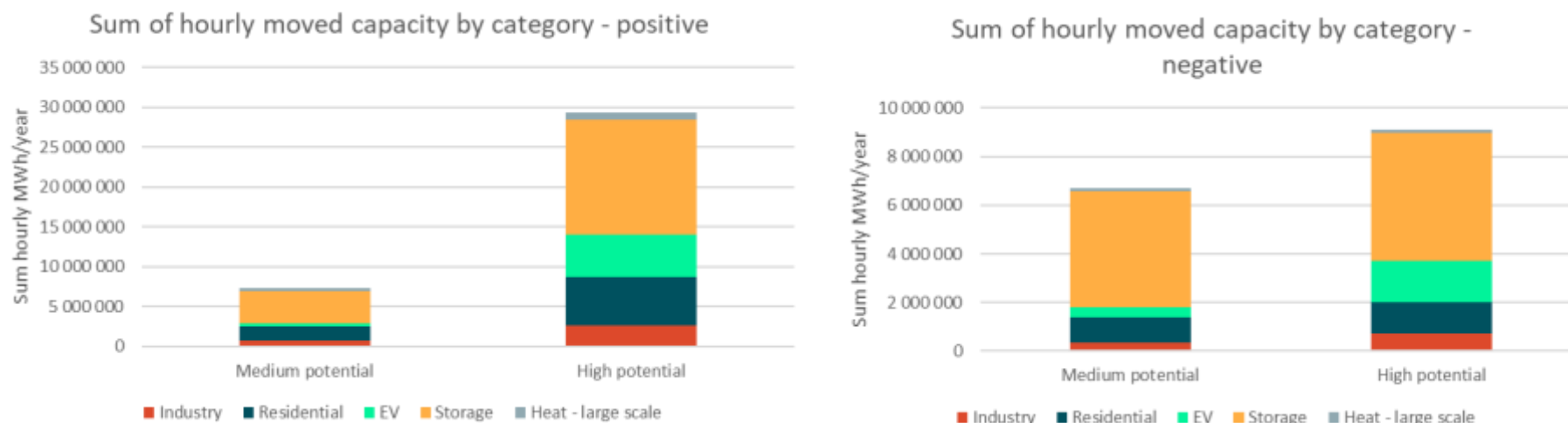


Similar to Figure 18, we also show the respective yearly sums. Here, the number does take into account the duration of flexibility activation (i.e., it is calculated as a sum of the power activated in MW by number of hours between activation and deactivation). We also provide these numbers specifically for surplus hours, marked as negative (i.e., the utilization of the excess load from RES).

Naturally, values of storage systems increase more (as the maximum possible shifts are longer). Nevertheless, the proportion of demand-side response technologies are still very significant. In the medium scenario, storage systems provide around 55% of the overall capacity while in the high scenario, the figure is around 50%. We also provide a figure for negative utilization, i.e., the utilization of surplus RES electricity.



Figure 21: Sum of hourly moved capacity



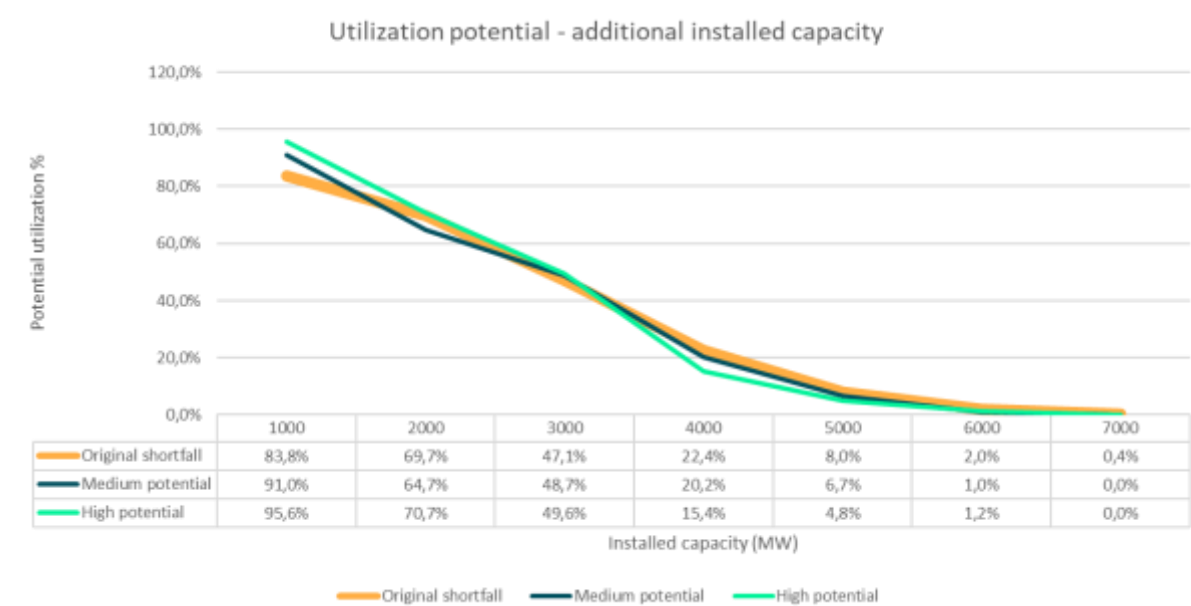
## Utilization potential - fossil generation requirements

Further, we show the utilization potential of additional installed capacity. We illustrate that flexibility can lead to a reduction of the maximum required capacity and the frequency of occurrence of extreme events. In the input scenario above, 6 GW of capacity would be used only 0,4% of the time. Both scenarios reduce such events to zero while also significantly reducing the utilization of 6 GW capacity from 2% to around 1%. Both scenarios also show a slightly higher utilization of the first and second GW of installed capacity (due to a combination of imperfect storage efficiency, the load shift from a higher to lower load profile and the reduced load to utilize excess RES production). Respective data are provided in Figure 22. The table below also shows utilization in terms of MWh of each additional unit, the total required MWh and maximum load.

In the model, we assume no exchange between the Czech Republic and its neighbours, since we don't have the capability to model other surrounding grids and generation units, as the Ember study did. It is then the responsibility of decision makers to choose

between building of the 5th GW capacity (being 100% resilient on the CZ scale) or speculating on a European portfolio effect capable of furnishing 1 GW 1% of the time (which indeed is not a big risk, but if not possible, demand curtailment remains the last option). The same consideration may be applied for the 4th GW capacity, 3rd one etc., with growing utilization factors.

Figure 22: Utilization potential of additional installed capacity

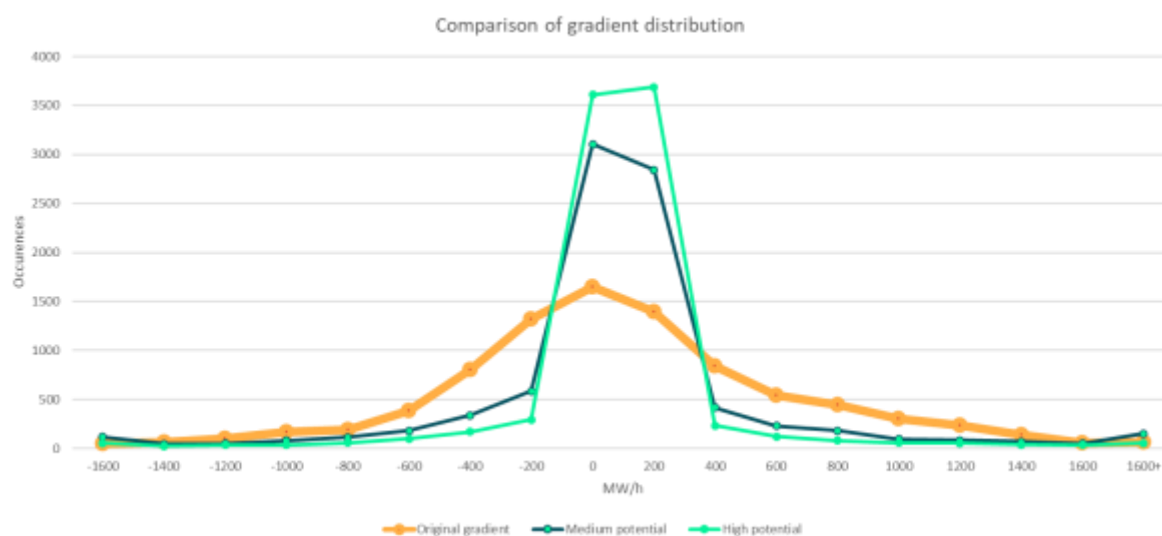


	< 1000	< 2000	< 3000	< 4000	< 5000	< 6000	< 7000	Total (MWh)	Max load (MW)
Original shortfall	7 338	6 105	4 129	1 964	701	179	32	20 448	6 392
Medium potential	7 496	6 096	4 439	1 789	587	84	0	20 491	5 464
High potential	8 054	6 505	4 391	1 349	421	103	0	20 823	5 110

# Gradient distribution

Last, we have analysed the change in gradient distribution, i.e., the rate of load change between respective hours. The distribution is presented in Figure 23. The figure illustrates how flexibility can in principle reduce the gradient distribution, increasing the occurrence of small changes (which are desirable within the system) and reduce larger gradient occurrences. In both scenarios, there is a significant increase of occurrences of  $\pm 200\text{MW}$ , while more higher gradient changes are significantly reduced.

Figure 23: Gradient distribution of the generation shortfall



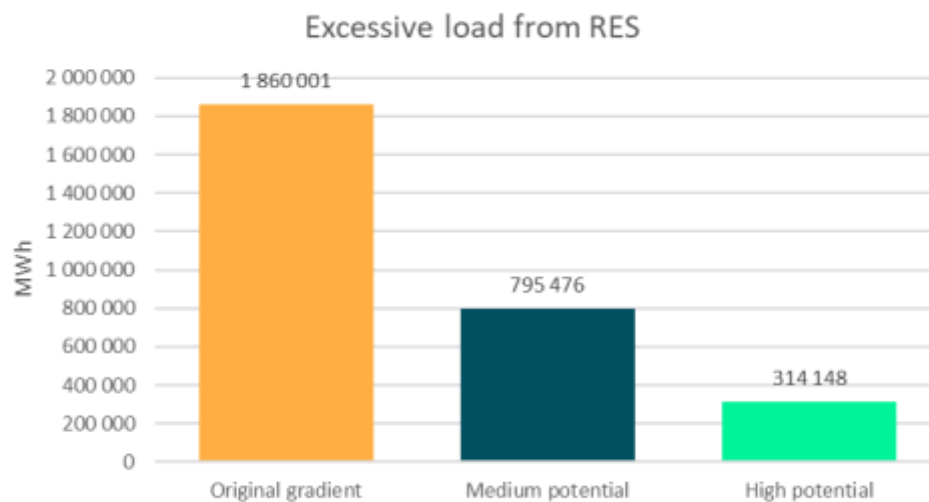
Concerning short-term gradients, the phase 1 study concluded that 8 GW of flexibility (in a conservative approach) would be necessary to accommodate short-term gradients from growing intermittent electricity production, of which 4 GW should concern the grid regulation (FCR and aFRR), which is not the subject of the above algorithm.

At least 3,2 GW of FCR/aFRR flexibility is gathered in the medium scenario (and even more than 4 GW in the high scenario). Thus, with approx. 4,8 GW (lower than the requirement for security supply) of additional flexible power, the gradient problem is solved.

# Flexibility and RES curtailment

When broadly deployed, RES may produce so much electricity that it cannot be used by consumers. At some point, it is even necessary to curtail RES production. The more storage and flexibility capacity, the less electricity needs to be curtailed, as shown in Figure 24. An additional 1-1,5 TWh of RES production is integrated to the grid. The stored electricity then reduces the need for extra generation, potentially saving fossil gas. Though a large amount of energy can be saved (and not wasted by curtailment) thanks to storage (more than 1,5 TWh in the high-potential scenario), the remaining RES surplus is highly seasonal and may be addressed by seasonal storage such as hydrogen/methane. Big electrolyzers might absorb the surplus of electricity from RES, but the question might be economical: how to amortize an installation that would run only some % of the time? This question must be answered at a high level and is not resolved here. Excessive production (less than 1% of the expected 70 TWh of consumption) must be here curtailed

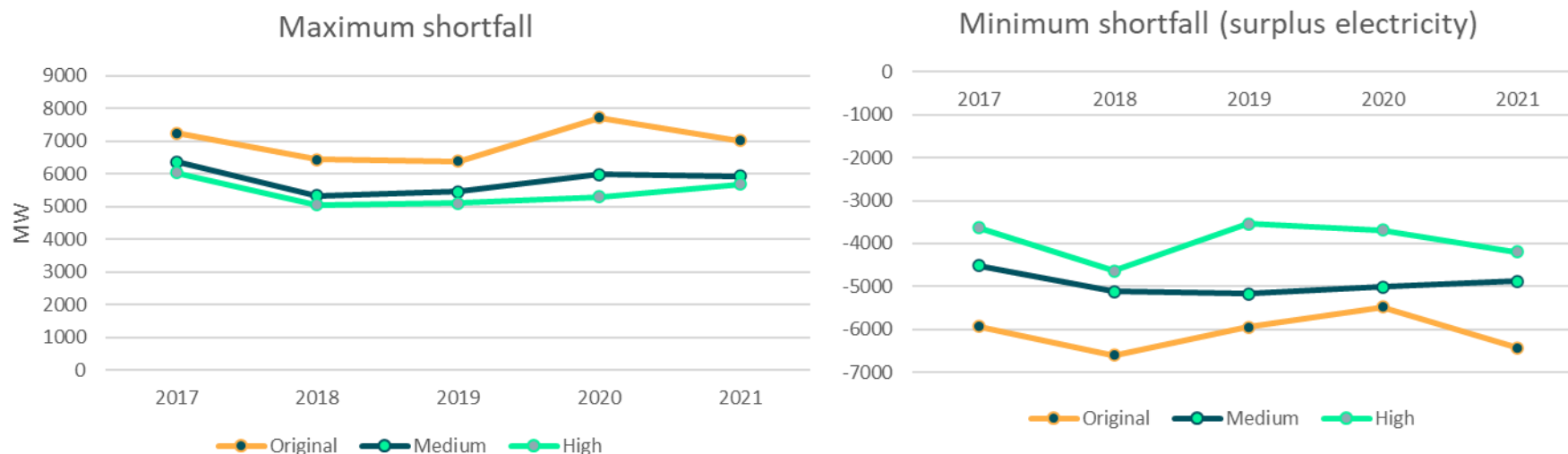
Figure 24: Excessive load from RES/curtailment



# Sensitivities

The analysis presented here was based on extrapolated data from 2019. For sensitivity purposes, we have also analysed the years 2017, 2018, 2020 and 2021. In Figure 25 we show the maximum and minimum shortfalls in the respective years for all analysed scenarios in a graph. Further, we also show the relevant statistical information in a table. The analysis shows that there are relatively high differences between the analysed years, reaching up to 1 GW in extreme cases. Nevertheless, the general trends and possible effects of analysed potentials hold in all cases.

Figure 25: Maximum and minimum shortfall in years 2017 - 2021



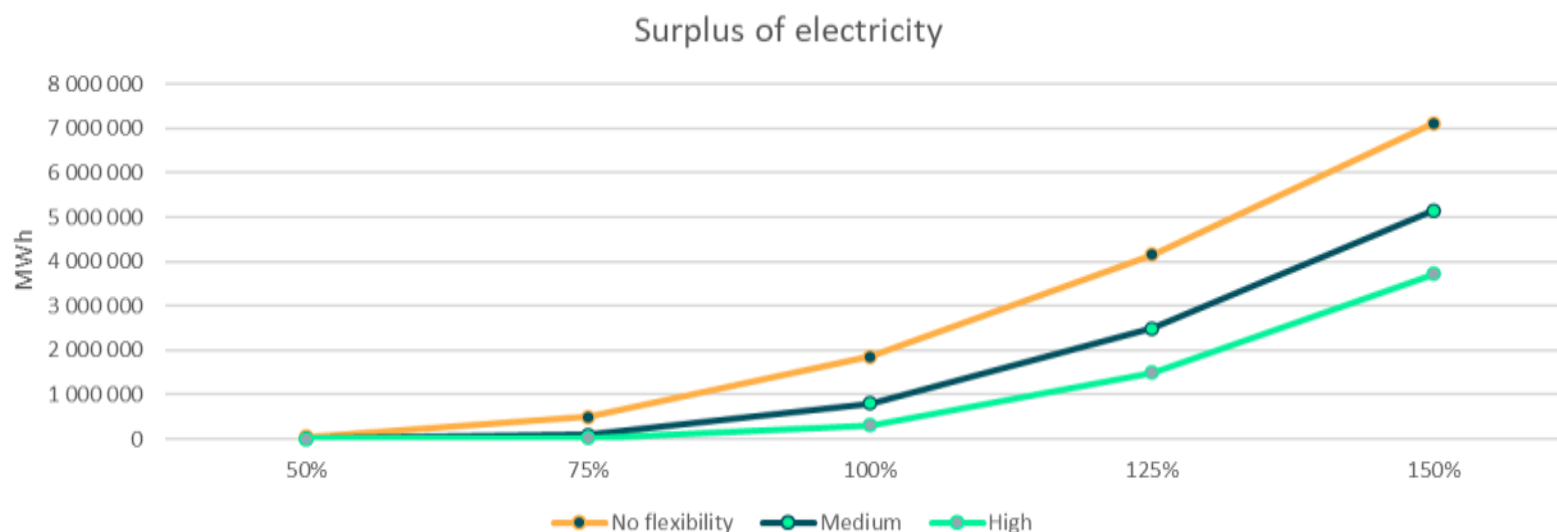
ORIGINAL (MW)	2017	2018	2019	2020	2021
Max	7 244	6 437	6 392	7 727	7 012
Min	-5 928	-6 594	-5 948	-5 476	-6 433
Average	1 910	1 721	1 695	1 651	1 815
Median	2 118	1 857	1 883	1 811	2 005
Standard deviation	2 010	2 030	1 811	2 051	2 077
Percentil 95%	4 955	4 871	4 375	4 889	5 002
Percentil 5%	-1 903	-1 980	-1 594	-2 274	-2 081

MEDIUM (MW)	2017	2018	2019	2020	2021
Max	6 373	5 334	5 464	5 988	5 926
Min	-4 519	-5 111	-5 172	-5 004	-4 876
Average	1 908	1 718	1 692	1 647	1 809
Median	2 233	1 876	1 949	1 728	2 053
Standard deviation	1 802	1 830	1 593	1 837	1 880
Percentil 5%	-838	-964	-680	-1 226	-1 161

HIGH (MW)	2017	2018	2019	2020	2021
Max	6 030	5 047	5 110	5 299	5 679
Min	-3 631	-4 630	-3 535	-3 685	-4 192
Average	1 934	1 761	1 733	1 673	1 835
Median	2 031	1 684	1 970	1 502	1 924
Standard deviation	1 580	1 625	1 351	1 643	1 705
Percentil 95%	4 679	4 379	3 922	4 584	4 705
Percentil 5%	1	-291	1	-265	-385

Further, we have analysed various sensitivities on RES penetration. In Figure 26 we show the surplus electricity based on the percentage of RES penetration envisioned by the EMBER study and the respective possible role of flexibility in utilization of surplus electricity. The sensitivity shows that the low penetration level does not result in a high surplus of electricity. As the RES deployment increases, the role of flexibility becomes more significant. In the extreme scenarios however, flexibility cannot provide sufficient capacity to include significant proportions of the surplus electricity as in the scenario examined.

Figure 26: Sensitivity on surplus of electricity in various RES penetration scenarios





## 6. Conclusion

The intent of this study is to give a vision of a Czech Republic free of coal power plants. This is a noble goal for different reasons: the high air pollution generated by burning coal, the high CO<sub>2</sub> emissions impacting the global climate, as well as the depletion of domestic resources. However, the potential deployment of new technologies (especially PV, wind turbines, batteries etc.) enabling this phase-out comes with lower but existing environmental or geopolitical impacts. These impacts are however not covered by the present study. At the scale of the Czech Republic, these potential impacts are certainly negligible. But were these technologies deployed globally, they would certainly come with new risks, environmental impacts, geological limitations, and geopolitical dependencies that would be important to assess as well.

Yet the main achieved objectives are:

- **Flexibility decreases the need for traditional dispatchable sources:** Using this flexibility can decrease the need for dispatchable power capacities from 0,9 to 1,3 GW.
- **Flexibility enables RES integration into the grid:** Using this flexibility enables the full accommodation of short-term gradients from RES production that would otherwise limit RES penetration below the desired level.
- **Flexibility enables higher utilization of renewable energy**
  - o An additional 1 000-1 500 GWh of RES production is integrated to the grid which would otherwise need to be curtailed or exported (from a total RES production of cca 20 000 GWh).
  - o The amount of surplus electricity decreases by 2-5 times from the 9% cited in the reference scenario.

# Enabling drivers

Our study is based on the realistic potential of various technologies in the year 2030. These differ in terms of operational model and their limitations. It is important to note that several assumptions are imperative for the realization of the potential of various technologies, mainly with respect to the regulatory framework, technological implementation, and market drivers. Below, we provide an overview of the enabling drivers.

## Regulatory

*Base-line definition*; a prediction of the consumption that would occur if the flexibility was not used for ancillary services. It is used to evaluate the flexibly managed state versus the business-as-usual state.

*Independent aggregator*: enables higher competition and faster development (currently, in the case of flexible management, it is necessary that the aggregator simultaneously supplies electricity to the take-off points).

*Technology subsidies*: such as for electric cars or heat pumps are necessary for the sufficient development of the analysed technologies and assumptions of the model.

*Data privacy*: framework need to be clearly established to allow safe participation.

## Technological

*Smart-meters*: widespread rollout of smart-metering technology is required and essential for demand side response.

*Technology implementation*: existing solutions need to be widely deployed, such as: batteries, retrofit of boilers, heat pumps, EVs , V2G/G2V technology, storage pilot projects, large scale heat pumps.

## Market

*Incentives:* for flexibility activation need to be high enough to promote interest in managing consumption. A combination of support for ancillary services and other market opportunities may or may not support the natural development of flexibility.

*Aggregation:* small decentralized sources of various technology providers need to be aggregated into large blocks to substantiate the business case. Aggregating of small entities (where the value is not substantial) is costly and may not be justified by the associated revenues (although the value for the system may be significant).

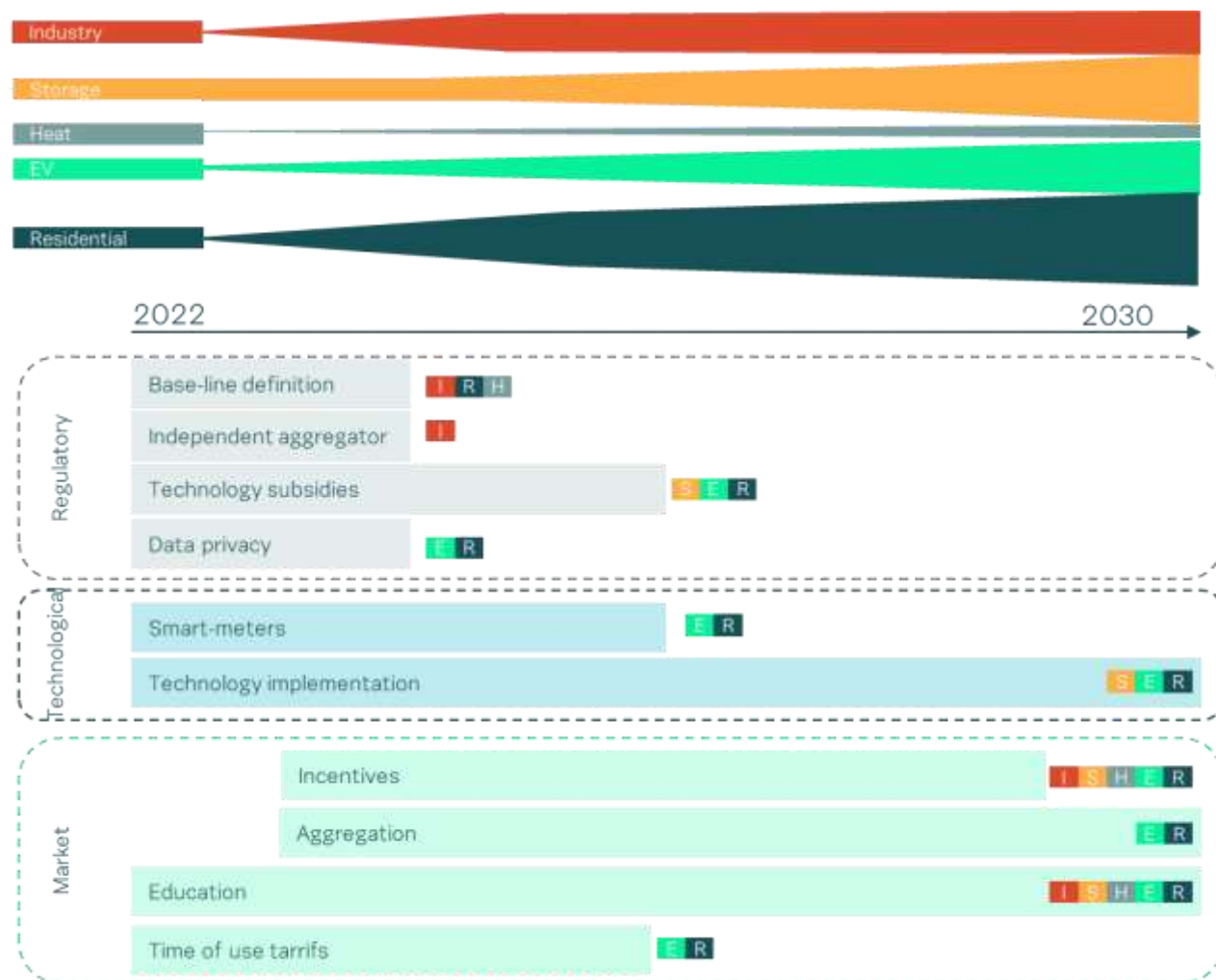
*Education:* market participants need to be educated to increase the adoption rate.

*Time of use tariffs:* i.e., tariffs derived from the current price of electricity, motivate entities to respond to price signals from the market (consume electricity when it is cheap and vice versa). Time of use tariff need to be introduced to allow and incentivize residential and EV flexibility.

We also show an estimated timeline for the possible utilization of various technologies for flexibility. The Industrial sector can provide reasonable DSR in a short period of time, given a sufficient regulatory framework and incentives. The residential and EV sectors require some technological development as well as large-scale deployment of various appliances. On a smaller scale, these technologies can be utilized in a short period of time, while a larger scale can be expected in the medium term. Storage (besides existing pumped hydro) requires significant investment into pilot projects, and we therefore see its utilization mainly in the long-term horizon.

We provide a summary overview in Figure 27.

Figure 27: Timeline of possible implementation of flexibility categories and main enabling drivers



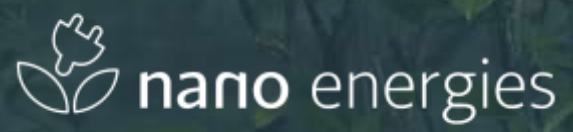
# Limitations of the model

There are several limitations to the model which one should keep in mind when interpreting the results. First, since we are optimizing past load profiles, we implicitly assume full knowledge of the shortfall distribution. It must be noted that one does not have full knowledge when predicting the status and requirements of the electricity network in advance. Predictability is naturally better for short periods of time in advance and decreases with longer periods. We thus analyse rather the potential than actual achievable profiles. However, we believe that such analysis can nevertheless help to understand the possible potential both within the system as well as for specific technologies and their contributions.

Further, we are basing our analysis on specific conditions of specific years (though we include other years in a sensitivity analysis). One can argue that load distributions may change in the future.

We would also like to emphasize that we extrapolate the PV and wind production based on the year 2019 (and 2017–2021, respectively, in the sensitivity scenarios). Though this approach may provide a reasonable picture of the projected scenario, we implicitly assume that the spatial distribution of wind farms and PV power plants will not change significantly. Mainly with respect to wind production, more diverse farm distribution should lead to electricity production that would be less concentrated in similar time periods. This means that by using only past production for the extrapolation, we arguably show a slightly worse case than that could be achieved should the distribution be more diverse.

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