CZECH POWER GRID WITHOUT ELECTRICITY FROM COAL BY 2030: POSSIBILITIES FOR INTEGRATION OF RENEWABLE RESOURCES AND TRANSITION INTO A SYSTEM BASED ON DECENTRALIZED SOURCES

Final Report

May 22, 2018
Author: Peter-Philipp Schierhorn, M.Sc.
Project team: Peter-Philipp Schierhorn, M.Sc., Sabrina Hempel, M.Sc., Dr. Thomas Ackermann

GLOPOLIS
FRANK BOLD
CEE BANKWATCH NETWORK
ALIANCE PRO ENERGETICKOU SOBĚSTAČNOST
HNUTÍ DUHA

energynautics
solutions for sustainable development

FOREWORD

Renewable Energy Sources: Let There Be Light!

“Fiat lux” is not a new model of car, but a Latin phrase meaning “let there be light”. Perhaps the best known quote from the Bible can be found at the very beginning of Chapter 1: “Now the earth was formless and empty, darkness was over the surface of the deep, and the Spirit of God was hovering over the waters. And God said, “Let there be light,” and there was light. God saw that the light was good, and he separated the light from the darkness.” (Genesis, Chapter 1, NIV)

This quote originally referred to the creation of the whole world, but it can also be used to describe the introduction of renewable energy into the power grid. In this case too, we have to shed more light on the issue and separate the light from the darkness or the facts from the myths.

There is ongoing debate over whether power grids with a higher share of renewable energy can function properly and deliver the service required. Sometimes it seems the consensus is that they can work everywhere except the Czech Republic. Czechs are indeed very good at finding reasons why things are not possible. We can identify many obstacles: Frequency stability, overvoltage, line wires thermal limits, jumps and drops, harmonics and distortion, disruption of phase voltage symmetry, short circuit behavior, reaction to changes in frequency, impact on centralized ripple control system, voltage fluctuation (flicker) etc.

When it comes to finding solutions to the problems, however, we are somewhat lagging behind. The results of Energynautics’ modelling of the impact on the Czech power grid of phasing out coal by 2030 are therefore essential, as they shed light on previously dark territory.

So, thanks for “the light at the end of the tunnel”, and thanks for all “the good” light that “separates the light from the darkness.”

Jiří Beranovský
Senior Analyst, Partner & Executive
EkoWATT CZ s. r. o.

CONTENTS

1. INTRODUCTION

Introduction

Just a glance into international energy statistics reveals a clear trend of past years: electricity production from renewable energy sources is rapidly growing in all major economies across Asia, the Americas and Europe. Installed capacity of renewables has in some countries grown so significantly that they can now cover a substantial part of all electricity needs. In 2017 renewable electricity already made up 30 % of EU electricity production, a doubling from 15 % in 2007. Nearly all of this growth has come from wind, solar and biomass, which made up a very low share of production a decade ago, whereas hydro - the more established source of renewable electricity – remained stable.

This trend also has implications for the management of the power grid. The conventional logic of the power system featured 'baseload' power sources covering most of the basic electricity demand and additional sources adjusting their production to cover variable electricity demand throughout the day. The new logic of power systems with high shares of wind and solar energy production features variable electricity supply by wind and solar, accompanied by flexible power plants, demand side management and energy storage.

The Czech Republic is lagging behind this trend so far. In a time of rapid transformation in many electricity markets in Europe, Czech decision makers both in governmental bodies and key energy companies continue to hinder the energy transition while highlighting the security of electricity supply as a main obstacle. However, policy assessments also provide absolute clarity on the need to decarbonize the power sector in the Czech Republic in order to address climate change. In other words, despite the Czech Republic's long history of electricity production from coal, at some point all coal power plants have to be shut down (only a small part of CHP with a preference towards heat production should be considered operational in 2030). There is simply no way to comply with the Paris Agreement on climate change while continuing to operate coal power plants such as Počerady, Prunéřov or Chvaletice. These efforts to phase out coal should, however, not be seen as a utopic vision for a distant future. About ten European countries including the UK, Italy or France have already put forward concrete plans to stop production of electricity in their coal power plants within several years or a decade. The Czech Republic is simply not among them yet.

One challenge on the road to making this possible will be to gain the support of Czech grid operators. While it should come as no surprise that a coal phase out is generally not favoured by the owners of the plants, the grid operators join them vocally with their concerns. This caution is understandable as the power system in the Czech Republic has seen only gradual change in past decades and provides a reliable service to customers with few exceptions, for example in cases of extreme weather events. The idea of retiring power plants that have served as the foundation of the conventional power system is viewed with skepticism by grid operators that are managing a complex technical system and are not yet familiar with this new operating paradigm. It is seen as even less attractive that this foundation may be largely replaced by energy sources that can no longer be fully controlled by the grid operator, but rather produce electricity according to prevailing weather conditions.

On the other hand, there is no doubt as to the potential of the new grid management techniques enabled by advanced IT infrastructure and smart regulation. Experiences from countries with high shares of renewable energy sources demonstrate that security of supply does not have to be compromised by the uptake of significant power production from wind or solar power plants. In fact, renewable energy giants like Germany or Denmark also score best regarding average length of power shortages affecting their customers.

Nonetheless, as the management of the grid is always system specific, the question of how to maintain the stability of the power grid in the Czech Republic if all coal plants are replaced by variable renewable electricity sources remains open. Will electricity production fall short on cloudy winter days with no wind? What will happen to the system on sunny summer days with a large supply of solar electricity but limited demand? Providing a full answer to these questions is of key importance in developing support for the energy transition in the Czech Republic from all relevant stakeholders.

The stability and security of power grids has been at the heart of Energynautics' work for many years. The company has developed software that enables modelling a simulation of the power grid operation. The results of the modelling are promising: a closure of coal power plants by 2030 and utilization of the potential of renewable energy would not put the Czech power grid (as part of the European network) at risk. Moreover, the Czech Republic would remain a net exporter of electricity although with reduced amounts. The supply of electricity to end users would be secured even in such an exceptional case as the unplanned shut down of a block of the nuclear power plant Temelín, the biggest source in the power system.

The Czech Republic is neither pioneering in the integration of the renewable energy sources nor in shutting down its coal fleet. The share of renewable sources in electricity production remains below the European average, while the share of coal is significantly above the European average. In fact, at times Denmark already supplies more than 100% of its electricity demand from wind power for entire days, and the United Kingdom – the cradle of the industrial revolution – has already gone several days in the last year with no coal production and plans to close all coal power plants by 2025. There is nothing to prevent the country from a gradual replacement of the existing coal capacities with cleaner alternatives. The simulation presented in this study reaffirms this point, by confirming that grid stability is not a barrier to the decarbonization of the power system in the Czech Republic.

2. SCENARIO AND METHODOLOGY

2.1 SCENARIO

2.1.1 Installed Capacities

The basic scenario investigated in this study for the year 2030 was based on data provided by the Czech Renewable Energy Association. The main characteristics of the scenario are the decommissioning of most of the coal fired power plants, which are replaced with increased renewable capacities:

- 6185 MW of lignite and 800 MW of hard coal fired generation are decommissioned;[1]
- 1825 MW of lignite and 696 MW of hard coal fired CHP (including industrial captive power plants) remain operational.

Moreover, nuclear power plants remain online, gas fired capacities are increased by both new large CCGT installations as well as small gas fired CHP (see Table 1).

Table 1: Installed conventional and hydro capacities.

Fuel and technology	Installed 2017	Installed 2030	Comment
Nuclear, VVER-440/213	2040 MW	2040 MW	Old Soviet baseload units
Nuclear, VVER-1000/320	2250 MW	2250 MW	Potential for some flexibility
Lignite	8707 MW	1825 MW	CHP with preferred heat remain
Hard coal	1496 MW	696 MW	CHP with preferred heat remain
Natural gas CCGT	1043 MW	1646 MW	Includes some CHP
Natural gas OCGT	170 MW	170 MW	Peak / backup plants
Natural gas small CHP	220 MW	980 MW	Dispatched by heat demand
Hydro	1090 MW	1142 MW	Both run-of-river and reservoir
Pumped storage	1130 MW	1175 MW	

---

[1] List of decommissioned units can be found in the annex.

Renewable capacities are expanded and distributed to the regions as given in Table 2.

Table 2: Installed renewable capacities in MW per region.

Region	PV	Wind	Geothermal	Biomass	Biogas
Ústecký	361	170	25	135	30
Vysočina	460	486	0	72	52
Karlovarský	218	116	0	27	9
Královéhradecký	324	28	0	54	31
Moravskoslezský	366	225	0	36	28
Středočeský	864	158	0	72	89
Olomoucký	355	130	0	99	34
Pardubický	313	134	0	63	32
Plzeňský	537	82	0	54	41
Praha	34	0	0	0	2
Liberecký	215	45	25	45	10
Jihočeský	687	149	0	81	50
Jihomoravský	502	291	0	117	57
Zlínský	265	35	0	54	20
Total	5500	2050	50	900	485
Installed 2017	2100	278	0	426	332

2.1.2 Grid Status

It is assumed that the reinforcements currently projected by CEPS will be implemented by 2030.[2] These include most notably the following EU Projects of Common Interest[3]:

- PCI 3.11.1: New double circuit 400 kV line between Vernéřov and Vítkov;
- PCI 3.11.2: New double circuit 400 kV line between Vítkov and Přeštice;
- PCI 3.11.3: Additional 400 kV circuit on existing line between Přeštice and Kočín;
- PCI 3.11.3: New double circuit 400 kV line between Kočín and Mírovka;
- PCI 3.11.3: Additional 400 kV circuit on existing line between Mírovka and Čebín;

The phase shifting transformers recently installed in Hradec substation remain in operation and govern the flows on the DE-CZ interconnector to reflect the actual trade volumes.

For the rest of Europe, it is assumed that the long term projects specified in the Ten Year Network Development Plan (TYNDP) 2016 published by ENTSO-E are built and commis-

---

[2] http://www.ceps.cz/en/transmission-system-development

[3] http://www.ceps.cz/en/pci-projects-of-common-interest

sioned by 2030.[4] For the sake of sensitivity analysis, a more pessimistic scenario is also analyzed in which the German HVDC corridors linking northern wind generation and southern load centers are assumed to be delayed until after 2030.

2.1.3 Operational Regimes

Considering the operational regimes of the dispatchable power plants, the following assumptions are taken:

- Biomass and biogas power plants are dispatched according to a heat demand curve (see Figure 1), but can provide some flexibility if necessary.
- Small gas fired CHP are under a must run constraint for the winter months, but may be dispatched for electricity only in summer.
- Most of the remaining coal units, ca. 1250 MW of (old) lignite and 410 MW of hard coal are operated as CHP but may be operated for electricity production without heat demand (with less efficiency).
- Three out of four blocks at Dukovany are always operating, resulting in a utilization rate of 75% for the entire plant.
- The two blocks at Temelin have planned downtime for maintenance during low demand periods in summer (individually, never both at the same time), resulting in a utilization of 80%.
- Nuclear units run at full power, but the two more modern blocks at Temelín can reduce their output by 60 MW each if absolutely necessary.

---

[4] http://tyndp.entsoe.eu/

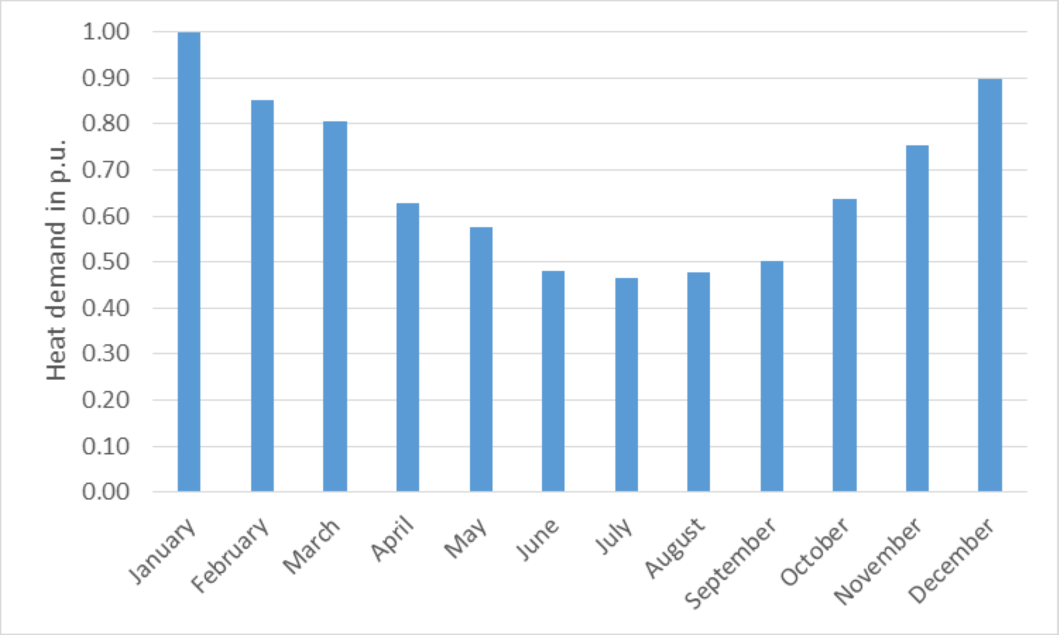


Figure 1: Per unitized heat demand per month. [1]

2.1.4 Neighboring Countries

Renewable energy development in neighboring countries can have a significant impact on cross border transactions with the Czech system. The following scenarios were assumed for the neighbors:

- Germany: NEP 2017 scenario B for 2025 onwards with high wind and solar capacities and a partial coal and full nuclear exit [2];
- Austria: Stromzukunft Österreich 2030 scenario with additional wind and solar capacities on top of the current hydro/gas fleet [3];
- Poland: Reduced coal capacities with high wind capacities according to Forum Energii 2030 scenario [4];
- Slovakia: Business as usual with the 2017 generator fleet continuing operation and slight increase in wind and solar capacity.

All other European countries were modelled with the installed capacities from Greenpeace’s Energy Revolution reference scenario [5].

Table 3: Variable renewable capacities in neighboring countries.

	PV installed	Wind installed
Germany	55 GW	63.8 GW onshore, 10.5 GW offshore
Austria	12 GW	7 GW onshore
Poland	2 GW	9 GW onshore, 1 GW offshore
Slovakia	1 GW	1 GW onshore

2.2 MODELS AND SIMULATIONS

2.2.1 Grid Model

The European Grid Model is an aggregated model of the ENTSO-E transmission grid (see Figure 2), representing major load and generation centers in Europe as 200 nodes, connected by more than 400 large transmission corridors. The model was developed during studies of the entire European system, with the Czech system within the model highly aggregated. As the focus on this study is on the Czech transmission grid (see Figure 3), a more detailed model had to be developed and integrated into the framework.

Figure 2: Energynautics' aggregated European Grid Model.

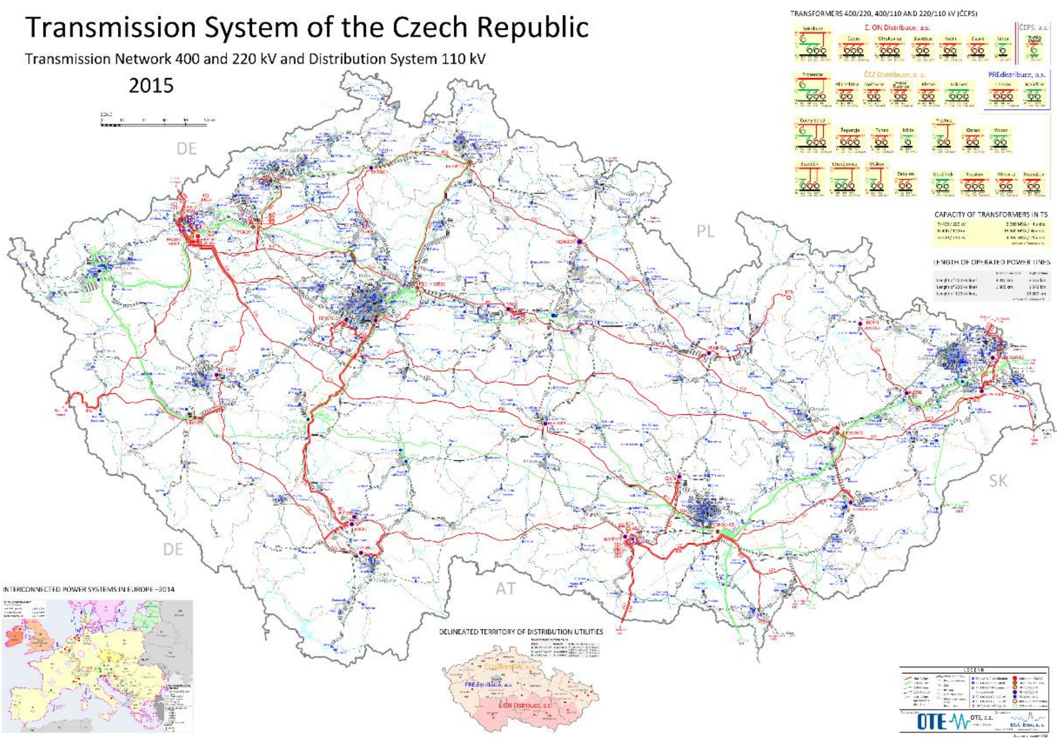


Figure 3: Czech transmission grid.[5]

With detailed data not available, the Czech model had to be developed based on publicly available data such as the map given in

Figure 3 (which specifies the line lengths, number of circuits and number of transformers) and data available through ENTSO-E. Line parameters had to be approximated using the same standard parameters used in the development of the European grid model (see Table 4). [5]

Table 4: Line parameters for the European Grid Model.

	Rated current [A]	Reactance [Ω/km]	Resistance [Ω/km]	Thermal limit [MVA]
400 kV OHL, single	2575.8	0.2460	0.0297	1695
400 kV OHL, double	5151.6	0.1255	0.0149	3390
220 kV OHL, single	1290.0	0.3010	0.0594	491
220 kV OHL, double	2580.0	0.1495	0.297	982

---

[5] Source: http://www.ote-cr.cz/statistics/long-term-balance/download/download

For 400/220 kV transformers, a standard type with a Yy0 configuration, a capacity of 500 MVA and 3 % short circuit voltage was used.

The resulting model as given in Figure 4 displays the characteristics of the Czech transmission grid as best as possible at the available data. The model is set up in DIgSILENT PowerFactory and can be improved with additional data, should such become available through the TSO.

Figure 4: Model of the Czech transmission grid (400 kV lines in orange, 220 kV lines in green). Includes the grid reinforcements planned by CEPS until 2030 (see section 2.1.2).

The model is capable of calculating full non-linear power flows using the Newton-Raphson method. However, in this study, a linearized approach neglecting voltage differences and reactive power was used to approximate the line loadings within the security constrained optimal power flow (SCOPF) of the dispatch model described in section 2.2.2. Full non-linear Newton-Raphson calculations were performed for a number of key situations to confirm the validity of the linearized model.

Phase shifting transformers are not modelled in the AC grid model itself (as no detailed calculations were performed using the actual AC model). To emulate the behavior of the installed phase shifters, the flows on the lines through Hradec are modelled as controllable (within the thermal capacity of the lines) in the DC model.

2.2.2 Dispatch Model

ENAplan is a software tool developed in-house by Energynautics that uses a linearized grid model (in this case, the European grid model with the more detailed Czech model as described in section 2.2.1), unit commitment heuristics and linear optimization to determine the least cost generator dispatch possible without violating applicable grid constraints[6] and generator parameters.

Linearized grid models are chosen for such optimization calculations – both for the linear optimization with heuristics chosen here, as well as for more advanced mixed-integer based tools – as optimization algorithms require convex solution spaces. A full power flow calculation typically uses the Newton-Raphson algorithm, which is iterative, as a single step calculation of the highly non-linear problem is not possible. Such an iterative process is inherently incompatible with optimization problems, as it not only requires high computation capabilities, but also impacts the shape of the solution space.

For a linearized model, voltage differences and the resistive components of lines are neglected. Both are usually rather small, the flows of active power are mostly determined by the reactive component of the line impedance. The power flow problem can thus be linearized with relatively little error to form a simple linear matrix, the Power Transfer Distribution Factor (PTDF) matrix that specifies the impact of a change in power balance at each node on each line in the system. This, however, also neglects the reactive power flows. Reactive power is typically provided locally, as reactive flows cause unnecessary grid losses, it is thus permissible to neglect it in the first iteration. Typically, the results from such a linearized calculation are loaded into a full non-linear model to check for additional reactive power constraints (this is the way utilities and grid operators also operate, and some outlook is provided in section 3.3.1). A full non-linear power flow thus always a multi-step approach relying on operational experience and heuristics.

Linearized power flow calculations are often referred to as a “DC power flow” as the properties resemble a DC system (while it is in reality a simplified AC system that is being simulated), while the full iterative process is referred to as an “AC power flow”.

ENAplan provides the following outputs:

- Unit commitment and generator dispatch optimized for least cost;
- Renewable dispatch and curtailment (if allowed);
- Line loadings and necessary grid reinforcements;
- Cross border trades and flows, including exports of renewable energy.

Conventional generators with more than 10 MW output are listed individually according to fuel and technology, with the single blocks of large power plants being treated as individual units, and connected to the node closest to the real location.

---

[6] ENAplan is capable of full (n-x) safe security constrained optimal power flow (SCOPF) dispatch for smaller systems. For the European system, (n-1) security is approximated by limiting allowed line loading to 70 %, which has proven to deliver reasonably accurate results, see section 3.2.

Technical properties such as startup and shutdown times, minimum up- and downtime and allowed ramp rates during operation are assigned to each category. Selected data is given in Table 5. The given ramp rates are the maximum ramp rates, which especially large fossil fired steam units cannot sustain all the way through their allowed area of operation (see Figure 5). Moreover, Czech nuclear units are considerably less flexible during real operation than indicated in Table 5, mostly running at full output power (see section 4.1 for more information and recommendations on the issue).

Table 5: Modelling parameters for conventional generation.

	ΔPmax [% of Pn / min]	Pmin [% of Pn]	Tstart, cold [h]	Tstart, hot [h]
Lignite CHP	1 – 3	50 – 60	5 – 8	2 – 3
Hard coal CHP	2 – 4	25 – 40	3 – 5	1 – 2
VVER-1000[7]	4 – 6	25 – 50	12	1 – 2
VVER-440/213	0.5 – 1	80	24	-
CCGT	7 – 9	25 – 40	1 - 2	0.5
OCGT	12 – 15	40	0.25	0.1

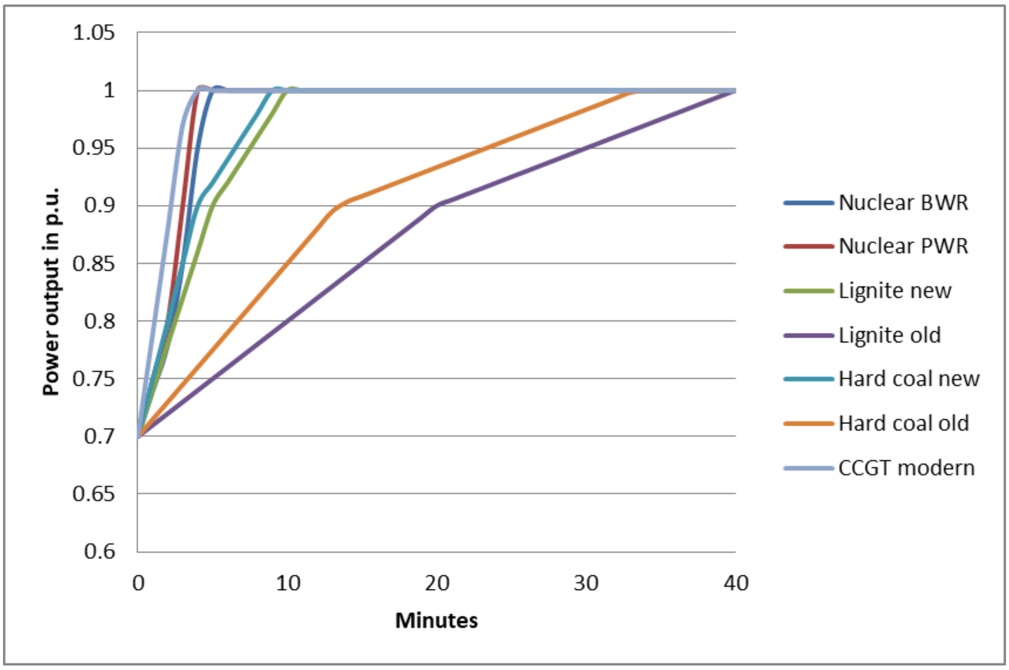


Figure 5: Ramp rates of different conventional units (Germany) between70 and 100 % power output, showing different ramping speeds in different areas of operation.

---

[7] Flexibility in VVER-1000 reactors is very rarely used in real life, as they are used for baseload operation in all countries that have them installed. It is theoretically possible to load-follow with this reactor type, though (even to below 80 % of rated output). More information is provided in section 4.1.

Generation costs were originally taken from [6]. Larger and newer fossil fuel fired power plants were assumed to be more efficient and less expensive than older and smaller units, with the sensitivities taken from [7]. For all of Europe, nuclear, lignite and run-of-river hydro units come first in the merit order, followed by large hard coal and CCGT units, small hard coal units and small CCGT, gas fired steam turbines and open cycle gas turbines (OCGT.) The costs of reservoir and pumped storage hydro generation are dependent on the reservoir level and in the range slightly below gas-fired peaking plants for most of the year.

Renewable feed-in is given priority, with curtailment allowed in case of grid overloading. Conventional generators go online according to generation cost, with the schedule being determined the day ahead and based on the residual load, assuming perfect foresight. Redispatch and renewable curtailment during the day are determined using optimal power flow (OPF) calculations. Unit startups are implemented as must-run ramps until stable minimum loading is reached, at which point the OPF optimizer takes over and assigns a desired power output to the unit, which can vary at each step according to the allowed ramp rate. Reservoir and pumped storage hydro as well as OCGT can be started and shut down by the optimizer, while all other units are started and shut down according to the pre-determined day-ahead schedule. Nuclear power plants are only shut down for maintenance, but their output can be varied by the optimizer within the allowed boundaries. The generation for each node by technology is recorded as well as the loading of each individual unit. [8]

2.2.3 Weather and Load Time Series

Historical wind speed and solar irradiation data from reanalysis for the year 2012 (average wind and solar year in central Europe) in 15 minute resolution available at Energynautics is used in conjunction with standard wind and solar power plant models to calculate the power output for each node for each hour of the year.

Load time series data is taken from ENTSO-E’s transparency platform.

The load distribution inside Czech Republic was determined based on population density (NUTS-3 regions) and data published by ERU. [1]

2.2.4 Simulation Methodology

The scenario is run two different simulations:

- Simulation across one year with renewable curtailment allowed to estimate how much wind and solar power would be curtailed with no grid expansion;
- Simulation across one year with no curtailment and optimization of grid expansion to estimate the investments in the grid necessary without curtailment.

Both cases are simulated in hourly step across an entire year.

2.3 ANCILLARY SERVICES

The power system model used does currently not contain detailed models for ancillary service provision. However, results can be used to provide some insight on possible issues arising with the decommissioning of the coal powered generator fleet and the transformation into a renewable based system.

3. RESULTS

3.1 DISPATCH

3.1.1 General Results

The following results of the security constrained optimal power flow calculations in ENAplan are found to be true independent of curtailment and grid reinforcement regime:

- Very little curtailment of renewable energy occurs, and no grid expansion is strictly necessary for renewable energy.
- Czech Republic remains a major exporter of electricity estimate for net electricity consumption in 2030 is 65 TWh – see Table 7 on page 24). Exports go mainly to Poland and Germany, while the import/export balance with Slovakia is almost even, and slightly more power is imported from Austria than exported there (mostly sold on to Poland).
- In winter, exports are more continuous, while in summer, exports depend mostly on the fluctuations of PV feed-in. Congestions on the cross border interconnectors cause a small amount of wind and solar curtailment.
- The phase-out of coal generation capacity transforms the conventional power fleet away from baseload coal and toward a more balanced generation mix with flexible and mid-merit generation capacity. While nuclear power and biomass continue to more or less provide baseload power at a high level of utilization, gas fired units, reservoir hydro and pumped storage provide flexible generation.

3.1.2 Examples

In Figure 6 through Figure 11, results from three different dispatch situations (in the basic scenario without any additional reinforcements, but HVDC in Germany in place) are plotted. Each one is presented in two different plot styles:

- “Excess generation representation” shows load and generation plotted from zero up. Where generation exceeds load, exports occur. Pumping is represented as negative generation.
- “Demand coverage representation” shows generation plotted to exactly match the load, exports are shown as negative, imports as positive generation. Pumping is represented as generation exceeding load.

Figure 6 and Figure 7 show seven days in January. Except for the second day, where a small amount of wind power is imported from Germany, Czech Republic generates on average 1 GW more than it needs, exporting during most hours. Renewables and gas are actually able to cover the load alone, but the remaining (expensive) coal power plants are ramped up to boost exports due to the high loads and low renewable availability and correspondingly high prices in the neighboring countries. Wind and solar power contributions are small.

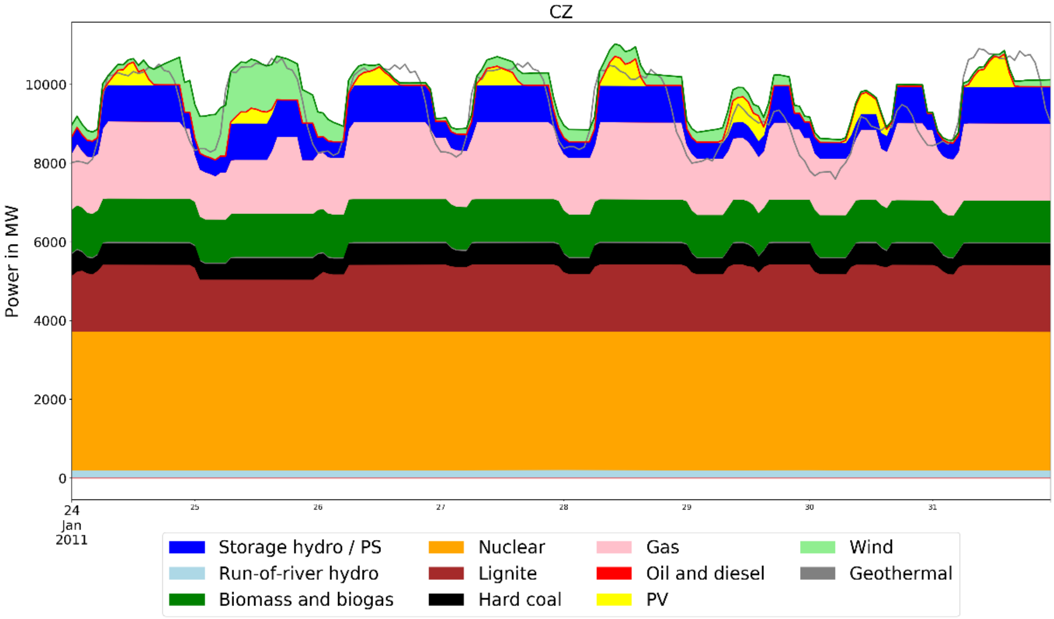


Figure 6: Dispatch for a week in January, excess generation representation.

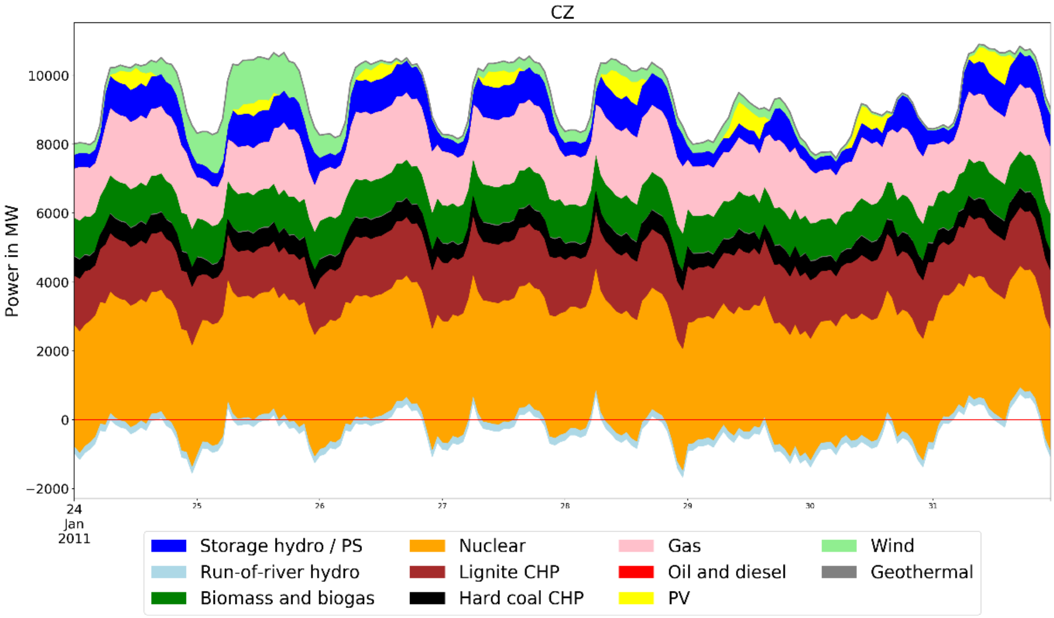


Figure 7: Dispatch for a week in January, demand coverage representation.

Figure 8 and Figure 9 show seven days in July with considerably higher PV feed-in. A large amount of solar power is exported, while pumped storage does not act as bulk storage for PV energy, but merely provides some regulating capacity during the morning and evening ramp, when CCGT units are started up and ramp up slower than the pumped storage, and during the evening load ramp, where units are being switched off slower than demand goes down. During the low load weekend (middle of the graph), almost no fossil fired generation (save the two industrial coal power plants) are running, no pumped storage is engaged and a part of the PV power is exported.

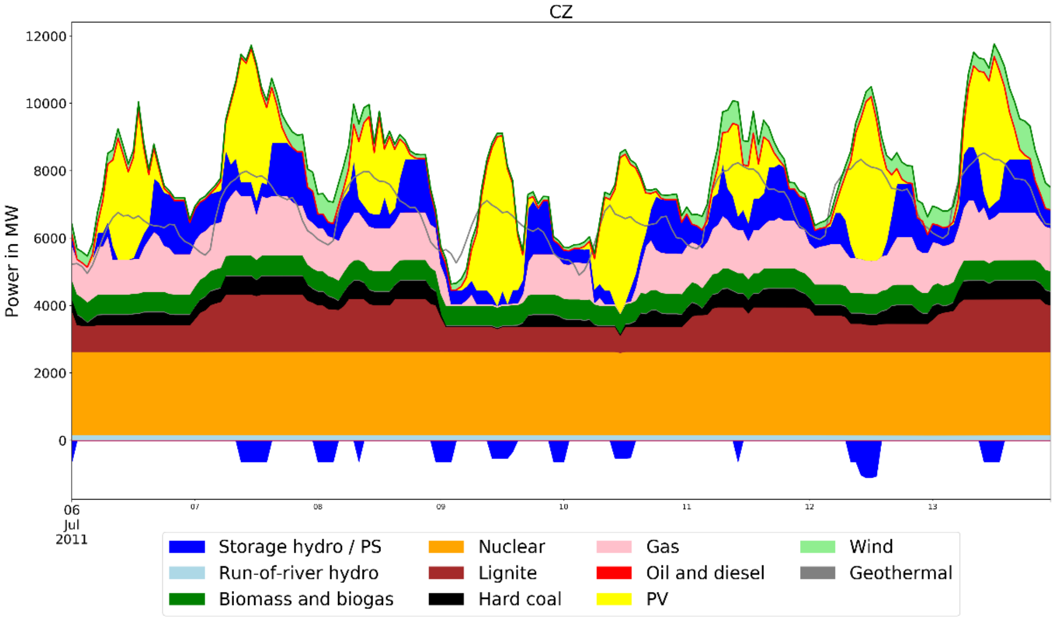


Figure 8: Dispatch for a week in July, excess generation representation.

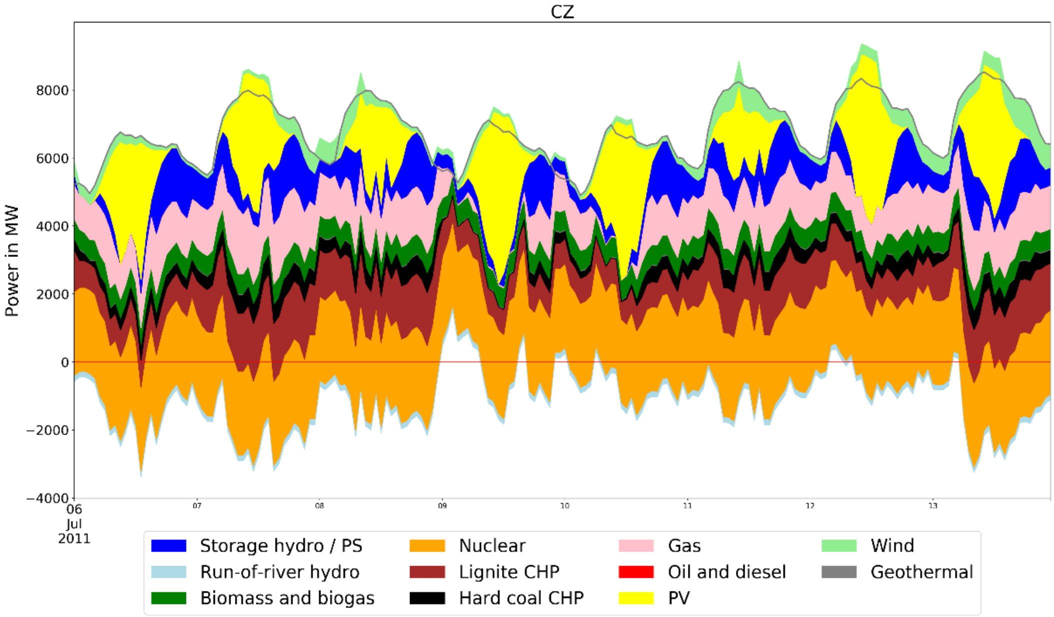


Figure 9: Dispatch for a week in July, demand coverage representation.

Figure 10 and Figure 11 show seven days in October with mostly little solar, but higher wind availability. Notably, pumped storage is now used to store excess wind (and to some degree solar) power during low load periods and provide peak generation during high load, while less exports take place and less gas power plants run. High wind availability in the neighboring countries drives down wholesale prices, so gas and fired generation in the Czech system is reduced and excess renewable energy is mostly stored in pumped storage rather than sold. Exports correspond stronger to solar feed-in and the load curve than to wind generation.

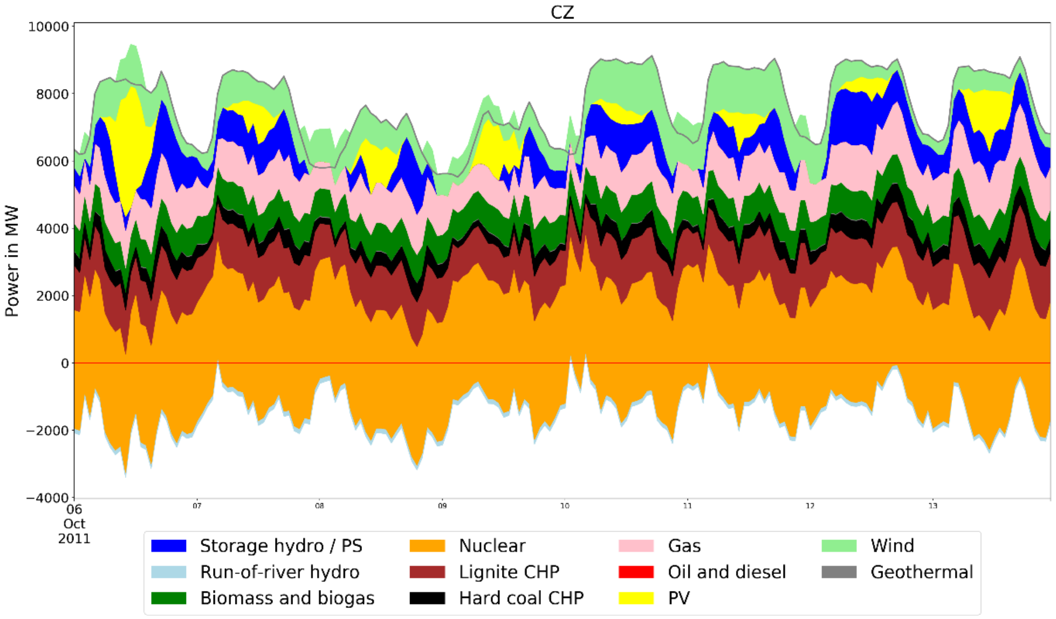


Figure 10: Dispatch for a week in October, excess generation representation.

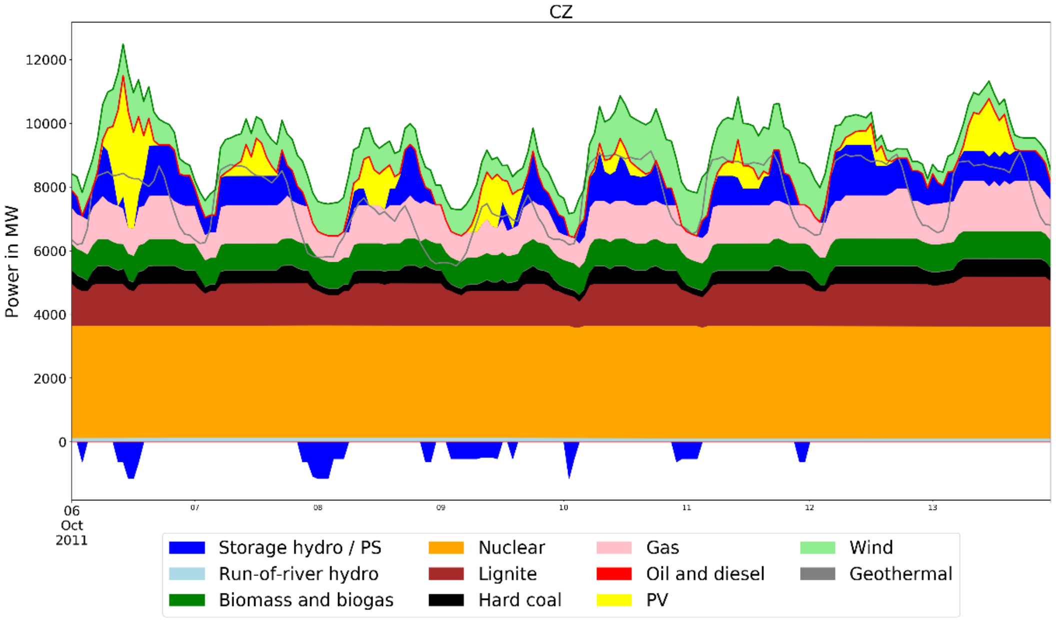


Figure 11: Dispatch for a week in October, demand coverage representation.

3.1.3 Curtailment, Capacity Factors and Electricity Exports

As described in section 2.2.4, the Czech 2030 coal reduction scenario was run in three different subscenarios:

- No additional grid expansion and all projects from TYNDP implemented;
- No additional grid expansion and delay of north-south HVDC in Germany;
- Optimization of grid expansion (frequently overloaded lines reinforced, see section 3.2.2 for more detailed results).

All scenarios showed very little necessary curtailment of wind and solar, see Table 6. The delay of the German HVDC corridors has the most profound impact on Czech VRE curtailment as the constantly stressed German grid limits exports of wind and PV generation (in contrast to overall net exports, which increase – see below). However, in any case, curtailment is low and far below the threshold of 3 % of annually curtailed energy that is for example considered acceptable in Germany.

Table 6: VRE curtailment

	No add. reinforcements	No add. reinforcements, no HVDC	Optimized reinforcements
Wind curtailed	0.22 %	1.39 %	0.005 %
PV curtailed	0.12 %	0.76 %	0.002 %

The cross border trades show a higher sensitivity to the different grid reinforcements than the renewable generation, as shown in Table7. With the delay of the German HVDCs, more exports to southern Germany are required. With optimized grid reinforcements, Czech Republic remains a net exporter, but exports decrease and imports increase. With reinforcements mainly on the cross-border lines, more (cheaper) peak power can be imported from Austria, and due to the additional grid reinforcements in Germany, southern Germany needs even less imports from Czech Republic.

This characteristic is directly visible in the capacity factors by technology as given in Table 8. With more reinforcements, capacity factors of Czech peaking power plants, such as gas turbines (with very high capacity factors in the scenario without German HVDC) and pumped storage, decrease drastically, as it is easier to import cheaper power from abroad during peak hours.

Table 7: Import / export balances.

	No add. reinforcements	No add. reinforcements, no HVDC	Optimized reinforcements
Demand	65 TWh	65 TWh	65 TWh
Losses[8]	4 TWh	4 TWh	4 TWh
Net generation	76.45 TWh	77.07 TWh	73.20 TWh
Imports	0.65 TWh	0.54 TWh	1.53 TWh
Exports	8.10 TWh	8.61 TWh	5.73 TWh
Balance	7.45 TWh	8.07 TWh	4.20 TWh

Table 8: Capacity factors by technology.

	No add. reinforcements	No add. reinforcements, no HVDC	Optimized reinforcements
Wind	26.2 %	25.9 %	26.3 %
PV	11.5 %	11.5 %	11.5 %
Biogas / biomass	60.1 %	59.8 %	60.2 %
Nuclear (Temelin)	79.4 %	79.4 %	79.4 %
Nuclear (Dukovany)	74.9 %	74.9 %	74.9 %
Lignite	68.7 %	68.7 %	69.3 %
Hard coal	63.6 %	63.6 %	63.8 %
Gas CCGT	33.0 %	34.01 %	31.1 %
Gas small CHP	91.3 %	91.5 %	91.6 %
Gas OCGT	25.0 %	45.5 %	1.3 %
Hydro	67.2 %	68.0 %	68.0 %
Pumped storage	31.1 %	32.5 %	2.0 %

---

[8] Estimated based on CEPS experience.

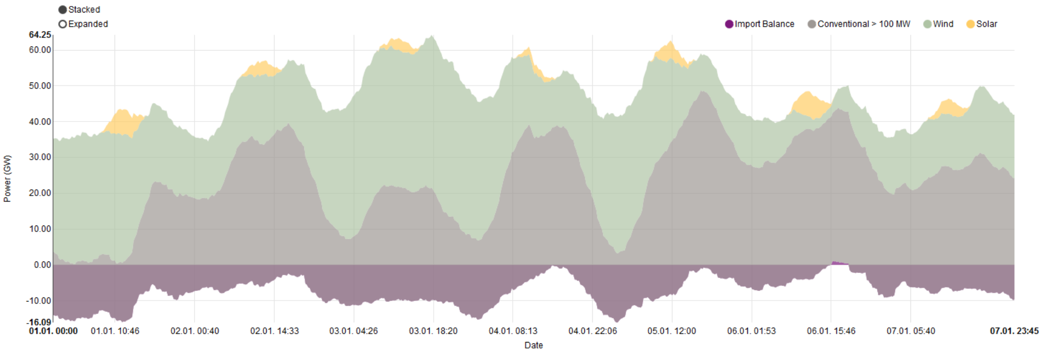
3.1.4 Instantaneous Non-Synchronous Penetration

Large, conventional power plants use so-called synchronous generators to produce electricity. Synchronous generators are connected to the power system via a direct, electromechanical link and have a considerable amount of spinning mass (inertia). VRE power plants are linked to the power system more indirectly via power electronics and have less or no spinning mass (inertia); VRE sources are thus said to be non-synchronous generation technologies. This property may require changes to how system stability is ensured, especially during periods of high shares of VRE in power generation.

Instantaneous non-synchronous penetration – in Czech Republic synonymous with instantaneous penetration of variable renewable energy, i.e. wind and PV – is the share of either load or generation that is provided by inverter based generation (or HVDC imports) at one specific point in time. For synchronously independent systems such as Ireland, this value is critical for stability as inertia in the system is low. For an interconnected system like the Czech system, it is mostly relevant because the higher the instantaneous penetration, the more conventional generation is offline, which may eventually make it more difficult to obtain ancillary services, especially reserves.

In an interconnected system with the possibility to import and export, there are two different instantaneous penetration values:

- The instantaneous penetration of load, which is a theoretical value, assuming that excess power that is exported comes from the remaining conventional generation (if there is any). This value can also exceed 100 %. Figure 12 shows a week in the German power system in January 2017 where the instantaneous penetration of load regularly exceeds 80 % and reaches 100 % at one point in time, while some conventional units still remain online and power exports are high.
- The instantaneous penetration of generation, which is the more critical value, as it describes the actual share of inverter based generation in the system.



Net generation of power plants for public power supply.
Datasource: 50 Hertz, Amprion, Tennet, TransnetBW, EEX
Last update: 24 Jan 2018 09:28

Figure 12: Instantaneous renewable penetration of load in Germany reaching 100 % on January 1st, 2018, while instantaneous penetration of generation is around 75 %, the difference being electricity exports. (Source: energy-charts.de)

The highest instantaneous non-synchronous penetration of load and generation occurs on a May day with low load and very high PV feed-in, with 81 % (without additional reinforcements) (Figure 13, Figure 14), resulting in and instantaneous non-synchronous penetration of generation of 65 %. While there is comparably little wind installed in the Czech system, high wind availability in Poland and Germany causes low wholesale market prices and prevents exports. Pumped storage is used to absorb some of the excess power, also providing valuable positive reserve. In this particular situation, some coal blocks also remain online and may be able to contribute reserves.

Such situations occur in the German system frequently, but may require some measures to procure additional (spinning) reserves (see section 3.3.3 for more details). In the Czech case, this may involve prequalifying biomass and biogas generators for the provision of reserves, as these usually remain online at all times.

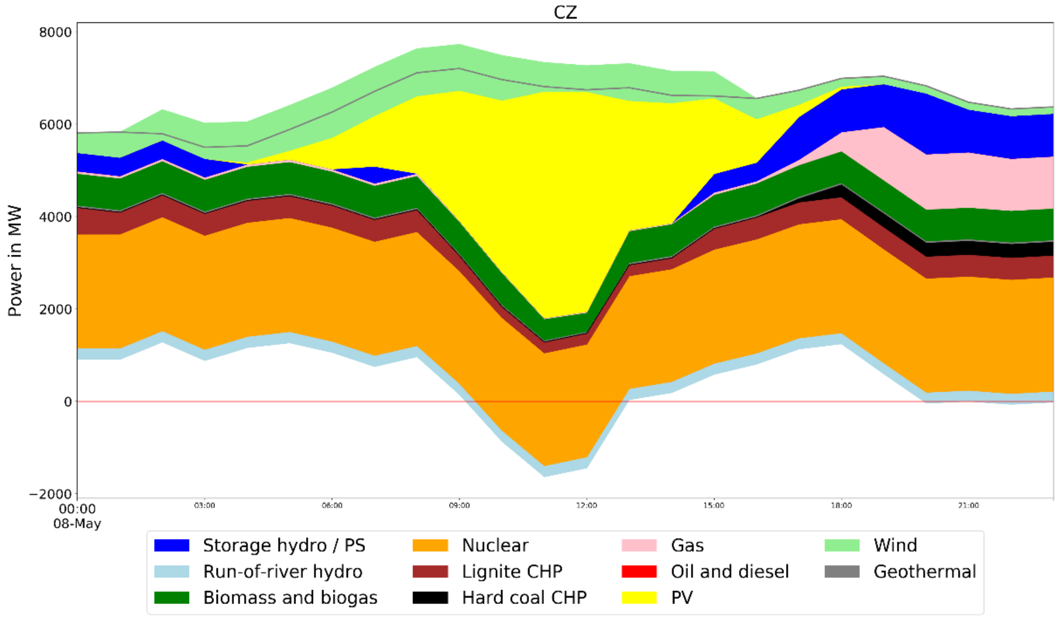


Figure 13: Dispatch on the day of maximum VRE penetration of load, demand coverage representation.

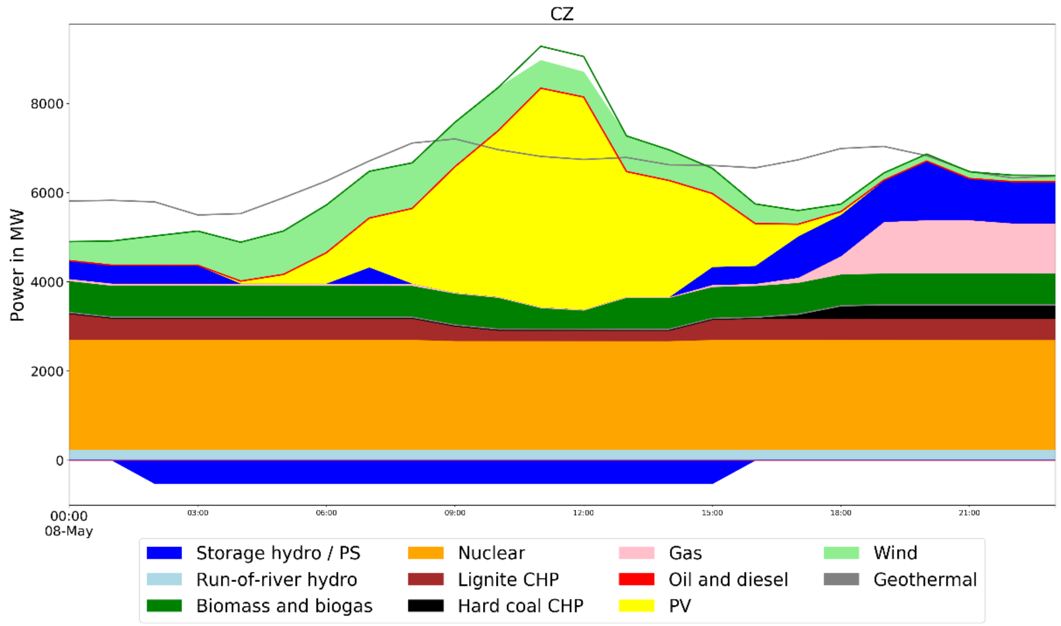


Figure 14: Dispatch on the day of maximum VRE penetraion of generation, excess generation representation.

As shown in Table 9, very high levels of instantaneous non-synchronous penetration of generation are rather rare occurrences. Allowing a small amount of curtailment to bring more conventional units online for spinning reserve should be feasible, if even necessary.

Table 9: Non-synchronous penetration

	No add. reinforcements	No add. reinforcements, no HVDC	Optimized reinforcements
Max. inst. penetration of load	81.2 %	85.8 %	89.3 %
Max. inst. penetration of generation	65.5 %	65.0 %	65.0 %
IP (gen) > 50 %	140 h	118 h	134 h
IP (gen) > 60 %	20 h	15 h	15 h

3.2 GRID SIMULATIONS

3.2.1 General Results

Under the given scenario, the Czech transmission grid presents no major obstacle to the transformation from mainly coal based generation to renewable energy. The reasons are the following:

- The Czech Republic is a fairly small country. The main issue in other high-renewable countries such as the UK, Germany and Spain is the transmission of wind power over long distances, which is not relevant in the Czech case.
- The Czech grid is designed to transport electricity from a few large generation centers (lignite areas and nuclear power plants) to (relatively) far away load centers. This is different from larger grids like Germany or the UK with more diverse resource and power plants traditionally placed close to the load centers.
- Due to this characteristic, the Czech grid is designed with a high degree of redundancy. With thermal capacities of lines potentially overestimated by the use of (modern) standard types, peak loading of most lines stays in the range between 15 and 35 %.[9] This means that even if capacities were overestimated by 100 % (which they are almost certainly not), (n-1) security would be maintained during almost all hours of the year with the real capacities. The approximation for the (n-1) criterion used by the dispatch model – limiting line loading to 70 % - underestimates the degree of redundancy present in the Czech grid, thus, the dispatch is actually (n-2) secure for most cases.[10]
- Renewable resources are well distributed within the country. Wind power is a major driver behind grid overloading and reinforcement and other countries, and wind capacities under the scenario are rather low. Biomass/biogas, CHP and rooftop PV are located close to the population and thus the load.
- A large share of the renewable generation comes from biomass and biogas, which are flexible and dispatchable to a certain degree.

3.2.2 Grid Reinforcements

No grid reinforcements were identified as strictly necessary under the 2030 scenario, but the following projects are to be considered:

- The interconnector to Austria connecting Slavetice (CZ) with Dürnrohr (AT) is frequently overloaded by Czech exports to Austria and needs at least one additional circuit. Alternatively, the double line from Sokolnice (CZ) to Bisamberg (AT) could be uprated to 400 kV, providing additional cross border capacity. Austria's hydro power plants (including major pumped storage resources) provide a great deal of flexibility for the Czech system.

---

[9] Exceptions and resulting reinforcements are explained in section 3.2.2.

[10] A number of contingency calculations were performed in DIgSILENT PowerFactory for key situations, confirming this.

- The single 400 kV line Prosenice-Otrokovice-Sokolnice is highly loaded, which can be resolved by uprating the 220 kV double circuit line from Prosenice to Sokolnice to 400 kV.

It is notable that all reinforcements are located in the eastern part of Czech Republic. The necessity for reinforcement arises partially from the transfer to renewable energy in the Czech Republic, but from the increased trades between Poland, Slovakia and Austria that impact the Czech grid, and partially from the increased trades between the Czech Republic and these countries.

The alternative to this grid expansion might be the installation of phase shifting transformers in the 400 kV substations of Nošovice and/or Slavětice to govern the flows in the eastern part of the Czech grid. This approach has been used on the German border and reduces or eliminates unplanned cross-border flows on the lines through Hradec (see Figure 15). A clear recommendation for such a solution would, however, require more detailed calculations.

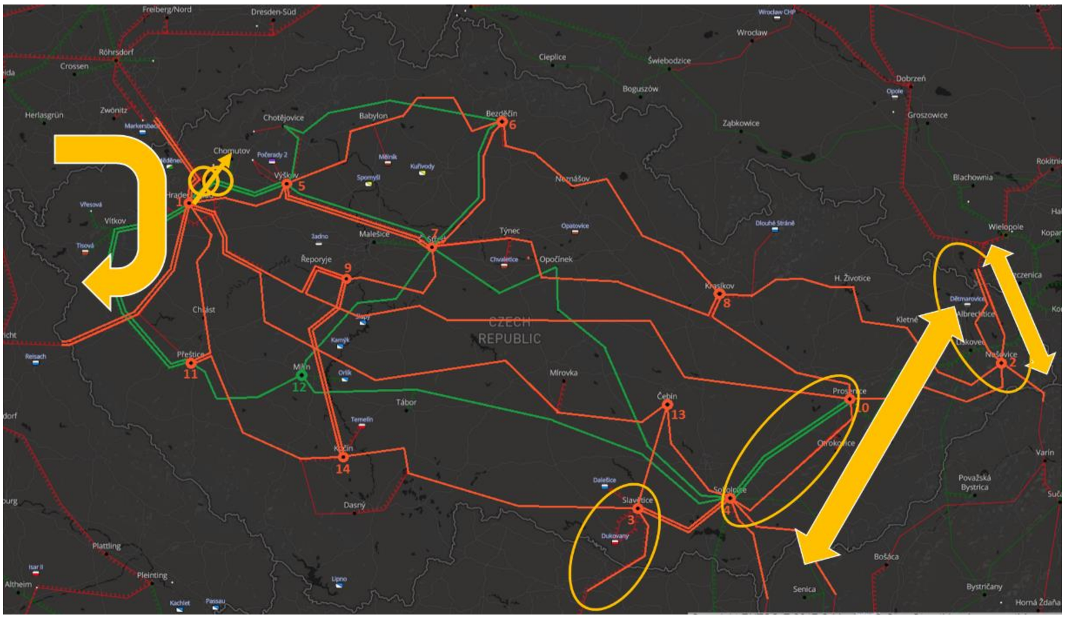


Figure 15: Unplanned flows through the Czech grid. Flows on the Czech-German interconnectors are governed by the phase shifting transformer at Hradec. Lines that cause redispatch and thus require reinforcements marked in yellow.

3.3 ANCILLARY SERVICES

3.3.1 Reactive Power

No detailed reactive power assessments were conducted for the entire year, as this requires a large amount of additional data on reactive power capabilities and operating regimes of power plants and other voltage control instances. The linearized ENAplan model neglects reactive power and voltages in the network.

A simplified calculation was performed for the maximum and minimum load situations in DIgSILENT PowerFactory to estimate the feasibility of reactive power provision and voltage control of the scenario. Assuming a power factor of cos(φ) = 0.95 inductive for the vertical grid load, the reactive power specified in Table 10 and Table 11 per model node is necessary to maintain the voltage at 1.0 p.u. at each node.

Both cases are generally feasible assuming that synchronous generators can realize power factors down to 0.8. The high reactive power demand at some border nodes (CZ01, CZ03, CZ04) is an artefact of the Czech grid operating decoupled from its neighbors in the calculation model, to avoid distortions from inadequate reactive power data of neighboring countries. No excessive reactive power flows across transmission lines are recorded in either case.

In reality, the grid will show stronger inductive behavior in both cases due to higher grid loading caused by cross-border and transfer flows. This presents no challenge in the peak demand case with moderate inductive reactive power demand, and is beneficial in the low demand case with its demand for capacitive reactive power.

Generally, reactive power should not be a problem, but there are some experiences from other countries with high renewable shares listed in the recommendations section.

Table 10: Active and reactive power per substation during peak load, rough estimate based on AC power flow model.

Terminal	Substation	Active Power	Reactive Power	Apparent Power	Power Factor
		MW	Mvar	MVA	Cos(φ)
CZ01	Hradec Vychod	448.00	-143.64	470.46	0.95
CZ02	Nosovice	380.00	154.73	410.29	0.93
CZ03	Slavetice	2418.00	-163.15	2423.50	1.00
CZ04	Sokolnice	420.00	-86.64	428.84	0.98
CZ05	Vyskov	970.00	47.75	971.17	1.00
CZ06	Bezdecin	827.00	196.01	849.91	0.97
CZ07	Cechy Stred	178.00	75.00	193.16	0.92
CZ08	Kasikov	665.00	301.51	730.16	0.91
CZ09	Chodov	449.00	150.00	473.39	0.95
CZ10	Prosenice	779.00	24.45	779.38	1.00
CZ11	Prestice	360.00	150.00	390.00	0.92
CZ12	Milin	488.00	138.32	507.22	0.96
CZ13	Cebin	283.00	150.00	320.30	0.88
CZ14	Kocin	2328.00	45.65	2328.45	1.00

Table 11: Active and reactive power per substation during minimum load, rough estimate based on AC power flow model.

Terminal	Substation	Active Power	Reactive Power	Apparent Power	Power Factor
		MW	Mvar	MVA	Cos(φ)
CZ01	Hradec Vychod	144.00	-250.00	288.51	0.50
CZ02	Nosovice	95.00	-150.00	177.55	0.54
CZ03	Slavetice	1608.00	-334.08	1642.34	0.98
CZ04	Sokolnice	134.00	-150.00	201.14	0.67
CZ05	Vyskov	209.00	-145.52	254.67	0.82
CZ06	Bezdecin	203.00	-22.05	204.19	0.99
CZ07	Cechy Stred	78.00	14.98	79.42	0.98
CZ08	Kasikov	152.00	9.58	152.30	1.00
CZ09	Chodov	174.00	-70.05	187.57	0.93
CZ10	Prosenice	248.00	-177.11	304.75	0.81
CZ11	Prestice	113.00	10.76	113.51	1.00
CZ12	Milin	56.00	46.56	72.83	0.77
CZ13	Cebin	167.00	-70.08	181.11	0.92
CZ14	Kocin	1070.00	-148.69	1080.28	0.99

3.3.2 Inertia

Inertia of grid connected synchronous generators determines the rate of change of frequency (RoCoF) in an imbalance event. RoCoF dictates the speed at which primary control (FCR) has to react. Inertia and RoCoF are global parameters that affect the entire synchronous zone. According to the dena Ancillary Services Study [9], even large scale integration of variable renewable until 2030 does not reduce the inertia in the Central European system to critically low levels.

3.3.3 Operating Reserves

Different terminologies for the different reserve products exist worldwide, however, by the EU Network Codes currently being drafted into European law, the following products and terminology are used:

- Frequency Containment Reserve FCR (formerly often “primary reserve” or “primary regulation”) is provided automatically and individually from participating spinning units based on measured frequency deviation (droop control) and has the task fo stabilizing the frequency at an offset value in case of a deviation. Activation time is 30 seconds in the Czech Republic.
- Automatic Frequency Restoration Reserve aFRR (“secondary reserve”) is provided by participating units to restore frequency back to the nominal value and

to eliminate area control errors. aFRR is activated by central load frequency controllers (automatic generation control, AGC) in a coordinated manner. Activation time is between 5 and 15 minutes.

- Manual Frequency restoration reserve mFRR ("tertiary reserve") can be provided from spinning and non-spinning units and is typically used to assist and replace aFRR in restoring frequency. Activation time is 30 minutes. [10][11]

Moreover, different offline reserve types (replacement reserves) can be procured by grid operators for activation during longer periods of demand generation mismatch.

FCR (primary) are dimensioned in the Central European synchronous zone to account for the possible outage of the two largest generator blocks in the system, which are currently French N4 design nuclear units with 1500 MW each. The 3000 MW of primary reserve demand are distributed to the control areas in the synchronous zone based on their share of demand, resulting in a requirement of 85 MW of FCR capacity (positive and negative, FCR is a symmetric product) for the Czech system. [11][9] This value is not expected to change based on expansion of renewable capacities and can without any problems still be provided by the system under the 2030 scenario. Even without small CHP (gas, biogas and biomass) and renewables being required to provide FCR, there are enough capable units online at all times:

- Some of the biomass units are prequalified for FCR;
- FCR can be provided by gas fired CCGT units and by reservoir hydro power plants;
- Theoretically, the turbine controllers of the nuclear units could be adjusted to run under a droop control (if they do not possess the capability already) and provide FCR, as is routinely done in Germany and France.

Moreover, there is currently a business case for FCR from battery installations, which already provide a share of FCR in Germany[11] and the UK.[12] Economic feasibility depends on the prices in the Czech FCR market. German prices have greatly decreased since 2012 due to an oversupply of units prequalified for FCR, but batteries for FCR still seem

---

[11] https://www.steag.com/en/news/insights/we-maintain-the-heartbeat-of-the-grid/

http://analysis.newenergyupdate.com/energy-storage/german-firms-turn-batteries-power-plants-aid-grid-control

[12] http://www.electroroute.com/insights/electricity-grids-ancillary-service-fad-diet

to be a business case. It is also technically possible to provide FCR from wind and PV, but this is not done in reality anywhere yet.[13]

The main reserve type typically affected by the fluctuations introduced into the system by variable renewable energy are aFRR and mFRR, which deal with imbalances on a time scale of a few minutes up to several hours. Experience from various European countries with high shares of variable renewable energy have shown that an increase in variable renewable capacities does not necessarily result in proportionally growing demand for aFRR. Known as the "German paradox", reserve requirements have actually been reduced with growing renewable shares, however, renewables were usually not the main driver behind this reduction. The actual demand for frequency restoration reserves depends on the design of the wholesale markets (pure day-ahead markets need more reserves than intra-day markets with short lead times) and the quality of available forecast.

A master's thesis realized at Energynautics in cooperation with KTH Stockholm in 2017 used Czech power system data[14] to develop a methodology of assessing the additional aFRR demand from variable renewable energy based on the fluctuations on a minute resolution time scale.[15] The results of the current system were validated against the current aFRR requirement (based on an ENTSO-E quota, much like FCR), as depicted in Figure 16. [12]

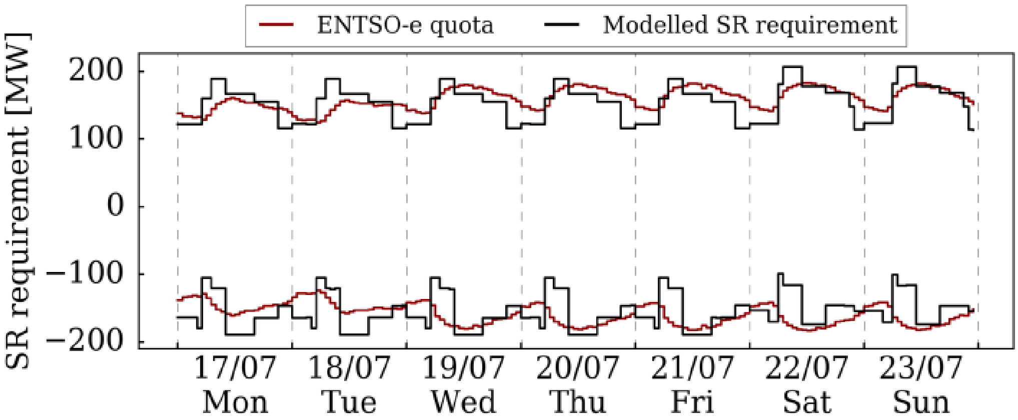


Figure 16: Model validation based on the ENTSO-e minimum recommended aFRR capacity quota. [13]

---

[13] Spain requires FCR from wind turbines, but FCR may be traded – resulting in wind power plant operators purchasing the required capacities from other power plants.

[14] Czech Republic was used as a model case simply due to the fact that high resolution operational data is publicly available.

[15] Available here: https://kth.diva-portal.org/smash/get/diva2:1152864/FULLTEXT01.pdf - thesis was supervised by the authors of this study.

The study came to the conclusion that aFRR requirements would slightly increase with higher installed wind and solar capacities, as given in Figure 17 for the scenarios given in Table 12 (with the first scenario being the current state of the system). [12] Requirements of up to 200 MW of aFRR are not uncommon in the Czech Republic as of today, but it needs to be determined whether the proposed power plant portfolio under the 2030 scenario used in this study can provide the necessary capabilities.

Table 12: Parameters of the proposed cases. [13]

	$P_{load,max}$ [GW]	P_{PV} [MW]	P_{wind} [MW]	VRE penetration [%]
●	12	2050	280	20.3
●	12	3000	500	29.2
●	12	4000	2000	54.2

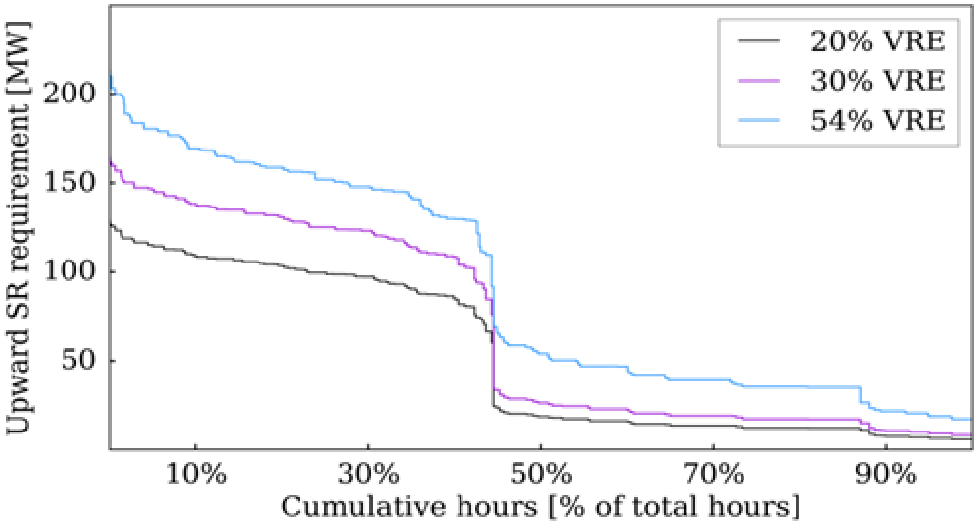


Figure 17: Duration curves of upward aFRR (SR) requirements due to solar PV and wind in the 20, 30 and 54% VRE penetration cases. [13]

Different from most European countries, aFRR in the Czech system is a symmetric product, which mandates units that provide positive capacity to provide the same amount of negative capacity. With reserves being provided all from conventional units, this is not an issue, but at rising penetration levels of variable renewable energy, it may be sensible to split the market up into positive and negative reserves. During times of high renewable feed-in, dispatchable generators such as retrofitted coal units, CCGT and even nuclear units could ramp down to their economic or technical minimum and provide positive reserves, while wind and solar could provide negative reserves by simply curtailing their output if needed. Even during operation outside of the maximum instantaneous renewable penetration hours, the split of the aFRR market in separate negative and positive reserve products will have the benefit of the least efficient / most expensive spinning units providing positive reserves (running at curtailed output) and the most efficient / least expensive spinning units providing negative reserves (running at full rated power).

Since cases of very high instantaneous penetration levels are still rather rare under the investigated scenario, the generator portfolio is generally capable of providing enough aFRR and mFRR. Theoretically, all reserves could be provided from pumped storage, which can provide both positive and negative aFRR and mFRR from stand still. As it is unsafe to rely on a very small number of units that are also subject to state of charge constraints, there are different options of providing aFRR and mFRR:

- CCGT units are usually flexible when spinning, and dispatched most of the time in the case of the 2030 scenario. These can provide aFRR and mFRR.
- The open gas turbines at Prostejov and Kladno can provide a combined 170 MW of mFRR from stand still. If the CCGT units have bypass stacks between the gas turbine and steam turbine cycles, they can provide 2/3 of their rated capacity as stand still mFRR as well.
- Retrofitted coal CHP units can provide aFRR and are dispatched for both heat and electricity demand most of the time.
- It would be possible to upgrade the controls of nuclear units to provide aFRR.
- Given a market structure that allows generator pools to bid for reserves, mFRR can be provided from small CHP generators, as is routinely done in Germany.
- Wind power plants can be used from negative mFRR (as currently done in Germany and Denmark) and possibly, with some control upgrades, for negative aFRR as well. Positive aFRR and mFRR are technically possible with wind turbines running at curtailed output, but require very accurate forecasting (Denmark is currently testing this on offshore wind power plants).
- Demand side management, especially with large industrial cooling houses where short power interruptions have only a small impact, may be used for positive aFRR and mFRR.

3.3.4 Black Start Capacity

As the Czech power system operator do not publish their black start plan, the impact of the system transformation cannot directly be determined. Principally, enough large conventional units that are capable of black start, such as hydro power plants (including pumped storage) and gas turbines (including CCGT) are available in the Czech system under the 2030 scenario.

3.3.5 Studies and experience from other countries

In this section, some experience on ancillary services at high penetration levels of renewable energy from other countries are discussed briefly.

3.3.5.1 Germany: Operating reserves from biogas plants

Biogas power plants can provide valuable operating reserve and thus replace conventional generators in that role. Biogas power plants, 4.5 GW of which were installed in Germany by the end of 2017 (see Figure 18), have been active in the German reserve markets since at least 2012.[16] Biogas plants are usually equipped with reciprocating engines and synchronous generators, giving them the capabilities of conventional thermal power plants, albeit mostly at a much smaller size.

In Germany, biogas power plants can be prequalified for aFRR and mFRR, both positive and negative. Typically, units running at partial load participate in the aFRR market (see Figure 19), while slower mFRR is provided with start-stop operation (usually, a gas engine can be brought online within a few minutes and shut off in an instant). [14]

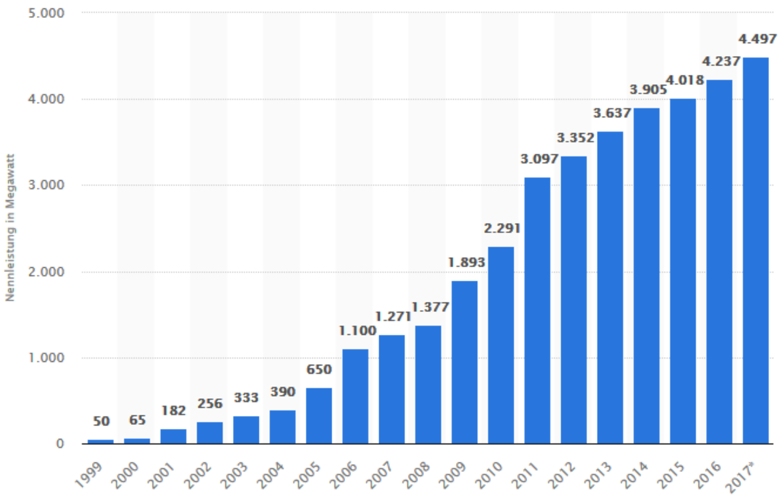


Figure 18: Installed biogas capacities (in MWe) in Germany 1999 - 2017.[17]

---

[16] https://www.next-kraftwerke.de/neues/erstmals-negative-regelleistung-aus-biogasanlagen-am-regelenergiemarkt-verkauft

[17] Source: https://de.statista.com/statistik/daten/studie/167673/umfrage/installierte-elektrische-leistung-von-biogasanlagen-seit-1999/

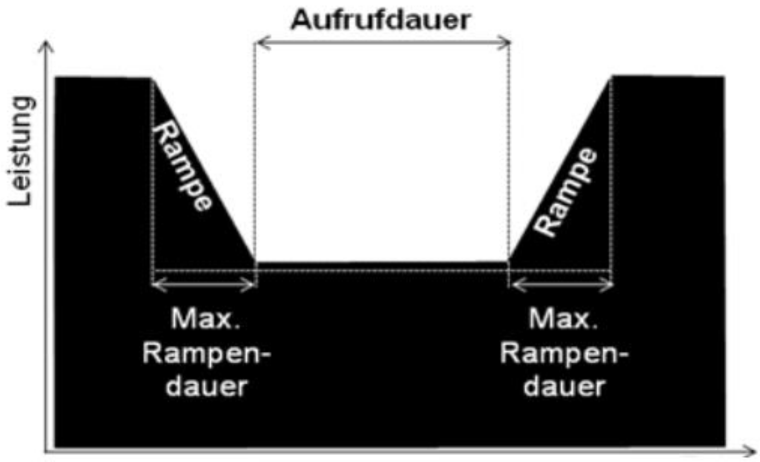


Figure 19: Activation of negative aFRR / mFRR for biogas in Germany. [14]

Provision of FCR from biogas plants is technically possible, as units are typically equipped with a generator speed governor with a frequency droop, which reacts to changes in the frequency by increasing or decreasing output power. However, biogas power plants are currently largely excluded from the German FCR market, as FCR has to be provided for a full week at a time, symmetrically and with a minimum bid size of 1 MW (which is too large for the mostly small installations).

3.3.5.2 Ireland: Ancillary services at high shares of wind

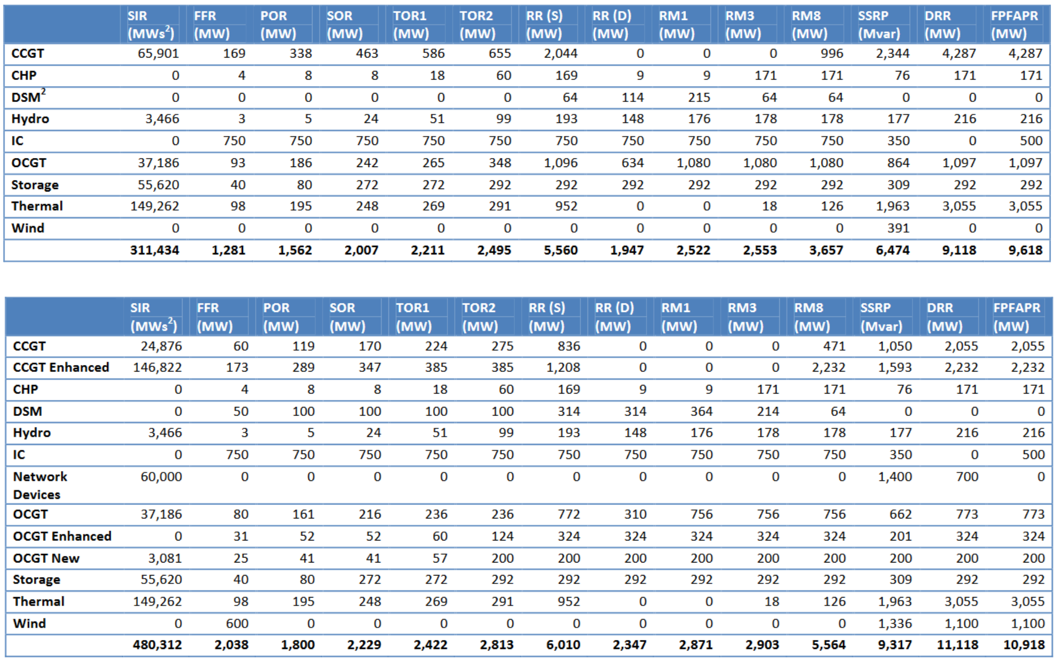
The Irish all island systems – including both Northern Ireland and the Republic of Ireland – currently runs 4 GW of wind in a synchronously independent 5 GW system. Conventional generation is mostly based on gas fired CCGT and peat fired power plants (similar to coal). TSOs Eirgrid and SONI thus have to pay special attention to ancillary services and have constantly updated their requirements and monitoring systems since the early 2000s. Table 13 explains the different ancillary service products present in the Irish systems, which are slightly different from those used in continental Europe.

Table 13: Ancillary services in Ireland. [15]

Abbreviation	Long form	Explanation
SIR	Synchronous Inertial Response	Inertia (determines RoCoF)
FFR	Fast Frequency Response	FCR split into three different products
POR	Primary Operating Reserve	
SOR	Secondary Operating Reserve	
TOR 1 / 2	Tertiary Operating Reserve 1+2	aFRR
RR (S)	Replacement Reserve (synchronized)	mFRR / RR
RR (D)	Replacement Reserve (de-synchronized)	RR
RM 1 / 3 / 8	Ramping Margin 1/3/8 minutes	
SSRP	Steady State Reactive Power	Mvar
DRR	Dynamic Reactive Response	Dynamic fault behavior
FPFAPR	Fast Post-Fault Active Power Recovery	

Based on detailed steady state and dynamic grid studies as well as operation experience, the TSOs regularly publish operational constraints applicable to the system. These, most notably, include a limitation of instantaneous non-synchronous penetration (including HVDC imports) to 60 % (75 % are planned for 2019), minimum values for inertia and reserves, and limits on inter-area flows. [16] Generally, the TSOs have a high degree of control over the system and can dispatch generators and curtail wind if necessary for operational security, enabling high shares of non-synchronous generation by constant monitoring and situational awareness.

Moreover, the TSOs are also constantly involved in studies for the development of the system 5 and 10 years out, results of which are published. This includes the analysis of ancillary service capabilities for the year 2020 as given in Figure 20. [15] Similar studies are recommended for the Czech system.



	SIR (MWs^2)	FFR (MW)	POR (MW)	SOR (MW)	TOR1 (MW)	TOR2 (MW)	RR (S) (MW)	RR (D) (MW)	RM1 (MW)	RM3 (MW)	RM8 (MW)	SSRP (Mvar)	DRR (MW)	FPFAPR (MW)
CCGT	65,901	169	338	463	586	655	2,044	0	0	0	996	2,344	4,287	4,287
CHP	0	4	8	8	18	60	169	9	9	171	171	76	171	171
DSM^2	0	0	0	0	0	0	64	114	215	64	64	0	0	0
Hydro	3,466	3	5	24	51	99	193	148	176	178	178	177	216	216
IC	0	750	750	750	750	750	750	750	750	750	750	350	0	500
OCGT	37,186	93	186	242	265	348	1,096	634	1,080	1,080	1,080	864	1,097	1,097
Storage	55,620	40	80	272	272	292	292	292	292	292	292	309	292	292
Thermal	149,262	98	195	248	269	291	952	0	0	18	126	1,963	3,055	3,055
Wind	0	0	0	0	0	0	0	0	0	0	0	391	0	0
	311,434	**1,281**	**1,562**	**2,007**	**2,211**	**2,495**	**5,560**	**1,947**	**2,522**	**2,553**	**3,657**	**6,474**	**9,118**	**9,618**

	SIR (MWs^2)	FFR (MW)	POR (MW)	SOR (MW)	TOR1 (MW)	TOR2 (MW)	RR (S) (MW)	RR (D) (MW)	RM1 (MW)	RM3 (MW)	RM8 (MW)	SSRP (Mvar)	DRR (MW)	FPFAPR (MW)
CCGT	24,876	60	119	170	224	275	836	0	0	0	471	1,050	2,055	2,055
CCGT Enhanced	146,822	173	289	347	385	385	1,208	0	0	0	2,232	1,593	2,232	2,232
CHP	0	4	8	8	18	60	169	9	9	171	171	76	171	171
DSM	0	50	100	100	100	100	314	314	364	214	64	0	0	0
Hydro	3,466	3	5	24	51	99	193	148	176	178	178	177	216	216
IC	0	750	750	750	750	750	750	750	750	750	750	350	0	500
Network Devices	60,000	0	0	0	0	0	0	0	0	0	0	1,400	700	0
OCGT	37,186	80	161	216	236	236	772	310	756	756	756	662	773	773
OCGT Enhanced	0	31	52	52	60	124	324	324	324	324	324	201	324	324
OCGT New	3,081	25	41	41	57	200	200	200	200	200	200	200	200	200
Storage	55,620	40	80	272	272	292	292	292	292	292	292	309	292	292
Thermal	149,262	98	195	248	269	291	952	0	0	18	126	1,963	3,055	3,055
Wind	0	600	0	0	0	0	0	0	0	0	0	1,336	1,100	1,100
	480,312	**2,038**	**1,800**	**2,229**	**2,422**	**2,813**	**6,010**	**2,347**	**2,871**	**2,903**	**5,564**	**9,317**	**11,118**	**10,918**

Figure 20: Projection of ancillary service capabilities in the Irish system for the existing system and the expected 2020 generator portfolio.

3.3.5.3 Spain: Ancillary services at high shares of wind and PV

Spain has been running with high shares of wind and PV for at least a decade, with the majority of the currently installed 23 GW of wind and 6 GW of solar (in a 40 GW peak system) installed between 2007 and 2012. With only weak interconnections to neighboring France, the Iberian system (including Portugal which has a comparably high share of renewables) needs to balance itself without help from the outside, making it almost an electrical island.

Spanish TSO Red Eléctrica de España (REE) thus had to implement a number of measures to facilitate balancing and procure the necessary ancillary services, especially operating reserves. Besides the introduction of forecasting systems, intra-day energy markets and a real time balancing market, renewable forecasts, production and the state of conventional generation is constantly monitored in REE's Control Centre of Renewable Energies[18] (see Figure 21).

Reserve capacity and activated reserves – especially aFRR, which is used to balance most of the fluctuations – are monitored and action is taken if not enough reserves are available:

---

[18] http://www.ree.es/en/activities/operation-of-the-electricity-system/control-centre-renewable-energies

- Units may be started up or shut down and/or ordered to provide reserves by REE;
- Wind generation may be curtailed by REE to enable conventional units to come online to provide reserves;
- REE may take action and dispatch more reserves than initially procured – and curtail wind and solar for it – if the weather forecast indicates that unusual events (like a storm) may occur;
- Besides the active provision of reserves by generating units, REE may trip individual generators for balancing purposes if no other measures are available.

The Spanish experience shows that high penetration of renewables is manageable from a ancillary services point of view, if the system is constantly monitored and the grid operator is authorized to interfere in real time if necessary[19]. [17]

Wind and solar power plants connected to the transmission grid are furthermore required to provide reactive power and control the voltage at the connection point by the Spanish grid code.

---

[19] Ancillary services reports available at http://www.ree.es/en/statistical-data-of-spanish-electrical-system/annual-report/ancillary-services-preliminary-report-2016

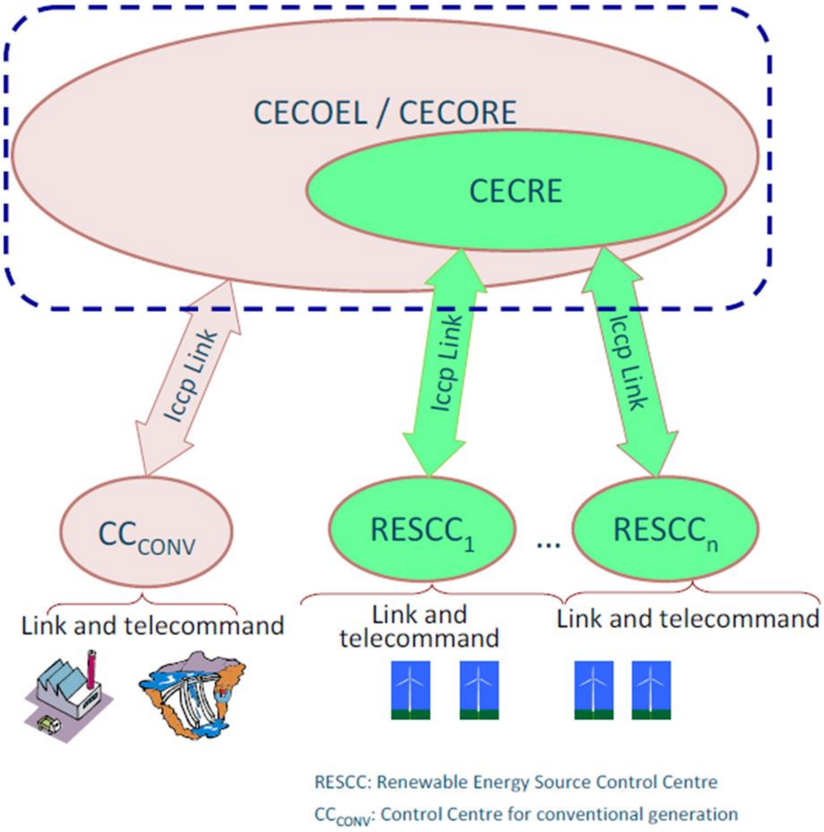


Figure 21: Functional structure of CECRE.[17]

4. RECOMMENDATIONS

4.1 FLEXIBILITY OPTIONS

Under the scenario investigated in this study, a considerable part of generation provides baseload power and is rather inflexible during operation. This is also one of the main drivers behind the high Czech power exports (a situation much similar to that of today). However, the opportunities for exports, especially exports at an economic advantage, are highly dependent on the development of demand and generation in the neighboring countries. An increased demand for operational flexibility may thus arise in other future scenarios in the Czech system, which can be covered with different flexibility options.

Currently, nuclear units run at full power output basically all the time, which is of course the most economically advantageous mode for their operators. Load following with nuclear units is not uncommon in France, Belgium and Germany though, as evident from Figure 22. [18]

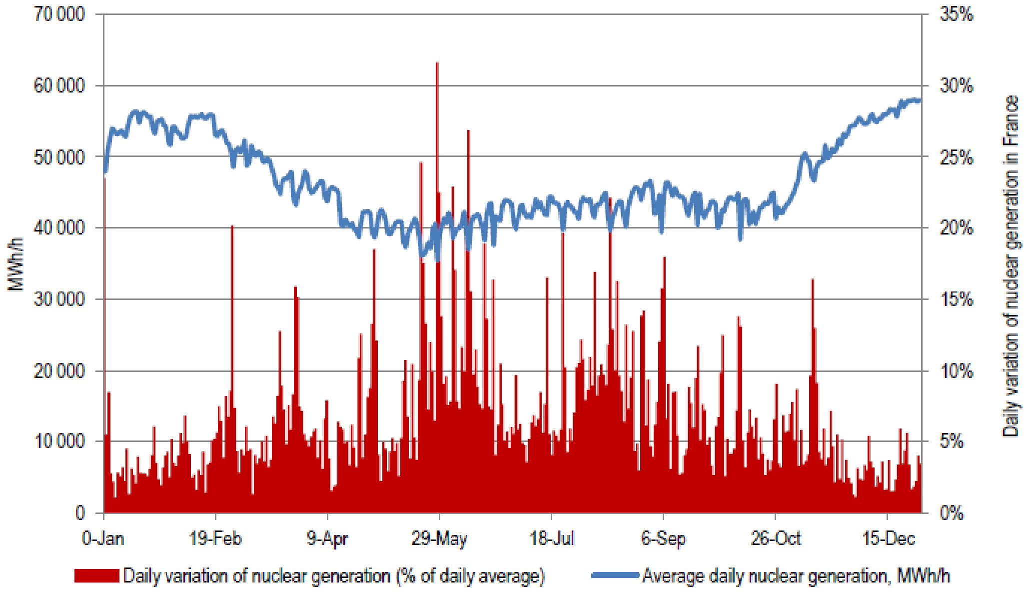


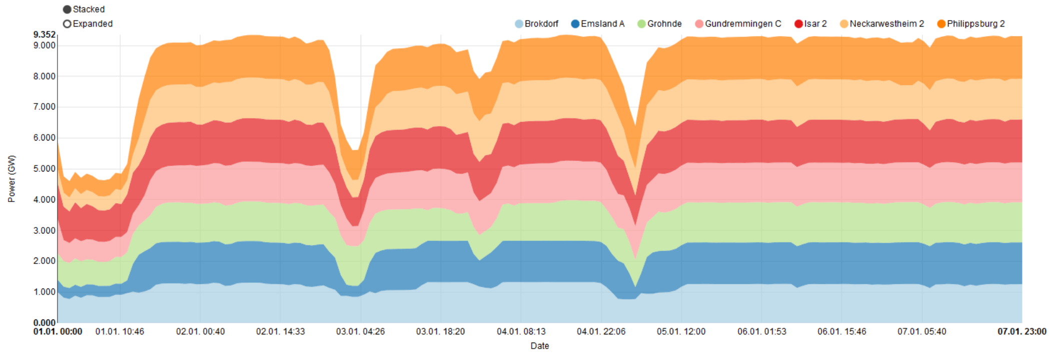
Figure 22: Flexibility of French nuclear portfolio. [18]

Czech nuclear power plants also currently possess some degree of flexibility, according to a report published by Masaryk University:

> *The Temelin nuclear power plant, therefore, up to 100 MWe per block, i.e. 200 MWe, Dukovany up to 80 MWe per block, i.e. 320 MWe The Temelin nuclear power plant is in reality, however, as a result of technical limitations, capable of regulation at the level of +/- 5 %, while the Dukovany nuclear power plant undergoes regulation only exceptionally.* [11]

The flexibility of Temelín reactors is actually used very rarely (output of the plant was reduced by 60 MW only once in the last two years).

Russian sources[20] confirm that the VVER-1000 reactor design used at the Temelin plant is principally able to load follow both in “shallow” and “deep” regimes, i.e. down to 80 % or even 50 % of its rated output. As there is little experience with the techno-economic ramifications of such operations with Russian design reactors, turbines and generators, the impact of ramping operations on plant lifetime needs to be evaluated in detail. French and German nuclear power plants have routinely been used for load following during the past decades and have not shown any significant reductions in lifetime (see Figure 23 for an example).



This data is published with a time lag of five days.
Datasource: EEX
Last update: 18 Jan 2018 21:14

Figure 23: Operation of German nuclear units in the first week of 2018. (Source: energy-charts.de)

Especially with renewable development also in neighboring countries and an increased need for flexibility, this capability may become an important asset in future scenarios. As the Temelin plant is a patchwork design of a Russian reactor with Western control and safety systems and may also differ from the original Soviet design in technical layout, some retrofits may be necessary, the cost of which eventually needs to be determined. Nuclear units may also be able to provide spinning reserves (FCR and aFRR).

Moreover, the flexibility that could be provided from other sources needs to be evaluated. As evident from the results given in section 3.1, there is a large must run block of CHP, gas and biomass fired, at all times. Under the given scenario, all CHP sources provide some flexibility, which means they can be decoupled from heat demand for brief periods of time. Due to the long time constants of district heating systems, this is usually already possible, and heat may also be provided without generating power (at an economic disadvantage though). The actual degree of operational flexibility of CHP needs to be looked into in future research, evaluating the following options:

---

[20] http://www.neimagazine.com/features/featureload-following-capabilities-of-npps/

https://link.springer.com/article/10.1134/S0040601514010030

- Heat storage for large CHP power plants;[21]
- Gas storage and larger generators for biogas plants (favoring high flexible output power over high capacity factors), as is currently incentivized by the German flexibility bonus system under the renewable energy law [19].[22]

Short-term flexibility and provision of reserves from stand still can also be obtained from gas fired CCGT power plants. The gas turbine part, which typically makes up 2/3 of output power in a modern unit, can be ramped up from cold to full power in a matter of minutes (< 5 minutes for small aero-derivative units, 10-15 minutes for larger heavy duty turbines). In a typical CCGT installation, the steam turbine attached to the gas turbine exhaust is the flexibility bottleneck, limiting startup times and ramp rates, especially in CCGT CHP units optimized for baseload operation. This issue can be addressed by the following options:

- Installation of optimized steam turbines for flexible operation in new units;
- Installation of bypass stacks between gas and steam cycle of CCGT units, allowing the gas turbines to ramp up quickly and the steam turbine to follow later (albeit at a temporary loss of efficiency during the ramping operation).

Other, non-conventional flexibility options may also be feasible, such as peak shaving storage for rooftop PV systems, or demand side management by large cooling houses.

4.2 REVISION OF RESERVE MARKET

With daily auctions and hourly products, the Czech FCR, aFRR and mFRR markets are set up well to enable participation by a wide variety of generators and technologies. However, the fact that aFRR is a symmetric product may be a major obstacle for large scale renewable integration, especially if the focus is more on wind and solar than biomass. This market should thus undergo a restructuring towards non-symmetric producers.

4.3 REACTIVE POWER

Reactive power is needed for voltage control, with reactive power demand coming from the reactance of the grid itself (capacitive behavior at low and inductive behavior at low loading) and the reactive power demand of loads. Reactive power in the transmission

---

[21] Example from Germany: http://www.decentralized-energy.com/articles/2016/11/kiel-cogeneration-plant-a-flagship-of-energiewende.html

[22] English document describing the incentive:
https://www.mwm.net/files/upload/mwm/issuu/referenz_flexpraemie_ahe_EN.pdf
German: https://www.next-kraftwerke.de/wissen/direktvermarktung/flexibilitatspraemie

system is currently almost entirely provided by the synchronous generators of large conventional power plants.

Smaller, distributed CHP units, which provide a large share of generation in 2030, are mostly connected to the distribution grid. This enables them to effectively control voltage and compensate reactive power demand close to the loads. On the one hand, this can potentially reduce the reactive power demand of distribution grid feeders, on the other hand, the necessity for voltage control and the change in characteristic of the vertical grid load due to increased generation in the distribution system may also lead to an increased reactive power demand in some cases.

Either way, sufficient reactive power capacities have to be present in the transmission grid for voltage control. Under the scenario of this study, there are generally enough large units left to provide reactive power and voltage control in the grid, but depending on the local load characteristic, reactive power shortages and thus voltage issues could appear at some points in the grid. These can be addressed by the installation of switchable reactive compensators (some are already installed in the Prague area for example) or FACTS.[23]

Another option that should be up for discussion is the use of the generators of decommissioned conventional power plants as synchronous condensers. The machines can with some retrofits be run as motors with no load (consuming a small amount of active power from the grid) and provide reactive power to the grid, adjustable by the excitation current. [20] This allows the use of the generator for reactive power, while boilers and turbines can be decommissioned, and no primary fuel is used. In comparison to new FACTs installations or even newly constructed synchronous condensers, such units provide a great degree of flexibility in reactive power provision at a rather low cost, and contribute to system inertia as well. A model case for this has been the reconstruction of the large 1200 MW A Unit generator at the decommissioned German nuclear power plant Biblis to provide reactive power as synchronous condensers.[24]

---

[23] Flexible AC Transmission Systems, reactive compensators and power flow controllers based on power electronics. More capable than traditional switched compensators, but currently also more expensive.

[24] https://www.energy.siemens.com/co/pool/hq/automation/automation-control-pg/sppa-e3000/Electrical_Solutions/BiblisA_RWE-Power-AG_electrical-solutions_generator_synchronous-condenser_sppa-e3000.pdf

4.4 FURTHER STUDIES

The following studies are recommended with a similar methodology:

- Analysis of the same scenario at different scenarios for the surrounding countries to determine the impact of cross border trades on Czech renewable curtailment and necessary flexibility;
- Sensitivity analysis with different CO_2 and natural gas prices;
- A scenario completely without coal fired generation;
- A scenario with higher shares of variable renewable energy and less biomass in the Czech system.

Moreover, more detailed research on reactive power flows and reserve capacities / capabilities of Czech power plants should be conducted at some point in the future.

5. SOURCES

[1] Energy Regulatory Office, “Yearly Report on the Operation of the Czech Electricity Grid 2014,” Prague, CZ, 2015.

[2] German TSOs, “Netzentwicklungsplan Strom 2025. Zweiter Entwurf der Übertragungsnetzbetreiber.,” *50Hertz Transm. GmbH (50 Hertz); Amprion GmbH (Amprion); TenneT TSO GmbH (TenneT); TransnetBW GmbH*, 2015.

[3] R. Haas *et al.*, “Stromzukunft Österreich 2030,” Wien, Austria, 2017.

[4] Forum Energii, “Polski sektor energetyczny 2050 - 4 scenariusze.”

[5] T. Brown, P. Schierhorn, E. Tr, T. Ackermann, and E. Gmbh, “Optimising the European Transmission System for 77 % Renewables by 2030,” *13th Wind Integr. Work.*, 2014.

[6] C. Kost, J. N. Mayer, and S. Philipps, “Stromgestehungskosten Erneuerbare Energien Version November 2013,” Freiburg, 2013.

[7] S. Wissel, S. Rath-Nagel, M. Blesl, U. Fahl, and A. Voß, “Stromerzeugungskosten im Vergleich,” Stuttgart, Germany, 2008.

[8] P. Schierhorn, T. Brown, and E. Tröster, “Cycling Requirements for Conventional Power Plants at High Shares of Renewable Energy,” *13th Wind Integr. Work.*, 2014.

[9] C. Rehtanz *et al.*, “Sicherheit und Zuverlässigkeit einer Stromversorgung mit hohem Anteil erneuerbarer Energien,” *dena-Studie Syst. 2030*, p. 310, 2014.

[10] ENTSO-E, “Current practices in Europe on Emergency and Restoration,” no. May, p. 22, 2014.

[11] T. Vlček and F. Černoch, *The Energy Sector and Energy Policy of the Czech Republic*. Brno, Czech Republic: Masaryk University, 2013.

[12] D.-C. Radu, “Strategies for Provision of Secondary Reserve Capacity to Balance Short-Term Fluctuations of Variable Renewable Energy,” Darmstadt, Germany / Stockholm, Sweden, 2017.

[13] D.-C. Radu, P.-P. Schierhorn, and N. Martensen, “Sizing Secondary Reserve Capacity in Grids with Increasing Shares of Variable Renewable Energy,” *Proc. - 2017 Wind Integr. Work. Berlin*, 2017.

[14] U. Keymer and K. Ikenmeyer, “Direktvermarktung und Bereitstellung von Regelleistung,” Freising-Weihenstephan, Germany, 2013.

[15] Eirgrid Plc, “DS3 System Services : Portfolio Capability Analysis,” Dublin, Ireland, 2014.

[16] Eirgrid Plc, “Operational Constraints Update 11/08/2017,” Dublin, 2017.

[17] I. de la Fuente, “Ancillary Services in Spain : dealing with High Penetration of renewable Energy,” Madrid, Spain, 2010.

[18] Nuclear Energy Agency, “Technical and Economic Aspects of Load Following with Nuclear Power Plants,” Paris, France, 2011.

[19] Bundesministeriums der Justiz und für Verbraucherschutz, “Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz-EEG 2017),” *Bundesministerium der Justiz und für Verbraucherschutz*, pp. 1–70, 2014.

[20] A. Deecke and R. Kawecki, “Usage of existing power plants as synchronous condenser,” no. 10, pp. 64–66, 2015.

ANNEX

Table 14: Lignite units in CZ to be phased out under the 2030 scenario.

Unit	Output in MWe
Installed capacity in 2017	**8707**
Počerady	1000
Ledvice II	220
Ledvice III	110
Mělník II	220
Mělník III	500
Prunéřov I	440
Prunéřov II	750
Tisová II	105
Tušimice II	800
Chvaletice	800
Ledvice IV	660
Vřesová	400
Opatovice (3 blocs with condensing turbines)	180
Overall phased out	**6185**
Remaining	**2556**

Table 15: Hard coal units in CZ to be phased out under the 2030 scenario.

Unit	Output in MWe
Installed capacity in 2017	**1608**
Dětmarovice	800
Overall phased out	**800**
Remaining	**808**

ČESKÁ REPUBLIKA
POMÁHÁ

This study has been produced with the financial assistance of the European Union, the Czech Development Agency and Ministry of Foreign Affairs of the Czech Republic within the programme Czech Republic Development Cooperation. The contents of this report are the sole responsibility of the Beneficiaries and can under no circumstances be regarded as reflecting the position of the European Union.

glopolis
Frank Bold
CEE bankwatch network
ALIANCE PRO ENERGETICKOU SOBĚSTAČNOST
Hnutí DUHA
Friends of the Earth Czech Republic