# Seminar Paper

as part of the Winter and Summer School

***ASSESSING THE RELEVANCE AND COSTS OF STORAGE: A COMPARATIVE ANALYSIS OF CZECH REPUBLIC AND AUSTRIA***

supervised by
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# Abstract

This semester's work is the output of students participating in an international project of the Institute for European Environmental Policy. Energy storage solutions are significant for managing renewable energy variability in the energy transition. Europe aims to become climate neutral by 2050 entailing 100% renewable electricity generation, leading to the need for energy storage to bridge flexibility gaps. The work deals with the definition of terms for energy storage, both short-term and long-term and their classification and field of application. Further, the specific acquisition and operation costs of different energy storage solutions are documented. The main aim of this seminar work is to quantify the relevance of energy storage in the energy systems of Austria and Czech Republic. The storage capacity needed for a system to successfully integrate existing and future renewable electricity production is determined for the years 2021 and 2030. The last part of the semester's work uses the collected data to compare the states' readiness for the transition from fossil fuels to renewable energy sources. The results show that both countries will have sufficient storage capacity in the energy system in 2021. Regarding 2030, the analysis shows that the Austrian grid offers readiness for flexibility demands, by providing approximately four times more energy storage capacity than needed, even for worst-case scenarios. In contrast, the energy system of Czech Republic could face challenges by being under-dimensioned especially for worst-case scenarios. Considering the goal of achieving 100% intermittent renewable energy production by 2030, the Austrian energy system remains readiness, while the Czech republican energy system is under-dimensioned. This work provides insight into the importance of energy storage solutions in the energy transition of Austria and Czech Republic.

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# 1 Introduction

Recently the electricity system is undergoing a structural change driven by policy implementations. In 2019 the European Commission proposed the Green Deal determining a climate-neutral target by 2050 for all European countries (European Parliament & Council, 2021). These changes are driven by three significant developments: decarbonization, decentralization, and digitalization. One central goal is the decarbonization of the energy system by increasing the use of renewable energy sources (RES) such as wind, solar, and hydro. Decentralization refers to the shift from central towards distributed electricity generation with increasing numbers of prosumers instead of consumers. The third key driver is digitization resulting in the emergence of smart grids and flexibility within the system. (Ajanovic et. Al, 2020) states that electricity storages play a crucial role in the energy transition.

**Increasing Generation from RES**

Renewable electricity generation from sources such as solar, wind, and hydropower has risen significantly since 2010. Figure 1 shows the development of renewable electricity generation in the European Union from 1965 to 2022 (Energy Institute, 2023). In total, the electricity generation from renewable energies rose from 214.72 TWh in 1965 to 1,078.58 TWh in 2022 (Energy Institute, 2023). Hydropower has always played a very large part in electricity generation. The share of wind, solar, and other renewable energies has increased tremendously since the year 2000. As renewable energies in the electricity system increase, so does the volatility of electricity generation. This results in the need for large amounts of flexibility.

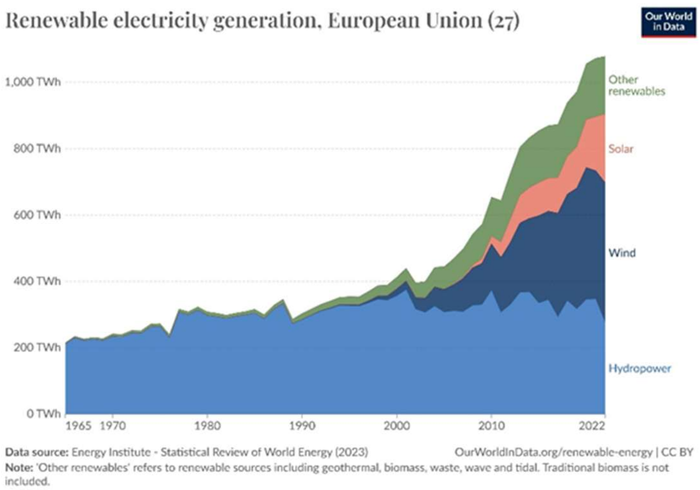


*Figure 1 Renewable electricity generation in the European union from 1965 to2022 (Energy Institute, 2023)*

## Balance of energy supply and demand

Electricity supply and demand must be in a constant balance to ensure the stability of frequency in the power grid. In the past, the power system was easier to control mainly due to the possibility of quick supply-side regulation. Due to the increased use of volatile renewable energies in electricity generation, the adaption of electricity supply and demand is challenging. (Sterner & Stadler,2017) state that energy storage is essential for the energy supply and the energy system as they can store electricity over various timescales from seconds, minutes, days, weeks, and months while balancing the supply and demand of electricity.

Different technologies can be employed to meet these requirements and, historically, pumped storage power plants have addressed short-term flexibility needs. However, with the adoption of new technologies, such as batteries, which now play a significant role due to their rapid power delivery capability, things are quickly changing. Batteries and EVs will sustainably contribute to meeting the flexibility demand (European Commission,2022), with the contribution of batteries and EVs increasing by 7% and 9% from 2030 to 2050. In contrast, pumped storage power plants are expected to lose significance due to their large capex costs (European Commission,2022). Long-term storage can balance the variability of electricity generation from RES over long periods (Ajanovic et. Al, 2020).

## The role of storage systems

Storage systems allow for selectively storing energy in specific time units and over a certain period which enables the balance of the supply and demand of energy supply over time and reduces the load on the power grid. With private users, use cases can vary from self-consumption and optimization, backup power supply, or even market-oriented applications using the spot market to trade, provision of frequency regulation capacities, balancing group management and grid-support for voltage regulation, dispatch, and black-start capability.

In the low voltage grid, PV systems and home storage are increasingly integrated into private households, as they allow homeowners to generate, consume, and store electricity from solar energy. This reduces the dependency of households on the current political situation, energy prices, and energy supply companies. The main aim for households is to optimize self-consumption and use electricity in times of low PV generation. Batteries offer a large potential for small-scale flexibilities, especially for demand-side management. In 2020, the PV and battery storage combination had a flexibility potential of 0.7 TWh. This value will increase to 30 TWh by 2030 highlighting the relevance of storages (Vogel, 2022).

## 1.1 Background and Motivation of the Research

Energy storage solutions are playing an increasingly important role in the energy transition, especially in overcoming challenges posed by the variability of renewable energies. The European climate neutrality target entails 100% electricity generation from renewable energies. The energy system lacks in RES integration readiness, marked by significant flexibility gaps that necessitate the deployment of energy storage systems.

Based on this background, this seminar work aims to assess the relevance of energy storage solutions in Austria and the Czech Republic. Central to this approach is the quantification of the relevance of storage, which will be done by determining the storage capacity needed for a system to successfully integrate existing and future renewable electricity production. Storage solutions increase flexibility and thereby the readiness of the grid for renewables penetration.

With this analysis, the seminar work aims to highlight the importance of energy storage solutions in the energy transition.

## 1.2 Objectives and Research Questions

The main objective of this seminar paper is to assess the relevance and costs of storage by comparing the Czech Republic and Austria. This paper aims to answer the following research questions (RQs):

- RQ1: Why are short- and long-term storages relevant in the EU, Czech Republic, and Austria?
- RQ2: What are the specific investment costs of short- and long-term energy storage?

The next paragraph on the method of approach explains the procedure for the assessment of the RQs.

## 1.3 Method of Approach

This work consists of qualitative and quantitative methodological approaches. The first step consists of data collection and literature review. Data including specific investment costs for short- and long-term storage is collected, and relevant literature is reviewed to provide a general overview and classification of storage systems.

The second step is quantifying the relevance of storage by calculating the amount of storage that would be needed to support the current and planned level of renewables penetration in the years 2021 and 2030 in the Austrian and Czech systems respectively. The needed amount of storage for a hypothetical 100% renewable system will also be calculated and subsequently compared with the actual and planned values for 2021 and 2030 for each country respectively.

Theoretical explanations regarding the relevance of storage in each system will be provided, based on findings from the literature review.

As a basis for our model to quantify the relevance of storage, we will use the web app "Energy Storage Ninja", https://energystorage.shinyapps.io/LCOSApp/, by Oliver Schmidt and Iain Staffel. It is based on the calculations done in their book (Schmidt & Staffell, 2023) and is already accepted as a valid and comprehensive model.

Degrees of readiness for 100% renewables penetration will be done by comparing the current situation with the theoretically needed 100% readiness amount of storage for each country.

As input parameters of the calculation, we need to provide power system data for the two countries, such as peak power demand, annual electricity demand and the respective system's share of intermittent renewable electricity supply. The output of the calculation would then be the needed storage- power and energy capacity needed to support each respective scenario.

System information input data for the web app will be obtained from entities such as APG, ENTSO-E, E-Control, ČEPS, and ERU, while storage data such as specific electricity storage technology investment cost data will be extracted from relevant literature, such as (Luo, Wang, Dooner, & Clarke, 2014) and (Schmidt & Staffell, 2023).

# 2 State of the Art

In this chapter, the term energy storage is defined and classified. Furthermore, the areas of application of storage systems are explained and the costs of the different types of storage systems are analyzed. This chapter provides insights into the regulatory framework for storage, as well as the current flexibility landscape and research.

## 2.1 Definition and Classification

(Sterner & Stadler,2017) describe a "storage unit" as a device that stockpiles, stores, and preserves goods or energy sources. The term "energy storage" is used for devices that store different types of energy forms such as internal, potential, or kinetic energy. The storing process consists of three steps in one cycle: charging, storing, and discharging, whereby energy converters charge and discharge (see Figure 2). Within the "storage unit" there is an energy source, that is able to store the energy.

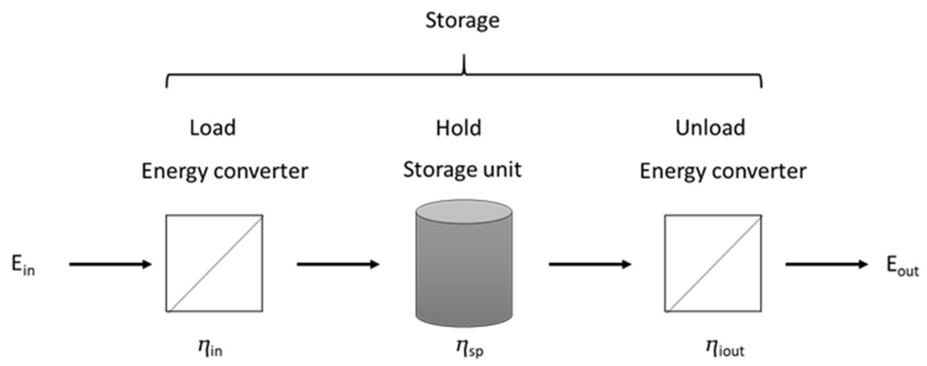


*Figure 2 The storing process consisting of loading, holding, and unloading (own illustration based on (Sterner & Stadler,2017)*

Short-term storages such as batteries contain all three process steps in one device. Power electronics convert energy (charging and discharging), so the energy is chemically stored in battery packs (storage units). In contrast, long-term storage such as pumped-storage power plants has separate devices for the different steps. In the first step, a motorized pump pumps water into the upper basin. The upper and lower basins represent the storage unit. Next to the pump, turbines, and generator are energy converters that convert water energy into electricity. Further definitions differ in primary and secondary, and sectoral and sector-coupling energy storages. Sectoral energy storages such as electricity storage, heat storage, and gas storage are used in one sector, whereas sector-coupling energy storages connect different storages. Examples are power to heat (heat pumps), power to gas (electricity storage), electromobility, etc.

Energy storage can be classified into four different categories such as: 1. mechanical, 2. electrochemical, 3. chemical, and 4. electrical. Their main difference lies in physical, energetic, temporal, spatial, and economic criteria. Important physical parameters are the storage capacity, energy density, storage and retrieval capacity, efficiency, and retrieval times.

Other than that, storages can be classified by their storage duration as short- and long-term storages. Short-term storages store energy from a nanosecond up to one day, whereas long-term storages can storage energy up to multiple years.
Table 1 provides an overview of short- and long-term storage types and examples. In general, the main use of energy storage is to provide a temporal balance of energy supply and demand. Based on their main characteristics (high cycle number and high cycle efficiency) short-term storages are mainly used to compensate for short-term fluctuations in the electricity grid. Long-term storage can compensate for seasonal fluctuations such as long-lasting wind lulls, low water volumes in the hydropower plant, or longer periods of darkness. The reason for that is,

*Table 1 Applications of energy storage (based on Sterner & Stadler, 2017)*

| | Storage | |
|---|---|---|
| | Short-term storage | Long-term storage |
| Type by duration | Second storage: Flywheels, superconduction electromagnetic energy storage, double-layer capacitors and batteries | Weekly storage: pumped storage, cavern and pore storage, sensitive heat storage |
| | Minute storage: Batteries, sensitive heat storage | Monthly storage: storage water, cavern and pore storage, sensitive heat storage |
| | Hour storage: batteries, pumped storage, compressed air storage, sensitive heat storage | Seasonal storage: storage water, cavern, and pore storage, sensitive heat storage |
| | Day storage; batteries, pumped storage,<br>compressed air storage, sensitive heat storage | |
| Character-istics | High cycle number, high cycle efficiency | High storage capacity, low in losses, cycle numbers and cycle efficiency |

Figure 3 shows different storage technologies and their power and energy ranges. Their amount of power and capacity gives insight into their storage duration. Short-term storages from 1 sec to 1 day are double-layer capacitors, superconduction coils, flywheels, batteries, pumped hydro, and compressed air. They rather have high power and small capacity. In contrast to that, long-term storage systems with a storage duration from 1 day to 1 year have high energy capacities.

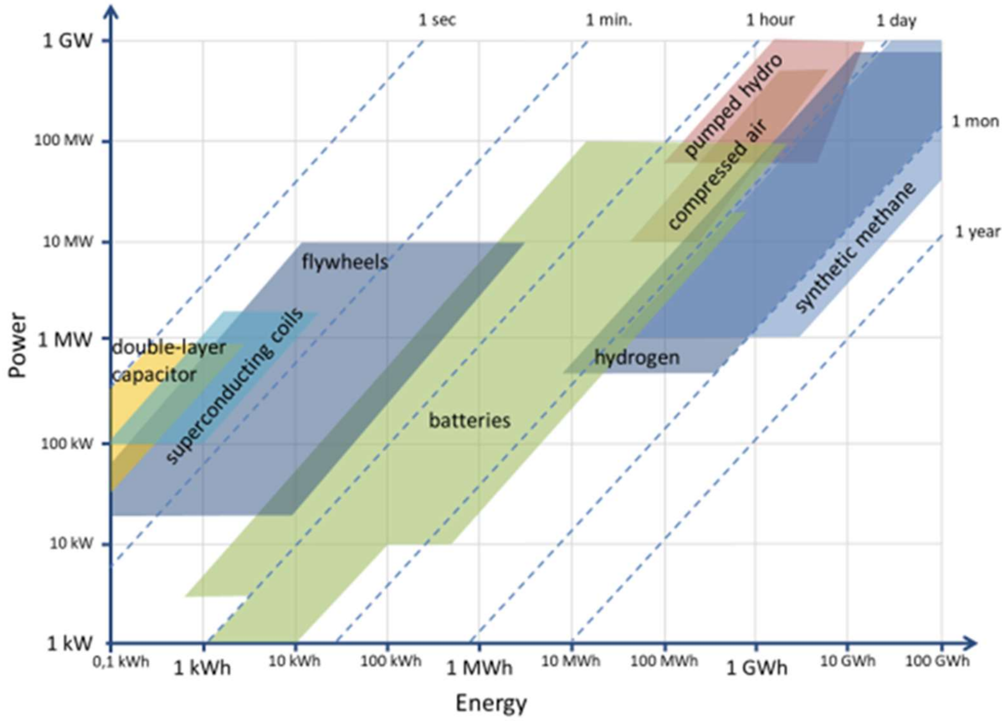


*Figure 3 Power and Energy of different storage types (EnTEC,2023)*

## 2.2 Field of Application

Energy storage solutions can be used for various applications within the power industry. Table 2 shows six energy services.

*Table 2 Applications of energy storages*

| |
|---|
| Services for generation support and bulk storage |
| Services for transmission infrastructure support |
| Services for distribution infrastructure support |
| Ancillary services |
| Services for behind the meter customer energy management support |

(EASE, 2022)

Generation support services bulk storage services support the operation and reliability of power generation facilities requiring a minimum technical standard to store energy from minutes to multiple hours. For example, Energy suppliers, and TSOs use PHS, PHES, CAES and LAES for these services.

Other services of energy storage are the support of transmission infrastructure and distribution infrastructure. Storages to support the transmission system need the requirement to quickly ramp up within milliseconds or minutes, whereas storages used for the support of the distribution system need to fulfill the requirement to store energy for one or more hours.

Ancillary services include operations to maintain operations to stabilize the grid frequency, thereby providing a balance between electricity supply and demand. Storage used for this application does not have specific requirements to fulfill.

Besides that, energy storage can be used for services behind the meter (see Figure 4). First households owning PV systems can use storage systems to store surplus energy from the PV-system. With energy storage, prosumers can optimize their self-consumption. Additionally, energy storage in combination with an energy management system (EMS) can be used for load shifting, peak demand reduction, and in some countries grid services.

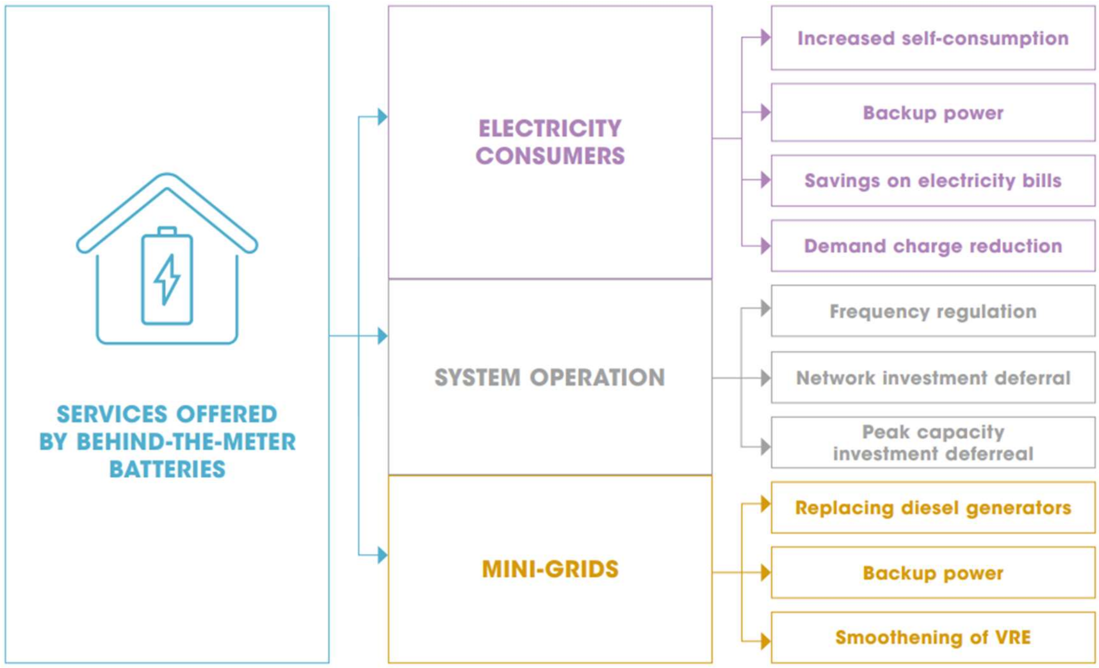


*Figure 4 Energy storage services behind-the-meter (IRENA,2019)*

## 2.3 Investment costs of energy storage solutions

operation costs (OPEX). Both are key performance indicators (KPIs) that describe the cost structure of storage and enable comparison among different storage types. CAPEX is stated as €/kW or as €/kWh and includes the investment costs for the technology. The OPEX is stated in terms of power €/kW or terms of capacity €/kWh or as a percentage of CAPEX. These costs consist of operation and maintenance e.g., for exchanging components and fuels or labour costs. The amount of OPEX depends on the storage solutions and ranges from 0.5 to 2.5 % of the CAPEX (see Tables 3 and 4).

(EnTEC, 2023) provides detailed data base different storage technologies and KPIs. The table shows selected technologies for short- and long-term storage from the data set of (EnTEC, 2023).

Only technologies that are expected to be significant, i.e. adopted on a TWh-scale, up to 2050 are included. The focus is on electricity storage; thermal storage is not regarded. Very short-term storage (e.g. flywheels) is not included as this time scale is not modeled in METIS. For home storage systems and electromobility, the potential can be used to mandatory include these technologies in the model. Short-term is defined as the duration of hours to a few days, medium-term as a few days to a week, and long-term as a few weeks to months. CAPEX, OPEX, efficiency, and lifetime are defined in Section 2.1.1. The loss rate is given in % loss per day or per month, depending on the technology. The potential is defined as the economic potential for each technology. More detailed data can be found in the Excel documentation delivered with this report.

*Table 3 Costs and KPIs of short-term storage*

| Short-term Storage | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CAPEX [€/kW] | CAPEX [€/kWh] | OPEX [% of CAPEX] | round trip efficiency [%] | Loss rate [%] | Lifetime [a] | Lifetime [cycle] | Potential up to 2050 [TWh] |
| large scale (LIB) | 1350 | 345 | 0.5-1 | 88-95 | 1% p.m | 15 | 3000 | min: 1.9 TWh max: 5.3 TWh |
| large scale (Lead-acid batteries) | 1000 | 400 | 1-2.5 | 85 | 0.1-0.4% p.d. | 10 | 15000 | 10-100 GWh |
| large scale (Redox-flow batteries) | 1500 | 400 | 1 | 70 | 0.4% p.a. | 20 | 7000 | will be a share of the ESS LIB market |
| large scale (Sodium- | 595 | 675 | 1.5 | 85 | 0.34% p.a | 15 | 4500 | will be a share of the |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| based batteries) | | | | | | | | ESS LIB market |
| PV-home storage systems (LIB) | 1200 | 1000 | 1-2 | 88 | 1% p.m. | 15 | 3000 | included in short-term storage LIB potential |
| Electromobility (LIB) | 75 pack cost | 160 pack cost | 2 | 90 | 1% p.m. | 8-15 | 3000 | min: 27.3 TWh max: 39.7 TWh |

*Table 4 Costs and KPIs of long-term storage*

| Long-term Storage | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | CAPEX [€/kW] | CAPEX [€/kWh] | OPEX [% of CAPEX] | round trip efficiency [%] | Loss rate [%] | Lifetime [a] | Lifetime [cycle] | Potential up to 2050 [TWh] |
| large scale (hydrogen) | 2979 | 10 | 30 €/MWh | 30 | Negligible | 25^5 | n.a. | 130 TWh |
| large scale (Lead-acid batteries) | 1000 | 400 | 1-2.5 | 85 | 0.1-0.4% p.d. | 10 | 1500 | 10-100 GWh |
| (Sodium-based batteries) | 595 | 675 | 1.5 | 85 | 0.34% p.a | 15 | 4500 | will be a share of the ESS LIB market |

The EnTEC Study on Energy Storage provides a figure (see Figure 5) showing the capital cost of power and energy for different technologies and providing insight into the competitiveness in short- and long-term applications (EnTEC, 2023).

Technologies with high cost per unit of energy and low cost per unit of cost are in the zone, where they are more likely to be competitive in application for short durations. Those technologies are lead Acid Batteries, flow batteries, and sodium batteries. In contrast to that are technologies that have low cost per unit of energy and high cost per unit per power. These technologies such as Pumped Hydro, Compressed Air Energy Storage, Pumped Thermal Energy Storage, and Compressed Hydrogen Storage are more likely competitive for long-term applications. Lithium-ion batteries are a special case, as they can be used for both short- and long-term applications (EnTEC, 2023).

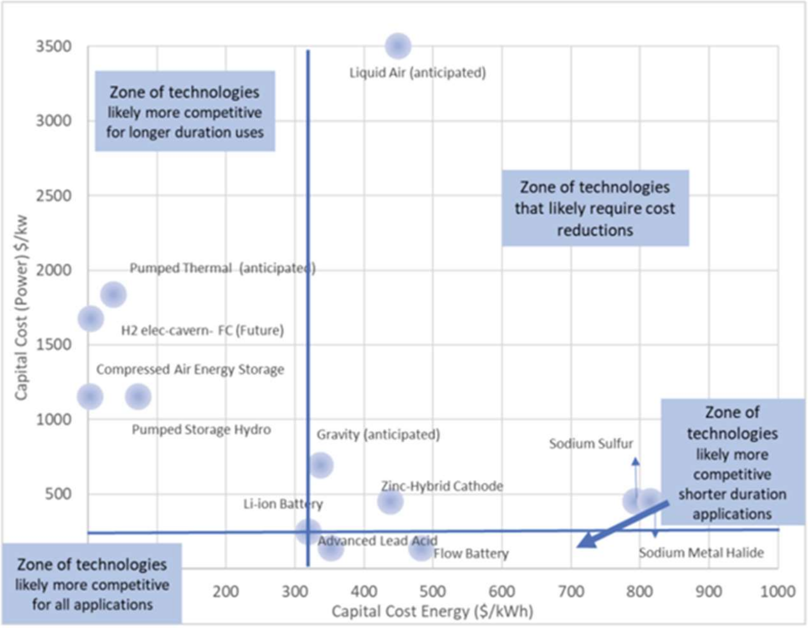


*Figure 5 The capital cost of power and energy for different technologies (EnTEC, 2023)*

## Calculation of costs of electricity storage

The costs of energy storages, especially electricity storages can be calculated by the following formula:

$$C_{sto} = \frac{I_{sto} \cdot \alpha}{T \cdot \eta_{sto}} + C_{O\&M} + \frac{P_{ele}}{\eta_{sto}} \qquad \text{[EUR/kWh]}$$

| | |
|---|---|
| $C_{sto}$ | Total storage costs per kWh of electricity [EUR/kWh] |
| $C_{O\&M}$ | Operation & maintenance costs [EUR/kWh] |
| $I_{sto}$ | Total investment costs [EUR/kW) |
| $T$ | Full-load hours [h/a] |
| $\alpha$ | Capital recovery factor [1/a] |
| $\eta_{sto}$ | Efficiency of storage [%] |
| $P_{ele}$ | Price of electricity [EUR/kWh] |

The calculation of the electricity storage costs includes investment and operation and maintenance costs and the cost of electricity. The formula includes parameters such as full load hours, storage efficiency, and price of electricity. Electricity storage costs are an important parameter, especially when deciding on investments and comparing different storage types to each other. (Ajanovic et al., 2020) calculated the average costs of different energy storages, as seen in Figure 6.

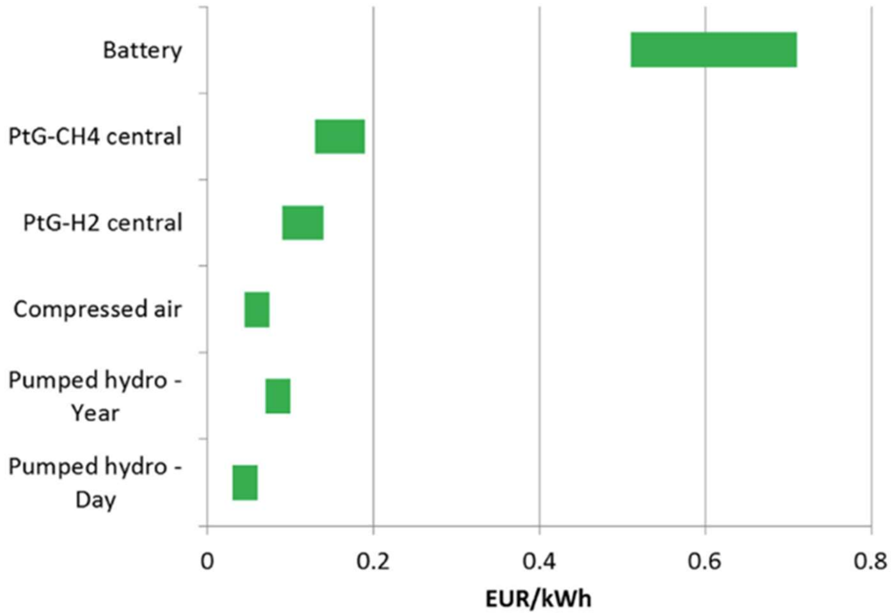


*Figure 6 Average costs of different energy storages (Ajanovic et al., 2020)*

**Development of costs in the future**

The future development of investment costs of different storage types shows a reduction in the upcoming decades (see Figure 7). The reason for investment reduction costs is due to technological learning (Hiesl, 2022). Investment costs of electrolyzers and methane plants will decrease by about 30% and of batteries by more than 50%. Batteries are expected to be applied in larger quantities leading to a higher decrease in investment costs.

An exception is pumped hydro as the investment cost will increase by 2040. This is mainly due to the no further TL for pumped hydro exists and there is a lack of affordable locations and a growing absence of approval (Hiesl, 2022).

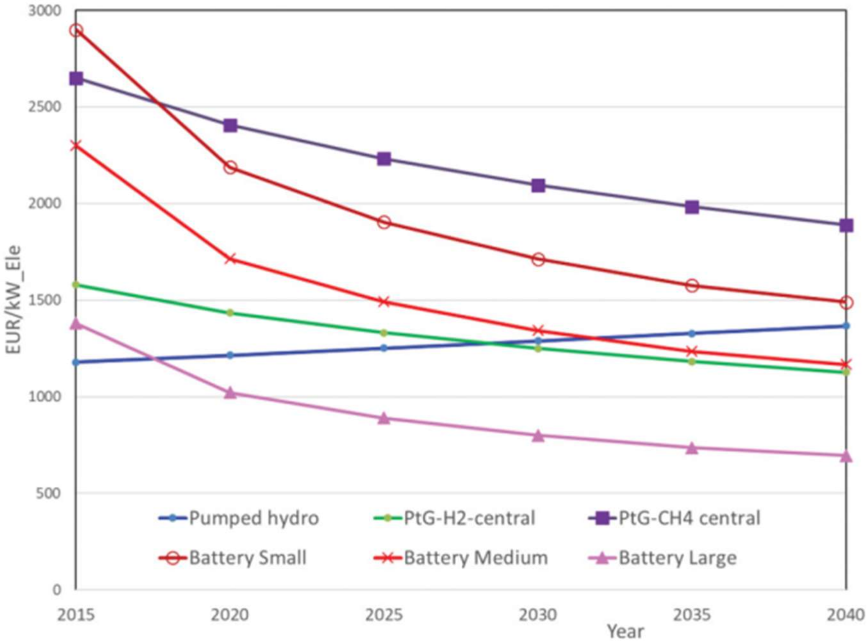


*Figure 7 The development of investment cost of different storage types (Short- and Long-term storage) (Hiesl, 2022)*

## 2.4 Regulatory Framework: Austria, Czech Republic, and the EU

One of the integral parts that, in addition to technological progress in the field of energy and its storage, the amount of costs of current energy storage technology, which is often very expensive, rather than not using energy, is regulated not only by the states but also by the EU. This part of the work will deal with regulations on the part of Austria, the Czech Republic, and the EU.

**The current situation of the legislation**

Legislation on the part of Austria and the Czech Republic is in different stages of preparation for a possible 100% RES. In the case of Austria, the legislative preparation for energy storage is at a higher level. It contains regulations regarding lithium and lead or nickel-cadmium batteries for energy storage. The legislation also regulates battery liability rights, placing the safe operation of batteries on the side of the battery installation company, not the manufacturer. The amendment of the legislation also applies to the transport of batteries, which is heavily regulated and must be marked as highly flammable.

The Czech Republic only approved the law on energy storage on 20. March 2024, the main purpose of which is to enable the storage of energy from the public grid, for example for balancing the grid. This law currently contains very little regulation. Regulations for energy aggregation will only be introduced in the amendment to the law "LEX OZE III". Energy storage in the form of batteries has not yet been possible according to legislation. (Czech Ministry of Industry and Trade, 2024)

Both countries have been operating in the field of pumped hydro for decades. While the legislation in Austria is set so that this type of reservoir behaves as a reserve (aFRR/mFRR) just like a battery, Hydro pumped generators in the Czech Republic are licensed in the energy sector as energy production and consumption on a similar principle to fossil power plants.

Regulations are also connected to EU law, which regulates the safety regulations of battery placement, and recyclizing battery waste. EU law was updated in February with restrictions connected to accounting for energy used in battery storage. EU law more likely gives recommendations to the law of EU states to regulate storage on their own. (Czech Ministry of Industry and Trade, 2024)

EU also enables storage of energy for primary customers, which is used much more for the households in form of batteries in combination with PVs via electricity or also by heated water collected with solar collector and stored in thermally isolated tanks. Both options are forbidden to be connected to the shared grid. Further information is described in Table 5 and 6.

*Table 5 Austria and Czech Policy Description*

| Austria – Policy description |
|---|
| Small-scale photovoltaic and storage system program |
| Increase the share of efficient renewable energy sources and district heating/cooling for heating, hot water, and cooling, including component activation, active use of hot water storage tanks and buildings as reservoirs for load balancing and load flexibility Investments in storage facilities, including heat storage facilities, rewarding storage facilities for system capacity |
| Storage (including hydrogen technologies) is currently addressed as a high-priority cross-cutting issue with cross-references to the mission-oriented priorities and the broad implementation initiatives |
| Increase of pumped storage capacity in Kaunertal |
| The countries of the Pentalateral Energy Forum address the impact of the implementation of flexibility options, including the role of demand response, PTX, and hydrogen as well as the role of storage and electro-mobility, and analyze specific electricity-related barriers to sector coupling * In addition to storage and pumped storage, a particular role is played by high-efficiency combined heat and power (CHP) plants, which are necessary to maintain the supply of electricity (for balancing purpose) and heat, particularly in agglomerations. |
| Activation of components, the active use of hot water storage tanks, and the use of buildings as reservoirs for load balancing and load flexibility increase or adapt investments in storage infrastructure (from short-term storage to seasonal storage) and transmission and distribution networks to increased demand |
| Digital and smart energy: Ensuring system integration of new energy storage and energy supply system flexibility technologies as basic enablers for a high proportion of renewable energy, coupled with security and resilience |

*Table 6 Austria and Czech Policy Description*

| **Czech Republic – Policy description** |
|---|
| System prepared for use of vehicle batteries as grid stabilizer and hydro pump storage |
| Support increase for companies and households to reduce energy consumption (warming, subsidies for water heating, solar panels, and batteries for households) |
| Battery storage increases to balance the power grid and increase electricity production by increasing the share of nuclear power plants as a substitute for fossil power plants. |
| Enlarging of Nuclear powerplant Dukovany (Josek, 2023) |
| The government plans to increase the flexibility of the system by using up to hundreds of thousands of energy storage sources across the country using LEX OZE II, there is also better protection of consumers and modification of the licenses of traders trading in the field of energy storage to increase the share of energy aggregation. (Ministry of Industry and Trade, 2024) |
| The main goal is also to digitize the infrastructure, so from July 1, 2024, all newly installed electricity meters enabling the use of RES must include remote access. (ENERGIEZAMENE, 2024) |

## 2.5 Current Flexibility Landscape

The status of the current flexibility of energy storage in Austria and the Czech Republic shows the gradual transformation of the network to the use of a greater degree of RES and strategic development in the field of energy storage. Both the Czech Republic and Austria are trying to achieve the goals of the European Union initiative called Fit for 55, which is also trying to achieve carbon neutrality thanks to such projects.

**Current storage capacities of the Czech Republic and Austria**
Pumped storage power plants have been used in Austria and the Czech Republic for several generations. In both countries, they play a major role in the stability of energy networks. While 3 pumped-storage power plants with a total capacity of 1.175 GW are in operation in the Czech Republic, there are 18 power plants of this type with a capacity of 4.645 GW in Austria. Detailed data on individual pumped storage power

plants can be found in Table 7&8, where pumped storage power plants are divided according to capacity. (OpenInfraMap, 2024)

The importance of these power plants lies mainly in equalizing the stability of the network and storing energy when it is currently available on the exchange at a low price and subsequently generating energy back when it is, on the contrary, at a higher price on the exchange.

In the data, it can also be observed that energy storage is almost fourfold in Austria. The main cause of this phenomenon is the previously prepared legislation regarding energy storage and better geographical conditions for the construction of such projects.

*Table 7 Hydro pump storages in Austria and Czech Republic. (OpenInfraMap, 2024)*

| *Hydro pumped storages in Austria* | |
|---|---|
| **Name of facility** | **Capacity of storage** |
| Malta Hauptstufe | 730 MW |
| Kopswerk II | 525 MW |
| Kavernenkrafthaus Limberg II | 480 MW |
| Reißeck II | 430 MW |
| Kraftwerk Häusling | 360 MW |
| Obervermuntwerk 2 | 360 MW |
| Rodundwerk II | 295 MW |
| Kraftwerk Kühtai | 289 MW |
| Lünerseewerk | 232 MW |
| Kraftwerk Roßhag | 231 MW |
| Rodundwerk I | 198 MW |
| Kraftwerk Innerfragant | 178 MW |
| Malta Oberstufe | 120 MW |
| Kraftwerk Kaprun Oberstufe Limberg (1) | 113 MW |
| Wasserkraftwerk Hintermuhr | 104 MW |
| Obervermuntwerk 1 | 29.00 MW |
| Rellswerk | 10.00 MW |
| Rifawerk | 7.00 MW |
| **TOTAL** | **4,645 GW** |

*Table 8 Hydro pump storages in Austria and Czech Republic. (OpenInfraMap, 2024)*

| *Hydro pumped storages in Czech Republic* | |
|---|---|
| **Name of facility** | **Capacity of storage** |
| Dlouhé stráně | 650 MW |
| Delašice | 480 MW |
| Štechivuce II | 45 MW |
| **TOTAL** | **1,175 GW** |

In Austria and the Czech Republic, there is only one battery energy storage facility in each country, historically due to insufficient legislative readiness. Battery storage is much more flexible in supplying/removing energy compared to pumped storage plants. At the same time, such devices allow placement almost anywhere in the countries. The disadvantages of these devices are relatively high acquisition costs and a shorter life than pumped storage plants. In Austria, a battery storage facility in Ardnoldstein has been in operation since September 2023. This storage has a capacity of 20.6 MWh and manages to return energy to the grid at a rate of 10.3 MW. (Murray, 2023) The Czech Republic launched its first battery storage in February 2024 with a total capacity of 2.8 MWh, but ČEZ (the manager of the Czech energy grid) has plans to build another 300 MW of battery storage by 2030. (ČTK, 2023)

## 2.6 Research on Flexibility/Storage?

Running 100 % RES means having a more versatile power grid, and one way of transforming today's grid into one will be to have energy storage around the system. This part explains what the short vs long-term storages are and how they can help with grid stability. The method used to have 100% RES will be covered in 3. Paragraph.

#### Short-term energy storages

Short-term storage is called once with a fast time of charging/discharging. Mostly used are battery systems. The energy grid is unstable and can change on a minute basis, that's why are this kind of storage important to handle small fluctuations, which will be even higher with weather conditions that influence the power generation via PV or Wind generators.
Another point on how to look at this topic is that energy consumption is going to be higher due to higher energy usage caused not only by EVs. (Schoenung, 2001) In both countries are theese kind of storages used only to keep the stable electricity supply – they are always being charged or discharged. (Schoenung, 2001)

#### Long-term energy storage

Storages that will be able to save energy for longer period could be divided into several parts starting with:
Balancing seasonal fluctuations - One of the main reasons for compensating long-term fluctuations is the impossibility of simply producing energy during the winter months, so it is necessary to store energy in a long-term source that will be able to be pumped just during the winter months. Long-term storages are mostly used in both countries to balance the grid as form of hydro pump storages for moments of cheaper electricity – mostly night (Table 6 and 7).
The second reason is global threats - With a larger capacity energy supply, it is possible to get by for several weeks even without energy supplies caused by, for example, sabotage of renewable sources. (Schoenung, 2001)

# 3 Methodology

This chapter builds upon Chapter 1.3 “Method of Approach” and provides a comprehensive look at the actions taken in this paper.

## 3.1 Power System Data Collection for Austria and the Czech Republic

The quantification of the importance of storage in energy systems was done for the years 2021 and 2030. The year 2021 will be used as a “representative year” for each system. As for 2030, it was chosen primarily as it represents a milestone year for EU countries regarding the decarbonization of their energy supply. Those milestones are represented in the National Energy and Climate Plans (NECPs) of EU countries which were introduced by the Regulation on the Governance of the Energy Union and climate action (EU)2018/1999. This regulation was agreed upon as part of the “Clean Energy for all Europeans” package, which was adopted in 2019. The NECPs outline how the EU countries intend to address the 5 dimensions of the energy union: decarbonization, energy efficiency, energy security, internal energy market, and research, innovation, and competitiveness.
The main reason for why they were established was to reach the EU’s climate and energy targets for 2030, including the reduction of greenhouse gas emissions by 55% compared to 1990 and 60% of renewable electricity generation.

Data, such as peak demand, gross domestic electricity production and percentage of intermittent renewable electricity production, which were established as the basis of the Energy Storage Ninja (Schmidt & Staffell, 2023) calculation, were acquired from APG (Austrian Power Grid): https://www.apg.at, E-Control: https://www.e-control.at/, ENTSO-E: https://www.entsoe.eu/, ČEPS: https://www.ceps.cz/, and ERU: https://eru.gov.cz/.

## 3.2 Power System Data

For both countries, only the electricity storage power capacities were able to be determined from the data as no comprehensive data for energy storage energy capacity was able to be found.

The power grid data for the representative year (2021) were acquired from ČEPS (Czech TSO) and ERU (Czech energy regulatory agency) for the Czech Republic and APG (Austrian TSO) and E-Control (Austrian energy regulatory agency) and they will be our web app input data for the calculations.

As for 2030, both ČEPS and APG provided their development plants for the grid for this milestone year. Data selection decisions for the year 2030 will be clarified below.

In 2030, both ČEPS and APG outlined their grid development plans. We focus on electric energy storage parameters relevant to the projected power system development. Specifically, we consider two documents: the "Resource Adequacy Assessment of the Czech Republic's Power Grid until 2040", (ČEPS, 2022), and "Grundlagen für die Netzentwicklung", (APG, 2023).

ČEPS conducts an annual national resource adequacy assessment (ČEPS, 2022) that explores various development scenarios for the Czech electricity sector. These scenarios—Respondent, Conservative, Progressive, and Decarbonization—evaluate resource adequacy up to 2040, considering factors like energy mix, import/export capacity, consumption, and socio-economic development. In our work, we focus on the Progressive scenario.

Meanwhile, Austrian transmission operators APG and VÜN create long-term scenarios for the Austrian transmission network based on European-level planning. The Ten-Year Network Development Plan (TYNDP) by ENTSO-E (Association of European Transmission System Operators) is published every two years. APG and VÜN have produced network development plans (NEP) since 2011, with updates occurring on a two-year cycle since 2021. These plans provide an overview of different planning horizons: National Trends (NT), Distributed Energy (DE), and Global Ambition (GA). In our work, we treat the Global Ambition (GA) scenario as relevant.

System data is presented in Tables 6 and 7.

*Table 9 Relevant system data for Austria and Czech Republic for the year 2021*

| Web app input data for 2021 | Austria | Czech Republic |
|---|---|---|
| **Gross domestic el. Consumption [GWh]** | **68.495,1** | **65.809** |
| **Peak demand [MW]** | **11.273** | **12.159** |
| **Percentage of intermittent renewable production [%]** | **24,48** | **11,63** |
| **Electricity storage power capacity [MW]** | **4.416** | **1.172** |

*Table 10 Relevant system data for Austria and the Czech Republic for the year 2030*

| Web app input data for 2030 | Austria | Czech Republic |
|---|---|---|
| Gross domestic el. Consumption [GWh] | 93.800 | 81.000 |
| Peak demand [MW] | 15.756 | 15.503 |
| Percentage of intermittent renewable production [%] | 56,21 | 44,77 |
| Electricity storage power capacity [MW] | 9.806 | 1.814 |

The data distinctly illustrates the trajectory toward complete electrification of the entire economy, as evidenced by the significant increase in peak demand and total domestic electricity usage.

## 3.3 Quantification Approach

By putting in system data, such as each country's respective gross domestic electricity consumption, peak load, and share of intermittent renewable electricity production, the web app, Energy Storage Ninja (Schmidt & Staffell, 2023), provides the most likely amount and its' possible range of needed storage power and energy capacity for integrating the given share of intermittent renewable electricity production without jeopardizing the security and sustainability of electricity supply.
In this paper, this output amount of needed storage power capacity will represent the quantified importance of energy storage for each grid.

Figure 8 shows the web app interface.

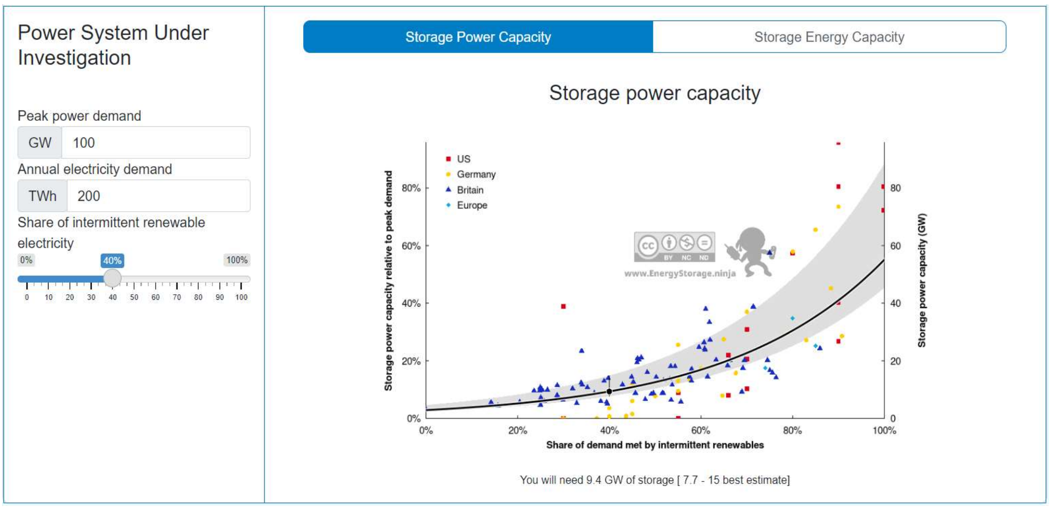

*Figure 8. Energy Storage Ninja Web App Interface. Energy Storage Ninja (Schmidt & Staffell, 2023)*

# 4 Quantified Relevance of Storage for the Grid and Readiness of the Power Grid for intermittent RES Penetration Results

As described in the Methodology Chapter, the output of the web app "Energy Storage Ninja" will represent the quantified relevance of storage for the respective country's power grid by stating the amount of storage (power and energy capacity) needed to successfully integrate intermittent renewable energy sources and maintain security of supply.

The output is the most likely amount and its' possible range of needed storage power and energy capacity. This output amount of needed storage will represent the quantified importance of energy storage for each grid. Since we lack the data for storage energy capacity, we have focused only on energy storage power capacity in this paper.

Readiness is calculated as a relative value of the respective year available energy storage power capacity on the grid in relation to the most likely amount of energy storage power capacity that would be needed to support that level of intermittent renewable energy production, given by "Energy Storage Ninja".

The results are presented in Tables 8 and 9 for Austria and the Czech Republic, for the years 2021 and 2030. A theoretical 100% RES scenario is also calculated in Table 10 for both countries.

*Table 11 Energy Storage Ninja output data for the year 2021.*

| **Energy Storage Ninja output data for 2021** | **Austria** | **Czech Republic** |
|---|---|---|
| **Most likely amount of energy storage power capacity needed [MW]** | **670** | **500** |
| **Electricity storage power capacity likely range [MW]** | **550 – 1100** | **410 - 800** |
| **Our own readiness of the power grid calculation** | | |
| **Readiness of the power grid [%]** | **659,1** | **234,4** |
| | | |
| **Power System Data for 2021** | **Austria** | **Czech Republic** |
| **Percentage of intermittent production [%]** | **24,48** | **11,63** |
| **Total storage power capacity [MW]** | **4.416** | **1.172** |

*Table 12 Energy Storage Ninja output data for the year 2030.*

| Web app output data for 2030 | Austria | Czech Republic |
|---|---|---|
| Energy Storage Ninja most likely amount of energy storage power capacity needed [MW] | 2400 | 1700 |
| Energy Storage Ninja electricity storage power capacity likely range [MW] | 2000 – 3800 | 1400 - 2700 |
| Our own readiness of the power grid calculation | | |
| Readiness of the power grid [%] | 408,58 | 106,7 |
| | | |
| Power System Data for 2030 | Austria | Czech Republic |
| Percentage of intermittent production [%] | 56,21 | 44,77 |
| Total storage power capacity [MW] | 9806 | 1814 |

*Table 13 Energy Storage Ninja output data for the year 2030 and 100% RES production.*

| Web app output data for 2030 and 100% intermittent energy supply | Austria | Czech Republic |
|---|---|---|
| Energy Storage Ninja most likely amount of energy storage power capacity needed [MW] | 8700 | 8500 |
| Energy Storage Ninja electricity storage power capacity likely range [MW] | 7200 – 14000 | 7000 - 14000 |
| Our own readiness of the power grid calculation | | |
| Readiness of the power grid for 100% intermittent RES [%] | 112,71 | 21,34 |
| | | |
| Power System Data for 2030, 100% intermittent energy supply | Austria | Czech Republic |
| Percentage of intermittent production [%] | 100 | 100 |
| Total storage power capacity [MW] | 9806 | 1814 |

## 4.1 Interpreting the results

We can see that the Austrian grid is robustly dimensioned for its current flexibility needs. This readiness is expressed by the fact that the current (2021 is used as a representative year) storage power capacity on the grid is more than six times greater than what would be optimally needed according to (Schmidt & Staffell, 2023). This is explained by the abundance of hydro potential in Austria that has been mostly exploited by using pumped hydro storage, which is an energy storage technology.

When looking at the Czech grid we notice this lack of geographical hydro potential in the amount of storage power capacity which is four times smaller than in Austria. By looking at the production mix in the Czech Republic we see that their dependence on atomic and coal power makes up for this relative lack of energy storage. Helped by its relatively small amount of intermittent electricity production of around 11,5% in 2021, the amount of storage that the Czech grid currently has is more than enough, which is reflected by its grid readiness of 234%.

As discussed before, each country's goal of making its energy mix 100% renewable by 2050 implies great changes in its power system. This is reflected in the 2030 power grid forecasts by APG and ČEPS. In Table 7 we see a dramatic rise in intermittent RES electricity production followed by a big increase in gross domestic energy consumption and peak power loads. This is explained by the already underway process of electrifying our economy and will be followed by a needed increase in grid flexibility as seen in the rise of energy storage power capacities.

Judging by the results presented in Table 9, the Austrian grid will keep up with the rising flexibility demands by still having approximately four times more energy storage power capacity than the most likely needed value, also covering the worst-case scenarios of 3,8 GW of needed capacity.

In contrast, we see that the Czech grid will be able to cover the mean part of the spectrum for 2030 but would struggle and be under-dimensioned in the case of a worst-case scenario of 2,7 GW needed energy storage power capacity. This is reflected in its readiness percentage of 106,7%.

Theoretically, we have also considered a case where 100% intermittent RES el. production would be achieved already in 2030. In this case, the Austrian grid would boast of a readiness of 112, 7% meaning that it would be able to cover the most likely scenario. The same cannot be said for the Czech system, as it would be seriously under-dimensioned for 100% RES electricity production in 2030, reflected in a low 21,34% readiness.

All these results show and quantify the growing importance of flexibility (energy storage) in our modern changing electricity systems and highlight the need for different storage technologies in each country, which would be adapted to mostly its geography and economy.

# 5 Conclusion

This paper defines and classifies short-term and long-term memories and shows their areas of application. Furthermore, the costs for the different types of storage are documented. The main part of the seminar paper analyzes the extent to which the relevance of energy storage can be quantified and thus justified.

The result of this work is an analysis that shows significant differences between the Czech and Austrian energy grids in terms of energy storage. The Austrian energy systems provides readiness by using the current infrastructure of primarily pumped-storage power plants, which exceeds six times the necessary capacity for energy storage. The energy storage network in the Czech Republic is many times weaker. The main reasons for that are primarily attributed to the geographical potential for the construction of pumped storage plants and the current lack of need for the Czech Republic to store energy to a greater extent, due to the use of coal and nuclear power plants, which do not show a significant need to balance fluctuations in energy generation. According to the analysis, the current readiness of the Czech Republic for RES is 234 %. The outlook for 2030 represents a significant transition to a higher rate of RES, which will lead to a higher rate of intermittent power supply from generators. The result of the associated analysis is the insufficient readiness of the Czech Republic for 100% energy generation from renewable sources (the current infrastructure would cover only ~1/5 of the required storage), while Austria's infrastructure would be sufficient in the optimal scenario, as presented in the last row of Table 14.

*Table 14. Readiness of power grids results.*

| Readiness of the power grid for intermittent RES generation [%] | Austria | Czech Republic |
|---|---|---|
| **2021** | **659,1** | **234,4** |
| **2030** | **408,58** | **106,7** |
| **2030 with theoretical 100% RES penetration** | **112,71** | **21,34** |

The results of this work point to the need for greater flexibility of energy storage in the future energy systems of countries and emphasize the need to maintain, if not expand, current energy storage capacities keeping in mind the geographical and economic conditions of countries.

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