Energy storage in a Positive Energy District

Conditions for the use of Pumped Hydro Energy Storage in Austria

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Abstract

Due to the current energy transition, renewable energies (RE) are becoming more common worldwide. This is leading to the development of concepts, such as Positive Energy Districts (PEDs), which aim to make the use of RE more attractive. The main idea of PEDs is that a defined urban area (district) is supplied with RE and has an annual surplus of emission-free energy (positive energy). There are three different forms of PEDs, which differ in terms of their geographic boundaries. A distinction is made between autonomous, dynamic, and virtual PEDs.

However, RE brings with it a decisive disadvantage. Renewable sources are often less predictable and therefore less reliable in comparison to fossil fuels. This is because renewable sources such as wind or solar radiation are not constantly available but depend on natural fluctuations. As a result, energy flexibility decreases. In order to maintain energy flexibility despite high RE shares, one possibility is to store surplus energy with e.g. pumped hydro energy storage (PHES). To ensure energy flexibility in PEDs, this research addresses the question of what conditions are necessary to use PHES as a storage option in PEDs, and how this differs across the three different forms of PEDs.

A distinction can be made between four conditions that influence the feasibility of PHES as energy storage in PEDs: Techno-environmental drivers, techno-environmental barriers, socio-economic drivers, and socio-economic barriers.

This research has shown that the most economically viable option is to use PHES in PEDs as virtual energy storage. However, this is only possible in virtual PEDs as they have the possibility to use energy facilities outside their geographical boundaries and the distance between the virtually used PHES and the PEDs is negligible. Autonomous and dynamic PEDs, unlike virtual PEDs, are more bound to their geographical boundaries, which makes it difficult to use PHES as virtual storage. One possibility, however, would be to establish PEDs in proximity to the PHES. However, this option requires a shared grid connection point and entails economic disadvantages such as lower efficiency of the PHES.

Keywords: positive energy districts, pumped hydro energy storage, energy flexibility, energy storage, renewable energy

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Abbreviation list

B.C.	before Christ
CO_2	Carbon Dioxide
DES	Decentralized energy system
e.g.	exempli gratia – for example
EBC	Energy in Buildings and Communities
EERA	European Energy Research Alliance
ESS	Energy storage solutions
EU	European Union
GHG	Greenhouse gas
i.e.	id est – that is
IEA	International Energy Agency
JPI	Joint Programming Initiative
KPI	Key performance indicator
kW	kilo Watt
MW	Mega Watt
OER	On-site energy ratio
PED	Positive Energy District
PHES	Pumped hydro energy storage
RE	Renewable Energy
SEB	Socio-economic barriers
SED	Socio-economic drivers
SET	Strategic Energy Technology
TEB	Techno-environmental barriers
TED	Techno-environmental drivers
VESS	Virtual Energy Storage System

1 Introduction

1.1 Energy Transition

The contemporary energy system is characterized by a transition due to climate change and the ambition to reduce greenhouse gas (GHG) emissions (Tsantopoulos, 2022). This transition is proceeding from non-renewable energies, in particular fossil fuels, to renewable energies (RE) (IRENA, 2020). REs are defined as energy sources that naturally renew themselves and will therefore not expire. Common examples include wind and solar energy or hydropower. In contrast, non-renewable energies are defined as energy sources that do not renew themselves and are therefore not sustainable in usage. Typical non-renewable resources are coal, mineral oil, and natural gas, which can be summarized under the term fossil fuels. Another key difference is that burning fossil fuels leads to a huge release of Carbon Dioxide (CO_2), which is a potent GHG and thus drives climate change (NationalGeographicSociety, 2019).

As the production of energy with fossil fuels is the most common emitter of CO_2, the use of energy is significantly involved in climate change (Sommer, 2016). In the European Union (EU) around 85 % of the general GHG emissions can be traced back to the energy sector (Welsch, 2017). Cities and buildings in particular play an important role in energy consumption in the EU, as they consume around 40 % of the total energy. This energy consumption is responsible for 35 % of GHG emissions and is therefore the main reason for pushing forward climate change. However, humanity is dependent on energy. It is hence important to make the energy sector as sustainable as possible in order to keep GHG emissions as low as possible (Gabaldón Moreno et al., 2021).

Due to this reason an energy transition is necessary. This energy transition represents the shift from non-renewable resources, in particular fossil fuels, towards RE resources with lower CO_2 emissions (Erin Bass and Grøgaard, 2021). However, this energy transition does not only include the technical shift from fossil fuels to RE but also requires a restructuring of the whole energy sector and social values regarding energy consumption. Such an energy transition needs a more bottom-up approach in which the transition is pushed forward by local communities (Villamor et al., 2020). That would result in a shift from a centralized energy system towards a decentralized energy system (DES). This means in more detail that the energy production is not done on a national level in a centralized way but is realized on the neighbourhood level (Aslam et al., 2021). DES has the advantage that RE can be produced in a more resilient and flexible way due to lots of smaller generation units (Strandberg, 2021).

There are multiple ways to achieve such an energy transition e.g. innovative technologies, such as RE or energy storage solutions (Rojey, 2009). Another way to foster the energy transition are Positive Energy Districts (PEDs). Such PEDs can be described as an urban area that is efficient and flexible in terms of energy and generates a surplus of RE over a period of time (Zhang et al., 2021) (the concept is further described in section 2 Theoretical Framework). Thus, the PED concept contributes to further decentralisation, as the energy production and consumption is regulated on a neighbourhood level (Aslam et al., 2021). To further develop this concept and put it into practice, the European Commission launched the Integrated Strategic Energy Technology Plan (SET-Plan) in 2015. This plan consists of ten priority actions to accelerate the energy transition. Sub-section 3.2 "smart cities and communities" of this SET-Plan is aiming for 100 PEDs in Europe by 2025 (SET-Plan, 2018).

However, Rojey (2009) states in his book that "higher efficiencies and greater use of renewable energies will necessitate new energy storage systems" (p. 43). This is due to the reason that RE sources are less predictable and therefore less reliable than fossil fuels (see section 2.1 Renewable Energy – The Need for Storage). The statement of Rojey (2009) thus shows the importance of energy storage within systems, which rely on RE, such as PEDs. This research is therefore investigating on energy storage solutions within PEDs, in particular pumped hydro energy storage (PHES) (concept is further explained in section 2.1.1 Pumped Hydro Energy Storage).

1.1.1 History of Energy

Using energy has a long tradition in the human history. It started already around 500,000 years ago, when early forms of the human species discovered fire as a source of energy. Thereupon, around 4000 years B.C. the power of animals was used for transportation. And as early as 400 years B.C., humans harnessed the energy of wind and water using waterwheels and windmills. Before the industrialization the main source for power generation was wood, which was next to other functions used for e.g. cooking. During the industrialization coal became available and provided a shift from energy production with wood to energy production with fossil fuels. This shift shows the first transition in the energy sector from renewable sources to fossil fuels (Penna, 2020).

Until today, fossil fuels, such as coal or natural gas remain an important factor in the production of energy (Güney, 2019). However, another transition is currently taking place, which is once again moving in the direction of renewable energies (Penna, 2020).

This brief historic overview shows that energy transition is something that already occurred in the past and that the energy sector is transformable. The first transition occurred in the time of the industrialization from RE to non-renewable energy, whereas the second and current transition, which was addressed above, occurs from non-renewable energy to RE (Tahvonen and Salo, 2001).

1.1.2 Energy System of the EU

The European Union (EU) is, together with China and the USA, the main emitter of GHG emissions, so the EU has, next to others, a great responsibility to push ahead with the energy transition, as this would significantly reduce emissions (see section 1.1) (Welsch, 2017).

Figure 1 (left) illustrates the energy mix in Europe, which clearly shows that fossil fuels, especially coal, gas, and oil still represent the most popular resources for energy production and that RE have only a comparatively small share of the total energy supply (IEA, 2022b).

The energy is transported in Europe via the synchronous grid of continental Europe, which is the largest energy grid in the world and covers 24 countries including Austria (Hofmann et al., 2020).

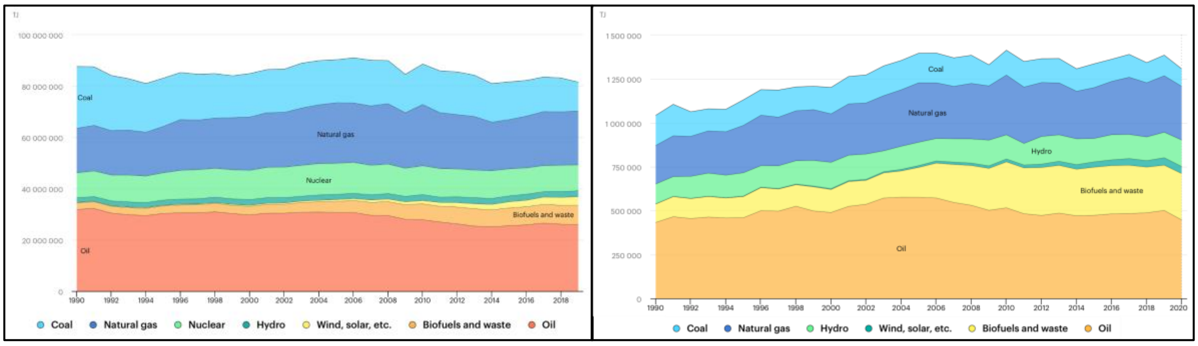


Figure 1 Total Energy supply by source in Europe (left) and Austria (right) between 1990 and 2020 (IEA, 2022 a and b).

And although the EU is a pioneer in terms of RE, the EU's energy transition targets have not yet been met. By 2030, at least 27 % of the energy consumed in the EU should be produced from renewable sources (IRENA, 2018b).

In particular mountainous regions, such as those found in Austria, offer great potential for the energy transition. According to Katsoulakos and Kaliampakos (2018), these regions are well suited to produce RE, such as wind and solar energy, because of climatic but also geographical conditions. Therefore, Austria is likewise working on the transition to RE and a more flexible energy grid, which should help to counteract climate change (Wenz, 2020, Katsoulakos and Kaliampakos, 2018).

Austria's energy production started with a centralized energy system in which the power stations were owned by the government. The old system was therefore defined by Wenz (2020) as a neo-mercantilist approach. However, this approach changed after the focus on the environment and the climate got bigger in the 1980s. The shift occurred from the neo-mercantilist approach to a more competitive and decentralized approach, which Wenz (2020) describes as an energy governance system.

Similar to other countries, Austria included the reduction of CO_2 and an energy transition into their energy strategy for the future (IEA, 2020). To achieve this the federal ministry for sustainability and tourism ("*Bundesministerium Nachhaltigkeit und Tourismus*") and the federal ministry for traffic, innovation, and technology ("*Bundesministerium Verkehr, Innovation und Technologie*") developed the Austrian climate and energy strategy "#mission2030". The goal of this strategy is to reduce greenhouse gas emissions by 36 % by 2030 (compared to 2005) and to achieve, that the total national electricity consumption is 100 % covered by RE. In addition, the strategy helps to further decarbonize various fields of action by 2050 (BMNT and BMVIT, 2018).

Figure 1 (right) shows the energy mix in Austria between 1990 and 2020. In contrast to Figure 1 (left), it is striking, that a significantly larger proportion of the energy is generated by hydropower (IEA, 2022a). It also stands out, that no energy is generated by nuclear power in Austria. This energy generation method was never part of the energy mix due to a plebiscite in 1978 (Wenz, 2020).

Since large parts of the Alps are located in Austria, the country has good topographic conditions for hydro power. In addition, Austria is rich in water due to a large number of rivers and a high precipitation rate (Pranz, 2020).

Therefore, it is not surprising that Austria owns together with Germany and Italy the highest number in PHES (Rehman et al., 2015). However, Austria has in contrast to Germany still the opportunity to install more PHES, which shows next to the topographical circumstances that PHES has a high potential in Austria (Weiss et al., 2014).

1.2 Research Questions

The research questions can be derived from the concepts described in the following section. The primary research question (PRQ) deals with how PHES can help to improve the energy flexibility of PEDs, and which conditions are important for this.

PRQ: Under what conditions could Pumped Hydro Energy Storage be used as an Energy Storage Solution for Positive Energy Districts in Austria?

This primary research question is answered with the help of further secondary research questions. The first secondary research question (SRQ1) focuses on which energy storage solutions (ESS) are possible in PEDs and which have already been integrated into PEDs. The second secondary research question (SRQ2) builds on the first by identifying possible conditions that are necessary to integrate ESS into PEDs. Finally, the third secondary research question (SRQ3) aims to explore the suitability of PHES to be integrated into the three forms of PEDs.

SRQ1: What types of Energy Storage Solutions are suitable for Positive Energy Districts and can already be found in those?
SRQ2: Under what conditions can Pumped Hydro Energy Storage be used as Energy Storage Solutions in Positive Energy Districts?
SRQ3: How can Pumped Hydro Energy Storage be applied as an Energy Storage Solution in autonomous, dynamic, and virtual Positive Energy Districts?

2 Theoretical Framework

2.1 Positive Energy Districts Definition

As described in section 1 Introduction the concept of Positive Energy Districts (PED) could be one possible solution to foster the energy transition. PEDs are described by the European Strategic Energy Technology Plan (SET Plan) as a building block for driving the energy transition forward faster and further, and thus promoting more sustainable and climate-neutral cities (Gabaldón Moreno et al., 2021, Lindholm et al., 2021). The term positive energy district is made up of two parts. On the one hand the *positive energy* and on the other hand the *district*. Positive energy refers primarily to an energy surplus, meaning that energy generated using RE exceeds demand and is therefore excessive. District in this context means a larger section of a city, which geographically delimits a PED (Derkenbaeva et al., 2020).

An extensive definition of PEDs is given by the International Energy Agency's (IEA) Energy in Buildings and Communities Programme (EBC) in the Annex 83 (IEA EBC Annex 83, 2020):

> "The basic principle of a PED is to create an area within the city boundaries, capable of generating more energy than is used, and agile/ flexible enough to respond to energy market variations. Rather than simply achieving an annual net energy surplus, it should also support minimizing impacts on the connected centralized energy networks by offering options for increasing onsite load-matching and self-use of energy, technologies for short- and long- term energy storage, and providing energy flexibility with smart control.
> PEDs can include all types of buildings present in the urban environment and they are not isolated from the energy grid. Within the research community, the PED is an emerging concept intended to shape cities into carbon neutral communities in the near future. Reaching the goal of a PED requires firstly improving energy efficiency, secondly cascading local energy flows by making use of any surpluses, and thirdly using low-carbon energy production to cover the remaining energy use. Smart control and energy flexibility are needed to match demand with production locally as far as practical, and also to minimize the burdens and maximize the usefulness of PEDs on the grid at large." (IEA EBC Annex 83, 2020)

Next to this definition PEDs are further defined by the following characteristics. First, PEDs have geographic boundaries, such as a separate part of a city, or even just a few buildings. Second, there are different ways of interacting with the energy grid. On the one hand, PEDs can be independent of the energy grid, or on the other hand, they can draw additional energy from the energy grid (see section 2.3.1 Techno-environmental conditions). Third, there are different ways to produce energy. Here, we distinguish between on-site and off-site energy supply. On-site means that the energy is produced within the geographical boundaries and off-site means that the energy sources are located outside the geographic boundaries. Finally, the balancing period is another criterion for PEDs. To determine this, various key performance indicators (KPIs) have been developed, of which the on-site energy ratio (OER) is the most commonly used. The OER calculates the difference between the energy supply and demand from local energy sources (Derkenbaeva et al., 2020).

Beyond that, Lindholm et al. (2021) state that the surplus of energy which is produced in a PED is "achieved by integrating renewable energy systems and energy storage, as well as improving the energy efficiency of the districts by optimizing the energy flows between the energy consumers, producers and storage" (p. 5). This clearly shows that several factors, such as the supply and demand side and energy storage, interact in a PED. This interaction of different factors in a PED is described in more detail in the following concepts.

2.2 Positive Energy District as a Concept

A considerable amount of literature has been published on PEDs, which focusses mostly on practical implementations of PEDs. However, as a PED is a relatively new and still emerging approach there is a relatively small body of literature concerned with the theoretical aspects of PEDs. Nevertheless, two concepts for PEDs are presented and compared in the following section.

The first concept of PEDs is an interaction of different factors, which are shown in figure 2. The concept is composed of an active interaction between energy generation systems (supply side), energy consumers (demand side) and energy storage within a district. Those factors are influencing the energy balance within the PED and must therefore interact with each other (Krangsås et al., 2021, Lindholm et al., 2021).

The supply side consists mainly of RE, which means that supply fluctuates more than if fossil fuels are the main source of energy. Important for the supply side in a PED is that it should be climate friendly but should still provide the consumer with reasonable market prices (Krangsås et al., 2021).

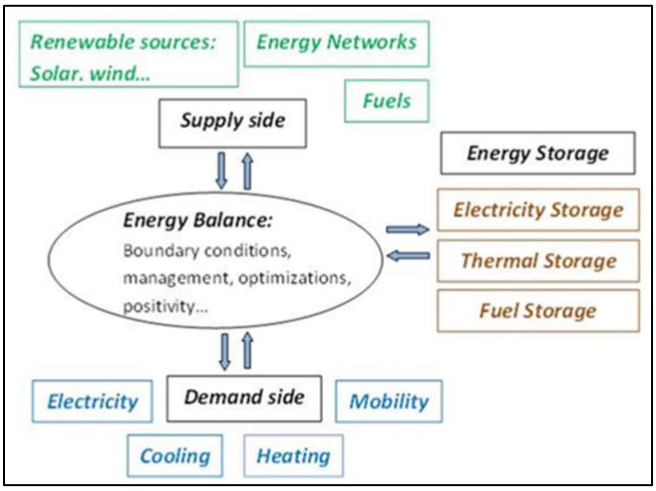


Figure 2 Energy Balance concept of a PED (Krangsås et al., 2021).

The demand side, on the other hand, changes in a PED in the way that consumers become more active. Thus, consumers control and change energy demand. This is also described by the shift from a centralised energy system to a decentralised energy system, which can also be seen as a shift from government to governance (ibid.).

However, as described above, RE complicates the balance between supply and demand. Thus, a third factor is crucial for the energy balance within a PED. This third factor is the storage of energy, which can be expressed as electricity storage, thermal storage, or fuel storage. However, the integration of energy storage solutions (ESS) into PEDs is a major challenge (ibid.). These challenges are mainly due to the high demand for ESSs, which entails both technical and economic difficulties. Technological challenges include the capacity and the high costs of ESSs. Whereas economic difficulties are, for example, the lack of policy support. This should be strengthened in the future so that there are e.g. political subsidies that facilitate the implementation of ESSs (Yao et al., 2016).

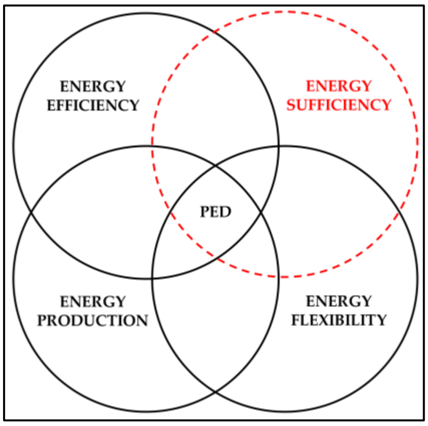


Figure 3 Illustration of the functions of a PED (Erba and Pagliano, 2021).

The second concept regarding PEDs is composed of energy efficiency, energy production, energy flexibility, and energy sufficiency, which will be described in more detail in the following (see Figure 3) (Erba and Pagliano, 2021).

Energy efficiency is one of the most important components of a PED. It means that the relation between input and output is improved. In a PED there is the requirement that it produces more energy than it consumes each year, which can be simplified with the help of energy efficiency. To improve this energy efficiency, there are several possibilities for PEDs. First, higher energy efficiency can be achieved with the help of short transport distances. For this, it makes sense that the districts are comparatively densely populated. Second, the buildings within a PED must have a generally low energy consumption in order to improve the overall energy efficiency. This concerns both low energy consumption for heating (including hot water), but also general energy consumption through for example lighting. To achieve this, the EU has established a directive on the energy performance of buildings (Directive2010/31/EU, 2010), which aims to help buildings being more energy efficient. An example for energy efficient housing is the concept of "passive houses" (ibid.).

The energy production in a PED should be based on RE. These REs should produce an annual surplus of energy, i.e. produce more than they consume. Therefore, a PED has no net zero GHG emissions, as RE does not emit as much as fossil fuels (ibid.). The three different forms of PEDs explained in section 2.3.1 Techno-environmental conditions also represent different forms of energy production in regards to geographical circumstances. Thus, in autonomous PEDs, energy production is only allowed within the geographical boundaries, whereas in virtual PEDs, production is also allowed outside the geographical boundaries (Lindholm et al., 2021).

The use of RE makes energy flexibility more difficult, as already from an amount of 30 % of wind and solar energy, energy flexibility becomes more problematic (this is described in more detail in section 2.1 Renewable Energy – The Need for Storage). To maintain the flexibility of the energy system, there are several possibilities. On the one hand, ESS can help to provide the necessary flexibility by storing energy in case of overproduction, which can be released again when demand is higher. On the other hand, an adaptation is that the buildings themselves become more flexible with regard to energy, which means that the buildings can respond to the supply and demand (ibid.).

The concept of energy sufficiency is a new emerging concept regarding PEDs. Sachs et al. (1999) is describing sufficiency in their book as following: "While efficiency is about doing things right, sufficiency is about doing the right things" (p. xix). Sufficiency therefore means a change in lifestyle. An example of this can be provided by the transport sector. Here, the introduction of fuel-efficient vehicles would reflect the concept of efficiency, whereas reducing transport in general for example by walking, cycling, or online conferences instead of meeting in person could be called sufficiency. Therefore, sufficiency can be paraphrased with shifting or improving. The IEA also provides various suggestions on how the sufficiency concept can be integrated into everyday life, for example by drying laundry on the line rather than in a tumble dryer, or by using car sharing instead of owning a car (Sachs et al., 1999, Erba and Pagliano, 2021).

This concept shows that all four subordinated concepts of efficiency, production, flexibility, and sufficiency are important for the implementation of a PED and that it is not possible to neglect one of those.

When comparing the two concepts, several parallels can be found between the two.

First, the "supply side" of the first concept of Krangsås et al. (2021) compares very well with the "energy production" in the second concept of Erba and Pagliano (2021). Both are concerned with where the energy comes from. However, the supply side is also related to another sub-concept. Thus, also the "energy efficiency" plays an important role for the "supply side", as the production of energy must be as efficient as possible. In addition, it needs the most efficient infrastructure possible to enable the supply side to transport the energy in an efficient way.

Secondly, the "demand side" can also be compared with "energy efficiency", as there must also be a certain level of efficiency on the consumer side, such as efficient buildings or efficient use.

Thirdly, "energy storage" is consistent with the sub-concept of "energy flexibility", as the storage of energy helps to maintain flexibility.

However, it is noticeable that the sub-concept of "energy sufficiency", which was introduced in the second concept, is reflected in all three components of the first concept. For the "supply side" it is important that behaviour is changed by shifting away from fossil fuels to RE. On the "demand side", it is also important to change behaviour, as energy consumption in general needs to be reduced and the demand needs to be adapted to the new circumstances of the energy transition. Equally important is the concept of "energy sufficiency" for "energy storage", as here also new behaviours and possibilities need to be explored in order to maintain the flexibility of the energy system.

This point is special in relation to this research. This is the case because the aim is to find out whether large-scale ESS such as PHES can mitigate the storage problem in PEDs by storing surplus energy from the districts in PHES in an efficient way. To achieve this all concepts presented above are necessary. The most obvious one here is the energy storage and the energy flexibility, as ESSs, such as PHES, help to maintain those sub-concepts. However, also the other concepts relate to the research question. To give an example, the sufficiency concept is important as new behaviours need to be utilized, as implementing PHES into PEDs is not common yet.

2.1 Renewable Energy – The Need for Storage

As explained in the introduction, RE is essential for the energy transition in the direction of a carbon free energy system. Next to the numerous advantages of RE, there are some difficulties that require new perspectives in order to overcome these challenges. One of those challenges is the unpredictability of RE, in particular wind and solar energy, which are the leading technologies for RE (Rehman et al., 2015). Wind and solar as energy sources are less predictable than fossil fuels. This is due to the reason that wind and solar radiation vary strongly during the year and even during a day (Stoppato and Benato, 2017, Ali et al., 2021). In addition to the day- or year-specific fluctuations, this is also reflected in the full load hours of RE, which depend heavily on the location of the plant. For example, the full load hours of a solar plant decrease if the plant is not optimally oriented towards the south due to roof inclinations, or if wind power plants are installed in less windy regions. For example, the full load hours of wind turbines in Germany can vary between 3200 hours per year (in selected coastal locations) and 1800 hours per year (in less windy locations). In comparison, the full load hours of non-renewable energies do not depend on external factors such as the solar radiation or wind, but on the demand or the costs of fuels or CO_2 certificate prices (Kost et al., 2021). This low predictability of RE makes it hard to schedule the supply (Stoppato and Benato, 2017, Ali et al., 2021).

However, it is highly important for the electricity grid to have a stable and predictable energy supply. This is due to the reason that electricity supply fed into the grid must correspond to the electricity demand which is taken from the gird. When the supply does not meet the demand the network frequency would change which would result in problems for the appliances connected to the grid (Christiner, 2016).

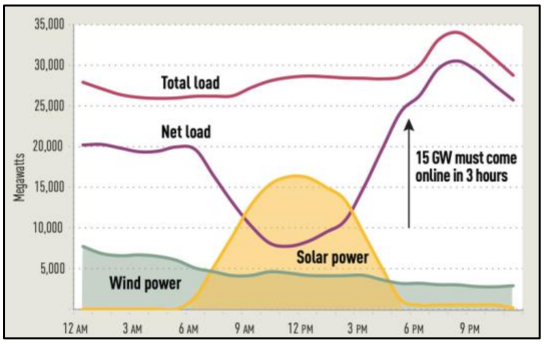


Figure 4 Duck Curve (Kosowatz, 2018).

One example which illustrates this problem well is the so-called "Duck Curve" (see Figure 4), which deals with variations in RE in regard to the energy demand over the day (Kosowatz, 2018). The "Duck Curve" represents the net load for a day in spring. This net load shows the "differences between the estimated load and the forecasted electricity produced from different generation sources" (Wong et al., 2020, p. 197237). The name "Duck Curve" emerges from the form of the curve, which looks like a body of a duck due to the decrease of the net load around 9am and the increase around 12pm and the decrease again around 9pm, which looks like the *head of the duck* (Wong et al., 2020).

As far as solar is predictable it can be said that solar radiation is the highest at the middle of the day (12pm) and the lowest in the night, as the sun is not shining (Kosowatz, 2018). This is resulting in a curve which looks like a gaussian distribution. The *belly of the duck* and the curve of the solar power overlap which shows that an overproduction of solar energy is likely. This overproduction could result in problems for the energy gird, as described above. However, the *head of the duck* in contrast shows that in the late afternoon and evening solar energy is no longer sufficient and other energy resources are necessary to meet the net load. One option to solve this problem of the “Duck Curve” could be energy storage solutions (ESS) (Wong et al., 2020).

This energy storage is in particular important for autonomous energy systems, which are mainly relying on RE, such as PEDs. This is important to maintain the balance between the energy production and the energy consumption (Canales et al., 2015). This is due to the reason that ESS can compensate power variations, as shown by the “Duck Curve” and therefore can help the system to stay flexible regarding supply and demand (Ould Amrouche et al., 2016).

Such energy storage can take different forms, for example, there are electrochemical, thermal, or mechanical ESS. A typical energy storage system is usually composed of a storage medium, an energy conversion system, and a system balance. Examples for electrochemical ESS are different forms of batteries, such as the most common Nickel-Cadmium (Ni-Cd) or Lithium ion (Li-ion) batteries (Ould Amrouche et al., 2016). Furthermore, there are hydrogen storage systems for electricity production (Ali et al., 2021). A typical form of a mechanical ESS is pumped hydro energy storage (PHES) (Ould Amrouche et al., 2016). The focus of this research is on this type of energy storage and will be further explained in the following.

2.1.1 Pumped Hydro Energy Storage

Pumped hydro energy storage (PHES) is the most used ESS (IRENA, 2018a). It is useful, such as other ESSs, for balancing the grid and equalize supply and demand by storing energy when the supply is high and providing energy when the supply is low, but the demand is high (Ali et al., 2021). PHES is superior to other ESS when it comes to stabilizing the energy grid, since PHES can be started quickly and thus produce energy at the push of a button (IRENA, 2012). Therefore, PHES is particularly useful when it comes to managing large power grids (Ali et al., 2021).

PHES originated in the Alps in the 1890s and spread worldwide, especially between 1960 and 1980, so that today more than 200 installations have been built (Ali et al., 2021).

PHES stores energy in the form of potential energy stored in water (Rehman et al., 2015). To achieve this, there are two different systems. The first one, which is called the closed-loop system, consists of a lower and an upper water reservoir, which are both artificial. The second one, which is called the open-loop system, consists of an artificial reservoir and a natural water body, such as a river or lake, which function as the other reservoir. Between those reservoirs of both open- and closed-loop systems the water can be pumped up with the help of electric generators using surplus energy (see figure 5). In open-loop systems the water can also flow in naturally and can then be stored without using the pumps. When energy is needed, the water in the upper reservoir can be released back down through hydro turbines, thereby producing energy (Ali et al., 2021, Ould Amrouche et al., 2016).

The electric generators are active when the price of electricity is low and therefore there is a large supply of energy. In contrast, the turbines are active when the price of electricity is high and therefore the supply of other RE is low (Rehman et al., 2015).

PHES can be divided based on their capacity. There is a distinction between large (>10 MW), small (max. 10 MW), micro (max. 100 kW), and pico (max. 5 kW) (Rehman et al., 2015).

Glasnovic and Margeta (2011) explain that large-scaled PHESs have the disadvantages of a “lack of locations for big storages, long lead time, impact on environment” (p. 1876), which is less of a problem in small-scaled PHES.

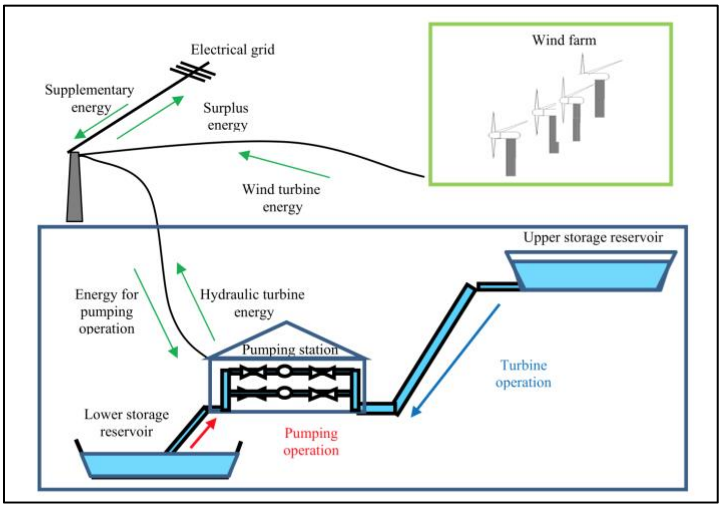


Figure 5 Illustration of a pumped hydro energy storage which is fed by electricity from a wind farm (Ould Amrouche et al., 2016).

PHES has numerous advantages for the energy system. This ESS is, as already mentioned, flexible in start and stop and can therefore deliver energy immediately when it is needed. This is supported by low maintenance costs. PHES is the cheapest compared to other ESS, such as different types of batteries or compressed air storage. PHES can be used to track load changes and adapt to them. Additionally, PHES is a sustainable way for creating energy, as the plants have a long lifespan (50 – 100 years) and reduce GHG emissions as they emit little CO_2 (Hino and Lejeune, 2012, Ali et al., 2021, IRENA, 2012).

Due to those advantages PHES is, based on theory, a great opportunity for PEDs to store surplus energy. This is also confirmed by Glasnović et al. (2011) who state that with the help of PHES an energy system could be completely relying on RE, such as PEDs do.

Next to the advantages there are also disadvantages of PHES. First, there is a lack in infrastructure. On the one hand, there is not enough infrastructure for the development of new PHESs, such as roads and, on the other hand, there is not enough infrastructure for transporting the produced energy to the grid. Second, PHES is dependent on the topography and therefore new PHESs need to be adapted to the specific circumstances or the area. Last, PHES can have a negative impact on biodiversity, such as on birds or fish (Hino and Lejeune, 2012, Ali et al., 2021).

However, next to those disadvantages PHES is a versatile method to support the deployment of RE, especially in small autonomous grids.

2.2 Energy Storage within PEDs – Status Quo

As explained above storage is highly important for the energy balance and the energy flexibility within a PED. However, the use of energy storage solutions (ESS) is mostly depended on the geographical circumstances (Lindholm et al., 2021). This means that not every ESS can be implemented in every PED. In particular, this geographical dependency applies to large-scale ESSs, such as PHES. This is due to the reason that PHES needs, as explained above, a specific topography, which can only be found in particular regions, such as the Alps (see section 2.1 Renewable Energy – The Need for Storage).

This section wants to describe what kind of ESS are implemented in or planned for PEDs. In order to do this, the PED projects from the “Booklet of Positive Energy Districts in Europe” published by Joint Programming Initiative (JPI) Urban Europe (JPI, 2020) were examined. This booklet provides an overview about numerous PED projects in Europe, which are implemented or in the planning phase. The ESSs used in the projects were elaborated and summarized in table 1.

Table 1 ESS in existing or planned PED projects in Europe.

PED Project location	Project name	ESS
Campus Evenstad Norway	ZEN Pilot Project	Batteries
Trondheim – Norway	+CityxChange	Batteries
Espoo – Finland	SPARCs	Batteries; 2nd life batteries
Åland Island – Finland	Flexens/ Smart Energy Åland	Batteries; Flywheels; Thermal energy storage
Alkmaar – The Netherlands	PoCiTYF	Hydrogen Fuel Cells; Batteries; VPP (standalone batteries, fuel cells)
Évora – Portugal	PoCiTYF	2nd life batteries
Oulu – Finland	Making-City	Energy storage tanks; thermal borehole energy storage
Trento – Italy	Santa Chiara open Lab	Thermal energy storage
Hennigsdorf – Germany	Heat Hub Hennigsdorf	Thermal energy storage
Florence – Italy	REPLICATE	Thermal energy storage
Odense – Denmark	Coal phase out by 2025	Thermal energy storage
Freiburg im Breisgau – Germany	Dietenbach	Thermal energy storage (Ice storage)
Turku – Finland	/	Thermal energy storage
Hoogeveen – The Netherlands	Hydrogen district Hoogeveen	Hydrogen Storage

Table 1 shows clearly that PEDs mainly use batteries or thermal energy storage at the moment. Occasionally, there are also hydrogen storage or flywheels. The booklet does not present a PED that uses PHES as ESS. However, the SET-Plan ACTION n°3.2 Implementation Plan (SET-Plan, 2018) recommends that innovative technologies for storage solutions in PEDs should be further developed and that the research for such innovations should be supported. This shows that it is extremely important to investigate other ESSs, such as PHES, with regard to PEDs and to find out to what extent these ESSs can be integrated into PEDs.

Lindholm et al. (2021) state that ESS is mostly important for autonomous PEDs, as such PEDs should not import energy from outside the geographical boundaries and therefore need to store the excess energy for times when the demand exceeds the supply. This does not apply to dynamic PEDs, as they are allowed to interact in both ways with the general energy grid, meaning that they could import energy from outside the geographical boundaries. In their study, Lindholm et al. (2021) investigate different kinds of ESSs, which are suitable for PEDs. In particular, they examined two types of batteries (lithium-ion and lead-acid batteries), compressed air storage, and pumped hydro energy storage (PHES) and the associated possible geographical locations, installation costs, energy density, lifetimes, and the round-trip efficiency. They came to the conclusion that compressed air storage and PHES is superior to batteries in regard to costs. Problematic is, however, the low energy density, which makes it almost impossible to implement such ESS in urban areas, which are mostly densely populated and in which PEDs are located. This means that PHES is only suitable as virtual energy storage and therefore only in virtual PEDs (Lindholm et al., 2021).

However, Canales et al. (2015) demonstrated that PHES is due to the ability to compensate the natural fluctuation of RE a technology that is suitable to support autonomous energy systems, which are mainly supplied by RE (Canales et al., 2015).

2.3 Conditions for PEDs and PHES

Positive Energy Districts (PED) and pumped hydro energy storage (PHES) and related to this the whole energy system is affected by numerous conditions. Ali et al. (2021) state two different categories of conditions, namely techno-environmental and socio-economic. Those factors are explained in the following in detail.

2.3.1 Techno-environmental conditions

Ali et al. (2021) define techno-environmental factors as "those that reflect the positive and negative impacts of the employment of PHES [or other energy facilities, such as PEDs] due to the technical and environmental reasons" (p. 2).

Boundaries of PEDs

The European Energy Research Alliance (EERA) Joint Programme Smart Cities organized on the 6th of May 2019 a workshop with the aim of elaborating a clear and extensive definition of PEDs. One of the outcomes was the differentiation between three definitions of boundaries. First, the geographical boundary, which describes the spatial borders of a PED. Second, they defined functional boundaries, which can be paraphrased with the "limits of the PED in terms of energy grids, e.g. the electricity grid" (Wyckmans et al., 2019, p. 11). Third, a virtual boundary was defined, which is focusing more on the contractual boundaries of a PED. This means for example a "power generation infrastructure owned by PED residents but outside normal PED geographical boundaries (e.g. an offshore wind turbine owned through shares by the PED residents' community)" (Wyckmans et al., 2019, p. 11).

Based on those three definitions of boundaries three different forms of PEDs can be distinguished, which are explained in the following and additionally in table 2 (Wyckmans et al., 2019).

1. **Autonomous PED**: In this form, there are clear geographical boundaries that are not allowed to exceed. This means that this clearly defined area is completely self-sufficient in terms of energy. Therefore, no energy is imported from outside and the entire energy demand is covered by RE generated within the area. However, energy that is not consumed by the area itself can be exported (Wyckmans et al., 2019, Lindholm et al., 2021).

2. **Dynamic PED**: This form of PED also has clearly defined geographical boundaries like the autonomous PED. The annual production of RE in this area is greater than the annual consumption. However, it is possible that this PED interacts with the environment, such as the energy grid. This serves to compensate for possible fluctuations in energy production. However, the energy amount that is imported from the grid needs to be smaller than the amount that is exported (ibid.).

3. **Virtual PED**: This form of PED is less bound to geographical boundaries than the other two forms. It can therefore also use energy that lies outside the area of the PED. However, a prerequisite for this form is that the energy production during a year exceeds the energy consumption during a year (ibid.).

Interesting to note is that the use of ESS can be seen differently in the three forms of PEDs. Lindholm et al. (2021) explain this by declaring that batteries are often more expensive than PHES, which is the reason why for dynamic PEDs, it is often more cost effective to "interact with the electricity grid than to use batteries" (p. 21).

Table 2 Three forms of PEDs.

Three types	Main Characteristics
Autonomous PED	Clear geographic boundaries Interaction with environment restricted; Completely self-sufficient Import not allowed Export allowed
Dynamic PED	Clear geographic boundaries Interaction with environment allowed Import allowed Export allowed
Virtual PED	Geographic and virtual boundaries Interaction with environment allowed Import allowed Export allowed

Techno-environmental Characteristics of PHES

The techno-environmental factors regarding PHES are versatile and can be further divided into drivers and barriers and are referred to below as TED (techno-environmental drivers) and TEB (techno-environmental barriers) (Ali et al., 2021).

Techno-environmental Drivers of PHES

One important TED for PHES is **grid resilience**, which means that PHES has, among other things, a stabilising effect on the general energy grid, as they can store excess energy when demand is low, but supply is high. This also increases the use of RE, as PHES can be used to compensate for the natural fluctuations of RE (see above). Grid resilience also includes the ability of PHES to switch from energy storage to energy production within a comparatively short time (a few minutes) ("black and quick start") (ibid.).

Compared to other ESSs, PHES is the one that can store the largest amount of energy (Koohi-Fayegh and Rosen, 2020) and therefore it can be classified as **utility-scale storage** (Ali et al., 2021). Furthermore, PHES can store energy on a daily or seasonal basis (Javed et al., 2020, Glasnović et al., 2011).

Using PHES for energy storage of RE can reduce the CO_2 emissions produced by the energy sector and can therefore help to contribute to achieve clean energy (Ali et al., 2021, Fan et al., 2020). Next to this, Deane et al. (2010) state that PHES has compared to other ESSs a long lifetime with 50-100 years. Due to the fact that PHES helps to reach clean energy and have a long lifetime they can be designated as **sustainable** (Ali et al., 2021).

As already stated above (see section 2.1.1 Pumped Hydro Energy Storage), PHES requires specific **landscape characteristics**, such as a special topography (differences in the elevation) and the accessibility to water (Deane et al., 2010). If such requirements are met naturally by the landscape, such as in many places in Austria, the construction costs can be reduced, which is advantageous for the implementation of PHES (Ali et al., 2021).

Techno-environmental Barriers to PHES

Landscape characteristics can act alongside TEDs also as barriers to PHES and can be divided in three sub-categories. This includes on the one hand <u>landscape typology</u> (Ali et al., 2021). This is due to the reason that the special topography, which is needed for the implementation of PHES cannot be found everywhere and is therefore critical for the implementation of PHES (Lu et al., 2018). On the other hand, the factor of <u>water</u> can create barriers to PHES. For example, the lack

of water can be classified as a TEB, as without the resource water PHES cannot be built, as the transportation of water is considered as too expensive (Lu et al., 2018, Ali et al., 2021).
Lastly, the geography of the location of PHES is described by Ali et al. (2021) as a TEB, as the construction of PHES in unfavourable geological conditions can increase the costs and should therefore be considered in the planning (Kucukali, 2014).
As another TEB the **biodiversity** of the region can have negative effects on the implementation of PHES. For example PHES can reduce the number of bird habitats and is therefore influencing the biodiversity in a negative way (Lu et al., 2020). Those effects on biodiversity can function as TEBs, as this could draw the attention of environmental groups to the project, which could hinder the implementation of a new project (Ali et al., 2021).

2.3.2 Socio-economic Conditions

The socio-economic conditions can be described as "those that reflect the positive and negative impacts of the employment of PHES [or other energy facilities, such as PEDs] due to social and economic reasons" (Ali et al., 2021, p. 2).

Related Concepts to PEDs – Energy Communities

PED is a new emerging concept (see above) which is intended to promote the use of RE and decentralisation. However, next to this there are similar approaches, which are pursuing the same goals. In Austria, for example, there is the concept of renewable energy communities. This concept is promoted and supported by the Renewable Energy Expansion Act Package (*Erneuerbaren-Ausbau-Gesetzespaket*), which was adopted in the Austrian National Council on the 7th of July 2021 in BGBI. I Nr. 150/2021. Such renewable energy communities should produce energy from renewable sources and are allowed to consume, sell, or store it, while using the facilities of the network operator. The members of such renewable energy communities can be private persons, municipalities, or small and medium-sized enterprises, which are in close location to the energy supply facilities (Österreischiche Koordinationsstelle für Energiegemeinschaften, 2022).

Virtual Energy Storage

As explained above, ESSs play an important role to assure energy flexibility, when the shares of RE increase in the energy mix. However, ESSs are an expensive technology compared to the electricity price and next to this not every ESS technology can be implemented everywhere, as in the case of PHES (Oh, 2021, Ali et al., 2021, Liu et al., 2017).
To solve this problem a new concept emerged, namely virtual energy storage system (VESS). In literature this concept is also paraphrased as cloud energy storage system or shared energy storage system (Oh, 2021).
Such VESS is defined by Liu et al. (2017) as "a grid-based storage service that enables ubiquitous and on-demand access to a shared pool of grid-scale energy storage resources" (p. 227).
The customers of a VESS service can be private consumers or businesses, which have an energy storage demand (Liu et al., 2017).
A VESS service is composed of several steps. First, the customer has to rent the needed storage capacity, which can be used in the same way as an own ESS in regard to charging and discharging. The information about this charging and discharging is transmitted to the service provider of the VESS, who is operating a physical ESS (Oh, 2021).
In this way, the cost of an ESS to the consumer is reduced because of economies of scale, as the physically available ESS in a VESS is scaled larger than an individual ESS (Oh, 2021).

Socio-economic characteristics of a PHES

Next to the techno-environmental conditions, PHES is also influenced by socio-economic conditions, which can likewise be divided into drivers and barriers, which are described in the following as SEDs (socio-economic drivers) and SEBs (socio-economic barriers) (Ali et al., 2021).

Socio-economic Drivers of a PHES

The SEDs can be divided into two sub-conditions. On the one hand energy arbitrage and on the other hand proximity characteristics (Ali et al., 2021).

PHES has the advantage of **energy arbitrage**, which means that PHES can buy surplus electricity from the market, which is relative cheap and can sell this electricity when demand is high and therefore the electricity price is high (Ali et al., 2021, Deane et al., 2010).

Due to energy losses during the transport of electricity over bigger distances it is a SED for PHES to implement the PHES close to the producing energy plant, e.g. a wind park (Glasnovic and Margeta, 2011). This is described by Ali et al. (2021) as **proximity characteristics**.

Socio-economic Barriers to a PHES

Next to SEDs Ali et al. (2021) present different barriers to PHES, which can be allocated to the socio-economic factors.

The first SEB discussed here is related to **financial aspects** of PHES, which covers two points. On the one hand, Deane et al. (2010) state that the costs of PHES are highly depended on the location and can vary significantly. They also explain that especially the capital costs are high, which can therefore be seen as a SEB (Deane et al., 2010, Ali et al., 2021).

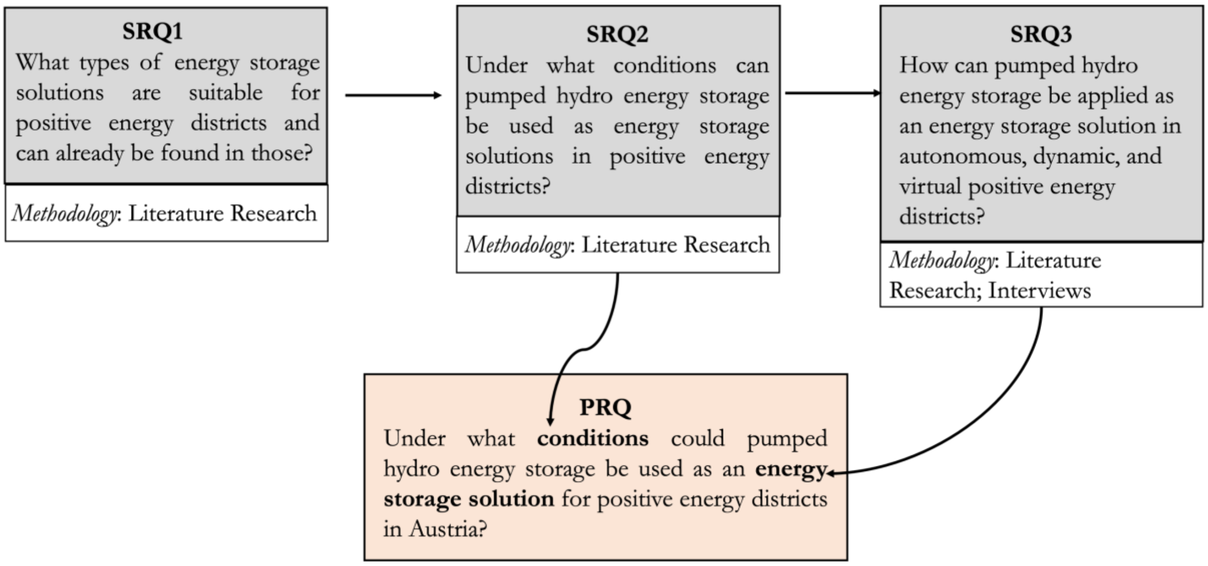
On the other hand, the project financing can be seen as a SEB. Building a new PHES is depended on the sponsorship, which is often covered by public investors (Ali et al., 2021).

Public opposition is another SEB which is presented by Ali et al. (2021). In support of this statement, another study points out that the lack of public awareness is a major barrier to the implementation of RE (Seetharaman et al., 2019, Ali et al., 2021).

Lastly, **Market failure** can be seen as an SEB, including, for example, the lack of needed labour or uncertainties in the market itself (Ali et al., 2021, Jaber, 2012).

3 Methodology

The main methodology of this research is a case study, which consists of two research techniques, comprising both primary and secondary research. Primary research is characterized by the fact that information is collected, whereas information for secondary research already exists (Manu and Akotia, 2021). On the one hand, a literature review was used to elaborate the different conditions which are necessary for implementing ESS in PEDs (SRQ1 and SRQ2). On the other hand, qualitative interviews were conducted to relate the conditions of ESS to the particular case of pumped hydro energy storage in PEDs (SRQ3).
This methodology should help to answer the research questions as shown in figure 6.



SRQ1
What types of energy storage solutions are suitable for positive energy districts and can already be found in those?
Methodology: Literature Research

SRQ2
Under what conditions can pumped hydro energy storage be used as energy storage solutions in positive energy districts?
Methodology: Literature Research

SRQ3
How can pumped hydro energy storage be applied as an energy storage solution in autonomous, dynamic, and virtual positive energy districts?
Methodology: Literature Research; Interviews

PRQ
Under what **conditions** could pumped hydro energy storage be used as an **energy storage solution** for positive energy districts in Austria?

Figure 6 Visualization of the research questions and the methodology

3.1 Case Study

A case study can be described as an empirical method which examines a specific case within its real-life context (Yin, 2017). The case study examines a specific phenomenon "within the boundaries of one social system (the case) […] such as people, organisations, groups, individuals, local communities or nation-states, in which the phenomenon to be studied enrols" (Swanborn, 2010, p. 12). The case in this research covers a social system of a state, namely Austria (see below). To conduct such case studies several data sources can be used. Such data sources are typically documents or interviews, which are used as well in this research (Swanborn, 2010).
The aim of a case study can be multifaceted, e.g. a case study can test or develop a theory. As the topic of this research has not yet been investigated the case study should help to create a basic idea about the topic. Therefore, a case study is well suited to explore new topics (Eisenhardt, 1989).

As already stated above, a case study covers a specific social system, which can be rewritten with geographical scope in this research. The geographical scope in which the interviews were conducted is limited to the country of Austria.
This country was chosen through three reasons. First, Austria is located in central Europe and is part of the European Union (IEA, 2020). Therefore it is included in the Strategic Energy Technology (SET) Plan from 2008, which specified that 100 PEDs should be developed till 2025 (Bossi et al., 2020). Therefore, it is likely that Austria is a country in which PEDs were developed and will be developed in the future.

Second, Austria was chosen due to the topographical circumstances. This is since PHES requires specific topographical formations which allow a difference in height between the two water reservoirs (Hunt et al., 2020). In general Austria has an exceptionally divers landscape. Two-thirds of the country are covered with mountainous areas, in particular the Alps (IEA, 2020); however, also flat land can be found in the Vienna Basin. In addition, 350 km of the Danube flow through Austria, which, among other sources, such as the Lake Constance, supplies the country with a considerable amount of water (StatisticsAustria, 2022).
Moreover, Lindholm et al. (2021) stated that Austria has "the highest potential for pumped hydro storage" (p. 14).
Finally, the specific geographic scope was selected so that the general context is the same or does not vary as much as between different countries. For example, the same climate and energy strategy is being pursued within Austria. Moreover, do the local prosumer (producer and consumer) regulations e.g. for the self-consumption, differ between the states of the EU. For instance, Spain is regulating the balance per month whereas the Netherlands are doing it per year (Hedman et al., 2021).

Two different methods were used to collect the data that would help answering the research questions (see above). The literature review on the one hand helps to familiarise with the topic and can therefore be considered as a basis. The semi structured interviews on the other hand help to collect information in an efficient way (Swanborn, 2010).
Those two methods will be described in more detail in the following.

3.1.1 Literature review

The literature review is based on secondary data and the results can be found in section 2 Theoretical Framework as the results are part or the theoretical background for the topic. This literature review was conducted according to the traditional/ narrative approach, which can be described as a "critical analysis of the relevant, available literature on the topic of interest being studied" ((Hart, 1998) cited in Manu and Akotia, 2021, p. 70). The aim of the literature review is to bundle information about a specific topic by giving an extensive overview of contemporary literature. This information is the basis for further goals, in this case the information serves as the basis for the qualitative interviews (see section 3.1.2 Qualitative Interviews). A traditional literature review consists of six successive steps: (1) identifying topic for review; (2) searching for literature; (3) literature analysis; (4) synthesizing the findings; (5) writing the review; (6) referencing the literature (Manu and Akotia, 2021).
The topic for the literature review is based on the secondary research questions. The first secondary research question (SRQ1) asks for the ESSs which are suitable for PEDs. This can be answered with the help of literature or governmental documents about already existing PEDs. Therefore, it can be figured out what kind of ESSs are already implemented in PEDs from which can be concluded what kind of ESSs are suitable for PEDs. The second secondary research question (SRQ2) seeks for conditions that are necessary for including ESSs, in particular PHES, into PEDs. For this it is also appropriate to search for literature about PEDs, which address the topic of energy storage. Additionally, it makes sense to research more on the topic of PHES and what conditions are necessary for implementing such energy storage plants. The third secondary research question (SRQ3) seeks to establish a link between the first two secondary research questions and relates to the three different forms of PEDs, which are explained in more detail in section 2.3.1 Techno-environmental conditions. However, this question cannot be answered solely with the help of literature research, so additional qualitative interviews were conducted (see section 3.1.2 Qualitative Interviews). However, literature research can help to collect information about PHES in advance and to work out possible combinations of PHES and PEDs, which can then be confirmed or refuted by the qualitative interviews.

3.1.2 Qualitative Interviews

Interviews are a specific form of qualitative data collection in which the data is collected in the process of oral communication (Misoch, 2019). They are more organized and structured than usual conversations. With the help of questions and answers the two parties, belonging to a normal interview setting, try to accomplish the goal of the interview or the research. Millar et al. (1992) define interviews as "a […] dyadic interaction in which one individual plays the role of interviewer and the other one takes on the role of interviewee […]. The interview is requested by one of the participants for a specific purpose and both participants are willing to contribute" (p. 2) (Millar et al., 2017, Wildemuth, 2016).

The purpose of the interviews was to answer the research questions, in particular the third secondary research question (SRQ3). The interviews were designed to help confirm or refute the conditions for ESS identified by the literature review. In addition, the interviews should provide information on the extent to which PHES can be used to create storage capacity in PEDs.

Interview structure

In theory there exist different kinds of structures for qualitative interviews. A distinction is made between three different structures: standardized interviews, semi-structured interviews, and unstructured/ narrative interviews. In this research, a semi-structured interview was chosen. This interview form is characterized by the fact that the interview is based on a guideline (see section Interview guideline). This guideline serves to give a thematic orientation and thus to structure and organize the interview. This method gives the interview partner the opportunity to answer freely, which is not the case within a standardized interview. However, it gives the interview partner a precise direction in advance of what the interview is aiming at, which is not the case within an unstructured/ narrative interview (Misoch, 2019).

A specific form of the semi-structured interview is the expert interview. The term expert is described in more detail in the following section. In expert interviews, a distinction is made between contextual knowledge and operational knowledge. In this research, the operational knowledge of the experts is of particular interest. This is characterised by the actions of the expert and how these actions are structured and justified. In the specific case of this study, people are interviewed who have special knowledge about the processes and procedures in PHES and can thus provide information about the extent to which these PHES can be combined with PEDs (See section Interview Partners).

The interviews were conducted via telephone/ online meeting places, such as google meet as this has the advantage that participants from any region can be interviewed without traveling (Knox and Burkard, 2009). This is in particular a great advantage in times of COVID-19, as traveling and meeting each other increases the risk of an infection. An additional advantage of interviews via telephone is that the quality of the collected data increases, as the audio can be easily recorded without any quality losses (Knox and Burkard, 2009).

Interview Partners

The selection of the interview partners is an essential key point for qualitative research. Rubin and Rubin (2012) developed several points, which are essential to note when interview partners are recruited. According to the authors it is highly important to find an interview partner which is knowledgeable and experienced in the field of the research (Seale, 2007, Rubin and Rubin, 2012). Those interview partners are described by Misoch (2019) as experts. Experts are people who have a specific knowledge, which is not part of the common knowledge. The experts acquired this specific knowledge through their education or specific activities within an organization (Misoch, 2019).

As described in the previous section the expert must have operational knowledge. Therefore, mainly persons were selected who have special and profound knowledge about the operation and the functioning of PHES. People were selected who work in these plants and are therefore confronted with the processes on a daily basis, which enables them to gain expert knowledge about PHES. This in-depth understanding of PHES by the experts will help this research to identify opportunities that could allow PHES to be combined with PEDs.

Furthermore, it is important to have a variety in interview partners, which present different views on the topic. This helps to increase the credibility of the research. The interviewees should therefore represent different vantage points on the topic (Rubin and Rubin, 2012). To achieve this, it was tried to find interview partners which have different positions and different foci on PHES. On the one hand, two interview partners with a technical focus and, on the other hand, three interview partners with an economic focus were selected. Moreover, the PHESs were picked from different geographical locations and different federal states within Austria.

The interview partners selected according to the above-mentioned criteria are listed in table 3.

Table 3 Interview Partner

Interviewee	Position/ Description	Focus	Knowledge about PEDs	Acronym	Date
Interview Partner 1	Operations Manager of a power plant group, composed of 10 individual storage and pumped hydro energy storage plants Head of Operations and Maintenance	Technical	Knows it from literature in the context of topics such as climate neutrality, energy supply of the future, CO_2 neutrality, and energy transition No connection to PHES	I1	25.05.2022
Interview Partner 2	Mechanical Engineer Responsible for the overall coordination of all new large-scale power plant projects Project manager	Technical	Never heard of PEDs but looked up some information about PEDs for the interview Knows similar approaches/ concepts	I2	25.05.2022
Interview Partner 3	Energy economics with a focus on the flexible plants, i.e. storage and pumped hydro energy storage plants Leads the development of optimisation software Planning of new plants	Economical	Already heard of it on conferences but no detailed information No connection to PHES	I3	20.05.2022

Interview Partner 4	Head of the energy economy Responsible for power plant optimisation (Multi market optimisation)	Economical	Never heard of PEDs but looked up some information about PEDs for the interviews The general idea of PEDs was known Knows similar approaches/ concepts	I4	29.06.2022
Interview Partner 5	Responsible for the ecological part of the revitalisation of old power plants	Economical	Never heard of PEDs Knows similar approaches/ concepts	I5	13.07.2022

Interview guideline

The interview guideline is the red threat for the interview and entails several purposes. Most important is that it helps the interviewer to remember every subtopic that should be addressed during the interview (Magnusson and Marecek, 2015, Misoch, 2019).

According to Misoch (2019) interview guidelines are following three basic principles. The first one is *openness*, which means that the questions should be as open as possible but at the same time as specific as necessary. The interview partner should know what the question exactly aims at but should have the possibility to answer this question as freely as possible. He or she should not be pushed into a specific direction by the wording of the question. This can be achieved by designing the interview guide with general questions and follow-up questions. The general questions give the interviewee the freedom to answer the question in his or her own words. The follow-up questions, in contrast, help to ask for more specific details. *Openness* also include that the interview guideline can be flexible and e.g. the order does not necessarily have to be followed during the interview (Magnusson and Marecek, 2015, Misoch, 2019).

The second basic principle is the *processuality*, which means that the meanings in the guideline are not static, but can change due to the social interaction of the interviewer and the interviewee (Misoch, 2019).

Lastly, the *communication* is a basic principle of an interview guideline. That means that the language of the guideline should be adapted to the interviewee and that the questions should be formulated in a clear and easy to understand way. Moreover, only one question should be addressed at a time to reduce misunderstandings (Magnusson and Marecek, 2015, Misoch, 2019).

The guideline is structured in such a way that it starts with rather general questions, which become more specific and topic-related during the interview. In addition, the guide can be divided into three sections that build on each other. The first block deals with questions about the interviewee and more general questions about the subject matter. The second block refers to the specific topics of the question, such as the three different forms of PEDs. The last block contains additional questions that play a subordinate role and could be discussed if there was enough time.

The complete interview guideline can be found in appendix 1.

Evaluation of the Interviews: Typologizing analysis

For the evaluation and analysis of the interviews, a typologizing analysis was conducted. This analysis procedure is composed of four different steps, which are explained in more detail below.

First, the audio recording of the interview is *transcribed*. When transcribing, the audio files are converted into text files. For this research, the scientific method of transcription was chosen, in which everything that was spoken is reproduced word by word. Thus, no changes are made to what was said, which means that sentence breaks or filler words must also be transcribed (Fuß and Karbach, 2019).

Second, the transcribed interview is *coded*. This means that the individual interview passages are sorted according to their topic. This helps to condense the interview and thus to focus on the important content (Misoch, 2019).

Third, the *thematic comparison* follows. Here, similar topics or codes of the different interviews are bundled (ibid.).

The last step is the *typological analysis*, in which the organization of the topics is changed. In the third step, the contents are still sorted according to the interviews. This changes in the typological analysis, in which the topics determine the sorting. Thus, the topics are in the foreground (ibid.).

3.1.3 Ethical considerations

As the research method, in particular the qualitative interviews, used for this research include external people (the interview partners), it is important to pay attention to the wellbeing and satisfaction of those. To ensure this, it is necessary to follow certain guidelines. These guidelines are based on Misoch (2019) and will be introduced in the following section.

Participation in the interview took place on a voluntary basis, about which the interview partners were informed (ibid.).

Before conducting the qualitative interviews, care was taken to ensure that the interviewees were informed about the topic and the objective of the research. For this purpose, a written declaration of consent form for the interview was concluded with the interviewee. This declaration of consent can be withdrawn by the interviewee at any time. In addition, consent was requested to audio-record the interview, and the further processing of the data was pointed out (ibid.).

Attention was also paid to protect the privacy of the interviewees by keeping them anonymous. This anonymity was assured to the interviewees in the written declaration of consent before the interview (ibid.).

In order to prevent misinterpretation of what was said, care was taken to ensure that the transcription of the interviews was carried out according to the above-mentioned guidelines (ibid.).

4 Results

This section is going to present the results of the conducted interviews. The structure of this section is based on the coding of the interview transcripts, which is strongly oriented towards the interview guide starting with the general technical and economic feasibility of the implementation of PHES into PEDs. Continuing with information about concerns, energy communities, origin and sources of energy, storage duration, and energy grid. Those coding topics are again divided into general and specific assumptions.

As the interviews were conducted in German, all interview quotes were translated into English without changing the content of what was said. For the sake of simplicity, the interviews are referred to below only by the abbreviations of the interview partners (I1 – 5, see table 3).

4.1 General Assumption

The general assumptions of the different interview partners about the topic of PEDs were often influenced by their professional background (see table 3). One interviewee, for example, never heard of PEDs before, however noticed a trend towards such concepts and stated: "also, in general, the idea is moving more towards regional/ local, more towards topics where people say they want to deal with the topic of energy and nature, resources, in a completely different way and, of course, completely new endeavours are emerging as a result" (I2). Next to this, I3 stated that the possibility of pumping water as a storage possibility increased in the past years strongly and explained that "in recent years [they] have mostly built pumping capacities. This is actually something that [they] have increasingly done in the last 10 to 15 years. In the past, it was primarily storage power plants and now pumps are increasingly being used as an additional option because there are more and more hours, or at least that is what [they] expect, when energy is almost free" (I3). This is strengthened by another interviewee who stated that a few years ago the share of coal-fired power plants was still over 50%, but this has declined significantly in recent times as the share of RE continues to increase (I5).

4.1.1 Technical and Economic Feasibility

The interview partners were asked about the technical and economic feasibility of the implementation of a PHES into a PED. They were asked about potential techno-environmental factors and socio-economic factors that could affect this implementation in a positive or negative way.

The general assumption about the technical feasibility was mostly positive. One interviewee responded that technically nothing would oppose the use of PHES as ESS in PEDs (I5). Next to this, I1 stated that the idea could indeed work, due to the beneficial characteristics of a PHES, such as flexibility in start and stop and the robustness and reliability of PHES (I1). This was also confirmed by three other interviewees (I2, I3, I4). For example, one interviewee said that "this technology is still the most efficient on a large scale and, with an overall efficiency of 78 to 80 %, it is still incomparable with all other technologies" (I2). Additionally, informant I3 highlighted that "[PHES is] a very attractive storage because it has such a high efficiency and because it naturally has a longer storage period" (I3) and that "if you need this product and if it makes economic sense for you, then of course this is the best you can find" (I3). Moreover, I4 reported that PHES fulfils exactly the functions that a PED needs, in particular the compensation of quarter-hourly electricity imbalances (I4).

In one case, a participant also focussed on the sustainability characteristics of PHES and reported that PHES compensates the produced CO_2 emissions within one year, while having a lifespan of almost 100 years (I2).

Next to the positive opinions there were also some potential obstacles mentioned by the interview partners. Technical concerns were expressed about the geological, geographical, and topological characteristics of the landscape by all interview partners (I1, I2, I3, I4, I5). For example, there was an increased debate about the availability of water and the availability of differences in altitude, which was mentioned by informant I1, who stated that "a certain geography or geology [and] differences in altitude [are needed] so that it is technically feasible at all, and if it is feasible, then also the resource water supplied somewhere [is needed]" (I1). However, one interviewee expresses that the specific landscape characteristics can also be seen in a more positive way by saying: "Europe is very interesting [for PHES] because the Alps are located between large conurbations and are very densely populated and cultivated and have a lot of power plants" (I3).

Participant I4 and I5 addressed next to the natural characteristics of a landscape also the importance of the availability of a connection to the energy grid, or the high-voltage grid. Based on those different landscape characteristics I4 concluded that "there are not so many places possible in the world for plants that are economically viable" (I4).

Next to the concern about the landscape characteristics, I1, I4, and I5 also mentioned that PHES is a major intervention in nature and that environmental concerns must be taken into account (I1, I4, I5).

Furthermore, participant I4 explained that a construction of a PHES especially for a PED is not economical and far too expensive (I4), which is due to the reason that many small components are needed for the construction of a PHES and that therefore the economies of scale play a major role (I4, I5). This is confirmed by interviewee I5, who stated that the construction of a PHES needs "an upper basin, a lower basin, drive water guides in between the basins; usually special plant components are also required to compensate for dynamic processes and a power plant in between. The power plant must at least have a pump, otherwise a generator and also energy cable infrastructure, transformer stations, and similar things, so that the whole thing functions technically" (I5). I5 further explained that the larger the PHES, the lower the transport losses, as a larger PHES can use high-voltage lines and can thus transport the electricity over further distances. He concluded by saying that the "smallest PHES [they] have developed has 15 MW and that it was clearly recognisable that the effort is significantly higher for a small PHES compared to the large ones, purely in terms of the specific costs. Just breaking down the different components from 100 MW, that such a PHES can have to e.g. 10 or 15 MW, has already meant that the specific costs have gone up enormously" (I5).

Next to the aspect of the economies of scale participant I3 gave another reason why a direct connection between a PHES and a PED is less economical. I3 stated that PHES always act in combination, thus generating better efficiency levels. This was further deepened by explaining that there is never only one plant which operates separately for one client, as the hydraulic losses of the PHES would increase in the case of a one-to-one transfer of energy (I3). This is also since the PHES would be more underutilised in a one-to-one transfer, as it would only be used if there was a local surplus of energy in the PED (I3). Therefore, participant I3 mentioned that they "never have a power plant that runs at full capacity for a customer or someone else, because then you would have very high losses, but we always try to adapt it optimally" (I3).

Next to the fact, that it is less reasonable to build or utilise one PHES for one PED, the interview partners mentioned a more economic related opportunity for implementing a PHES in a PED, which is the use of a PHES as a virtual storage method (I2, I3, I4, I5). Participant I4 declared it is virtually possible to return the energy from one PED to the same PED (I4), which can be done with the help of certificates (I2). Those certificates can provide the origin of the energy virtually or on balance sheet (I4). They can be produced if an energy provider has a surplus of energy (I2). Interviewee I3 stated that "virtually [you can] always provide these storages under the inclusion of the public grid, there is a lot of that, you can also offer that to other companies that want to balance" (I3). Such other companies could e.g. be large industrial companies that have a very high demand for flexibility- or balancing energy. Such companies can then buy virtual power slices from a PHES, which could also be possible for PEDs (I3). However, another interviewee expressed concerns about the current electricity price development, which occurs due to several political and non-political reasons, as the price for such virtual power storage is increasing as well (I5).

Next to the general idea of virtual storage, participant I2 proclaimed the concept of virtual solar storage. In this concept, energy from a private PV plant is fed into the public grid and then stored in PHES on a balance sheet basis. This energy can be taken back from the grid on a later date without paying grid fees. Instead, a certain monthly amount is paid for the service, which ranges from 10 € to 40 € (I2).

Lastly, I2, I4, and I5 addressed the social aspect of the implementation of PHESs in PEDs. Participant I2 argued on the one hand that the energy transition is a socio-political issue, and that the society has an influence on the pace of the transition and the possible solutions. I4 mentioned on the other hand that PEDs help to spread further the idea of RE and energy transition, which helps to bring RE technologies, such as PV, closer to the consumer. However, I4 mentioned that PEDs are not the only concept with this aim. Next to this, another participant argued that the socio-economic conditions are rapidly changing, which includes the perception of the society in regards of changes in the energy sector. However, he mentioned that the awareness of the importance of RE and therefore also the importance of PHESs is increasing due to higher pressure on the own demand of energy (I5).

4.1.2 Concerns

One most widespread concern about the implementation of PHES into PEDs was mentioned by I1, I2, and I4. Those three participants shared the view, that concepts such as PEDs question the existing synchronous grid of continental Europe (I1). This results in the fact that the energy system could be less flexible and resistant against fluctuations (I1). This is confirmed by I3, who stated that the energy grid in Europe is highly resistant and that the independence from this grid is not only advantageous (I3). Furthermore, this is underpinned by I4, who explained several advantages of the existing energy gird, such as the mutual support between countries in Europe, which is especially important if a power plant fails, or resources are lacking. As an example, I4 mentioned the energy exchange between Germany and Austria, in which Austria takes the function as energy storage. Another advantage that was mentioned is that the energy grid ensures financial savings for all involved (I4). Therefore, I4 stated: “if I break it down further and further and make it smaller and smaller, then the consequence is that the market will become smaller and smaller, that these mechanisms will become smaller and smaller and that I might possibly make an overinvestment because I always need the same infrastructure” (I4). Next to those concerns, I4 explained further that European legislation wants to further strengthen the “European copperplate” (I4) instead of dissembling it.

Another concern mentioned by interviewee I5 addressed the scale differences between a PHES and a PED. He argued that the “value of the energy that can be generated with such PHES is higher and this energy serves to ensure the right balance in the grid at all times and, above all, to balance the volatile renewable energies” (I5). This means in detail that this balancing energy is more important than compensating fluctuation in a small-scaled PED (I5).

Another concern regarding the implementation of PHES into PEDs is the lack or regulations regarding PEDs in Austria and achieving energy flexibility in those (I1).

4.1.1 Energy Communities

The concept of energy communities (see section 2.3.2 Socio-economic Conditions) was also mentioned by several participants (I1, I2, I4, I5). Those energy communities are supported by the European legislation (I4) and are small scaled and geographically restricted (I1). They can be composed of private or self-interested companies (I1), which can be e.g. neighbours, semi-detached houses, or high-rise buildings with several condominiums (I2). The advantage of such energy communities is that they can use the existing grid infrastructure, however, the energy is still produced and consumed locally (I1). The participant mentioned this concept, as they thought it is similar to the concept of PEDs, however, it is more widespread and thus better known in Austria.

4.2 Specific Assumptions

4.2.1 Origin and Source of Energy

The energy that is used in PHES for activating the pumps is always electrical energy within every PHES (I1). This electricity is taken from the existing public grid and is also returned to it (I1, I2, I3, I5). Therefore, the exact origin of the pumped electricity is not comprehensible, as the energy grid can be seen as an energy lake in which the water/ energy is blurred together (I4). However, the energy moves along the physical framework, which means that it flows along the least resistance (I4) and that the energy has a specific catchment area based on the voltage line (I2). Participant I2 further explained that "the higher the voltage, the further I can transport [the electricity] […] and there is also a rule of thumb, that says, that one km can be transported per kV; at 380 kV I am roughly in the order of 400 km" (I2). This has the effect that every energy plant, also those that are not renewable, within a radius of approximately 300 km to 400 km around the PHES is potentially stored in the PHES (I2).

Therefore, one interviewee stated: "as long as there are power plants in our area, let's say, somewhere within a radius of 300 km that are fed by fossil fuels, and we all know that there are still gas-fired power plants that are needed to cover peaks in order to be able to simply establish stability in the electricity grid, we cannot guarantee that we will have 100 % of this [renewable] energy here" (I2). This is the reason why PHESs are currently not seen as RE, as the pumped energy can never be 100 % renewable as long as non-renewable energy sources exist (I1, I2, I3).

However, this can be circumvented by providing information about the origin of the stored energy in the form of certificates (I1, I2, I3, I4, I5). These guarantees of origin can come from anywhere, for example from Austria itself or the company's own production, which also operates the PHES, or from Norway, a country that produces a lot of RE (I2, I4, I5). Such certificates could also be produced by PEDs, as they have their own energy generation facilities within a certain geographical or virtual boundary (I4, I5).

On the basis of this prove of origin the current regulatory framework is changing. This leads to the fact that the energy character of a PHES, if it is seen as RE or non-renewable energy, is potentially changing in the future, due a new definition (I3).

4.2.2 Storage Duration

PHES can store electricity about different periods. All interview partners (I1, I2, I3, I4, I5) mentioned three different forms of energy storage. The first one is the daily storage, which store the energy for 24 to 48 hours (I1) or e.g. from the morning to the evening (I3, I4). The second one is the weekly storage, which balances load peaks during the week (I3). The last one is the yearly storage, which helps to shift the energy from summer to winter (I3). For the yearly storage a huge storage capacity is needed (I4).

One interviewee explained that the storage duration of an open PHES with natural water inflow is influenced by two overlapping topics (I5). On the one hand, the water inflow is low in winter, as the water is bound in ice and snow, and high in spring and summer, due to snowmelt (I2, I4, I5). This leads to the fact that after the winter the storage capacity must be high so that the inflowing water can be stored (I5). On the other hand, the storage duration is influenced by the daily fluctuations of the energy grid, which need to be compensated by PHES (I5).

4.2.3 Energy Grid

In the normal case a PHES is connected to the electricity grid via a transformer station or a grid connection point (I1, I2) and feeds in at the highest voltage level (I3, I4). In special cases there can be direct connections between a generation plant and the PHES, if they have the same grid connection point and a small distance to each other (I1, I3). This is confirmed by I4 who explained that an off-grid option is possible if there is proximity of the two plants and they share the same grid connection point. However, it must be considered whether this really brings a meaningful economic advantage, or whether virtual storage is the more simple and more cost-effective solution (I4).

Therefore, participant I1 and I5 pointed out that technically it would be easy to circumvent the energy grid by building separate energy cables, however there are multiple obstacles, next to the proximity factor. For instance, it is not approvable to build a secondary grid, as the supply infrastructure may only be operated and constructed by the grid operator (I1). Therefore, I1 stated that "the framework conditions say that the grid infrastructure, i.e. the general supply infrastructure, is operated and built by the grid operator, and that only the grid operator is allowed to do this, so that there are no parallel structures" (I1). Such a parallel grid infrastructure would not make sense from an economical point of view (I1) as a functioning gird infrastructure already exists (I5). In particular, this makes little sense for small-scale PEDs, as the benefit of such a parallel network infrastructure would be very small (I5). Additionally, participant I3 was arguing that the existing energy grid is well functioning and that there is no reason to circumvent it: "if I am on a large grid, I am extremely resistant, i.e. extremely secure in terms of supply, if something fails again; and I can simply make the best use of the geographical strengths of the various regions; wind, water, solar is always somewhere else, so I am a fan of the grid and see virtual use as the most sensible, i.e. having a really strong grid" (I3).

5 Discussion

The present research was designed to find out to what extend it is possible to use PHES as a storage method in PEDs. Therefore, different conditions are elaborated, which are based on the categorisation of Ali et al. 2021. Those conditions are composed of drivers and barriers of techno-environmental and socio-economic factors and are based on the literature review and the interview results. In this section those conditions are discussed with regard to the three different forms of PEDs (see section 2.3.1 Techno-environmental conditions) to answer the secondary research question 3.

Before discussing the specific conditions, the general results (see section 4.1 General Assumption) of this research will be considered. They indicate that some of the interview partners never heard of the PED-concept, and no one heard of it in relation to PHES. This clearly shows that the idea of integrating PHES into a PED has not yet been discussed in practice nor in the literature, which means that more research is needed on this topic. However, RE shows a distinct effect on the use of PHES, e.g. one interesting finding was that the pumping possibilities of storage power plants increased in the past years due to the assumption that energy supply will change in the future due to RE (I3).

5.1 Conditions for using PHESs in PEDs

The conditions for using PHES as an energy storage method in PEDs are presented in the following in detail and are summarized in table 4.

Table 4 Techno-environmental and socio-economic factors influencing the implementation of a PHES in PEDs.

Drivers and Barriers	Factors	Interviewees
Techno-environmental drivers (TED)	Technical characteristics of PHES	I1, I2, I3, I4, I5
	Sustainability	I2
	Landscape characteristics	I3
	Minor grid losses	I3, I4
Techno-environmental barriers (TEB)	Energy sources	I1, I2, I3, I4, I5
	Proximity characteristics	I1, I2, I4, I5
	Landscape characteristics	I1, I2, I3, I4, I5
	Environmental concerns	I1, I4, I5
Socio-economic drivers (SED)	Virtual energy storage	I2, I3, I4, I5
	Certificates	I1, I2, I3, I4, I5
	Related concepts	I1, I2, I4, I5
Socio-economic barriers (SEB)	Economies of scale	I4, I5
	Synchronous grid of continental Europe	I1, I3, I4
	Social acceptance	I2, I4, I5
	PHES operate in a network	I3

5.1.1 Techno-Environmental Drivers

The techno-environmental drivers (TED) are composed of four different sub-categories, which will be discussed in the following: Technical characteristics of PHES, sustainability, landscape characteristics, and minor gird losses.

Technical Characteristics of PHES

The technical characteristics of PHES are favourable for the use of this storage method in PEDs. Those favourable technical conditions were explained by the interview partners. It was mentioned for example that PHESs have a high efficiency (I2, I3), that they are flexible in use, and robust and reliant (I1). This is also confirmed by literature, such as Hino and Lejeune (2012), Ali et al. (2021), or IRENA (2012), which stated numerous advantages of PHES. Those advantages of PHES could help to integrate PHES into all three forms of PEDs (autonomous, dynamic, virtual), as they are all seeking for energy flexibility (Erba and Pagliano, 2021) and an efficient way of energy storage (Krangsås et al., 2021) (see section 2.2 Positive Energy District as a Concept). PHES can therefore help to achieve this energy flexibility by providing an efficient and robust energy storage solution (I1, I2, I3). Because of these technical features and the general way, the power system is built, there is in a technical sense nothing stopping a PHES from being implemented in a PED (I1, I5).

The storage duration of a PHES can vary between daily, weekly, and yearly storage (I1, I2, I3, I4, I5). This is advantageous for all three forms of PEDs, as a PED is supplied by RE (Derkenbaeva et al., 2020). Different kinds of RE need different kinds of storage durations as they fluctuate not identically during the year and the day (Stoppato and Benato, 2017).

However, the natural water inflow of open-loop PHES, which is, due to icing and snowmelt, low in winter and high in spring and summer, needs to be considered (I2, I4, I5). This is because a PHES must have sufficient capacity in spring to absorb and store the water that accumulates (I5). This would probably mean for PEDs, that less water can be stored in spring and summer due to the high natural water inflow. Nevertheless, this depends on the size of the PHES, as larger PHESs can store a higher amount of water (I5).

The technical characteristics of PHES are addressed by all interview partners, which expresses the importance of this condition for the implementation of PHES in a PED as an energy storage solution. Based on those findings there is no opposition based on the technical conditions of PHES for the implementation of PHES in all three forms PEDs.

Sustainability

As mentioned in the literature review, Ali et al. (2021) explain that CO_2 emissions can be reduced, when PHES is used to store RE. On the one hand, this is because PHES does not emit CO_2 when producing energy (Hino and Lejeune, 2012). On the other hand, PHES-Plants have a relatively long lifespan (Deane et al., 2010). This was verified by one interviewee, who explained that the CO_2 that is emitted during the construction of a PHES is compensated within one year. The long lifespan of such a plant additionally increases the sustainability of PHES (I2). These results are in agreement with one of the main characteristics of PEDs, which says that PEDs should foster the energy transition and in particular climate neutral cities (Gabaldón Moreno et al., 2021, Lindholm et al., 2021). It can therefore be assumed that PHES could help to achieve this aim of PEDs, as it does not cause CO_2 emissions and contributes to the district's climate neutrality. Moreover, this applies to all three forms of PEDs, as they all aim for climate neutrality and as little as possible CO_2 emissions.

Landscape Characteristics

Landscape characteristics for implementing a PHES are mostly seen as TEB by literature and the interview partners (see section 5.1.2 Techno-Environmental Barriers). However, they can also act as TED. This is shown by one interviewee who stated that especially the Alps are an interesting region to locate PHES-Plants (I3). This is on the one hand due to the favourable geological and topographical conditions and on the other hand due to the reason that the Alps are located between large conurbations. This has the effect that the energy and electricity demand is high and therefore the demand for PHES is also high. This finding is consistent with that of Ali et al. (2021) who explain that the presence of specific landscape characteristics, such as found in Austria, can reduce the construction costs and is therefore advantageous for the implementation of a PHES.

In general, therefore, it seems that the Alps including Austria have beneficial landscape characteristics for PHES, which in the inverse is beneficial for the implementation of PHES in PEDs in Austria.

Minor gird losses

PHES-plants feed in at the highest voltage level (I3, I4), which has the effect that the electricity can be transported over long distances without a significant loss of electricity. According to this the distance of the PED to the PHES is less relevant. However, this statement only applies to virtual PEDs, as autonomous, and dynamic PEDs are restricted to their geographic boundaries and thus cannot use virtual storage outside these boundaries (Lindholm et al., 2021).

There are multiple TEDs, which help to implement PHES into PEDs. The technical characteristics, sustainability, and landscape characteristics apply to all three forms of PEDs, as those three sub-categories are not influencing the geographical boundaries of the PED or the interaction with the grid. The distance between a PED and a PHES is only relevant for virtual PEDs, as this is the only form, which is allowed to act within a virtual boundary and is therefore less bound to the geographical proximity.

5.1.2 Techno-Environmental Barriers

For the techno-environmental barriers (TEB) four sub-categories play an important role in the implementation of PHES into PEDs. Those four points, namely energy sources, proximity characteristics, landscape characteristics, and environmental concerns will be discussed in the following.

Energy Sources

The energy which is used for pumping the water to the upper reservoir in a PHES is in the normal case taken from the energy grid (I1, I2, I3, I5). As the sources of the electricity fed into the grid are indistinguishable, it cannot be physically guaranteed that only RE has been stored as long as non-renewable sources are present. This is the reason why PHES is currently not considered as RE (I1, I3).

This result is problematic because Derkenbaeva et al. (2020) define PEDs in such a way that they must obtain their energy exclusively from renewable sources, so that the districts are as carbon neutral as possible (IEA EBC Annex 83, 2020).

This issue is most relevant for dynamic and virtual PEDs as those two types are interacting to a greater extent with the electricity grid than autonomous PEDs.

However, to solve this issue certificates could help to provide information about the origin and therefore also the source of energy that is used for pumping (see section 5.1.3 Socio-Economic Drivers). Furthermore, one interviewee explained that the regulatory framework for this issue is currently changing and could be redefined so that PHES may be considered as RE in the future (I3). Should this change occur, this TEB could be abolished.

Proximity Characteristics

Ali et al. (2021) considered proximity characteristics as a SED due to the fact that energy losses during the transport would help to implement PHES close to energy generating plants, such as a wind park. However, when comparing this result with the statements of the interview partners different results were narrated. One interviewee reported that when transporting the electricity at the highest voltage level there are hardly any losses (I3), and PHES normally feeds in at the highest voltage level (I3, I4). This finding contradicts the finding of Ali et al. (2021), and states that the distance between PHES and the consumer or the energy supplier does not play a decisive role with regard to the loss of electricity.

However, in this research the proximity characteristics can rather be seen as a TEB. As mentioned in Lindholm et al. (2021) autonomous and dynamic PEDs are strictly bound to their geographical boundaries in regard to energy generation. Therefore, only a small distance between a PHES and a PED would make the combination of both possible, so that the PHES would lie inside the geographical boundaries of the PED. One interview partner reported that it is indeed possible to have an off-grid connection if there is a close proximity (I4). Anyway, this is only possible if the PED and the PHES share the same gird connection point (I1, I3) otherwise there would emerge a parallel grid infrastructure, which is not approvable, as only the grid operator is allowed to build and maintain the gird (I1). Furthermore, the interview partners questioned the economic viability and suggested that a virtual solution could potentially be less elaborate (I3, I4).

Often a proximity between a PED and a PHES is not possible due to the special landscape characteristics of PHES.

Landscape Characteristics

As already indicated above, the landscape characteristics are mostly seen as a TEB. All interview partners agreed in the opinion that for the implementation of a PHES-plant certain geographical, geological, and topographical circumstances and the access to the resource water are necessary (I1, I2, I3, I4, I5). This finding is consistent with that of Ali et al. (2021) who listed landscape topology, water, and geography as separate TEBs. This study confirms that those landscape characteristics are highly important for the successful implementation of a PHES. Those special landscape characteristics can be found in Austria, as explained above, however this is not transferable to countries with a lack of those characteristics, which makes it almost impossible to implement PHES in such countries.

With regard to PEDs, this TEB poses, especially for autonomous PEDs, a significant problem. Due to the special and often inaccessible locations of PHES, it is often not possible to have an urban area, such as a PED, in the close surrounding. Autonomous PEDs are, however, not allowed to interact with the energy grid (Lindholm et al., 2021) and are therefore heavily influenced by proximity characteristics (see above). This is further confirmed by Lindholm et al. (2021) who elaborated in their study that PHES is the most cost-effective method for ESS, but it cannot be implemented in urban areas because of the low energy density.

Furthermore, this TEB constitutes a problem for dynamic PEDs. These are allowed to interact with the grid in both directions but are not allowed to generate energy outside the geographic boundaries (Lindholm et al., 2021), which is why the problem of proximity applies likewise to dynamic PEDs.

It can therefore be noted that landscape characteristics complicate the implementation of PHES in autonomous and dynamic PEDs, due to the proximity issue explained above. This TEB poses consequently less of a problem for virtual PEDs, as those PEDs are less bound to the geographical boundaries and are allowed to generate and obtain energy within a virtual boundary, which allows the PED to have a greater distance to the generation plants (Lindholm et al., 2021).

Environmental Concerns

Previous studies evaluating conditions of PHES observed that implementing PHES has a negative impact on biodiversity and the environment (Lu et al., 2020, Ali et al., 2021). Consistent with that literature, the interview participants narrated that environmental concerns must be taken into account when implementing and maintaining PHES (I1, I4, I5).

This must be seen as a TEB, especially if a new PHES would be built for a PED, however one interviewee saw such a construction of a PHES for a PED as too expensive and therefore not as economically sensible (I4).

Next to this, the concept of PEDs is aiming for carbon neutrality and hence tries to foster the energy transition (IEA EBC Annex 83, 2020). This energy transition follows the overarching goal of protecting the climate and thus the environment (Tsantopoulos, 2022). The unsustainable aspect of the PHES, which is described above, speaks against these ambitions and thus in a way contradicts the rules of the PED-concept.

The TEBs explained above could be potential obstacles for the implementation of PHES into PEDs. They are specifically obstructive for autonomous and dynamic PEDs, as those two types are highly limited in regard to their geographical boundaries and are not allowed to use virtual power plants, such as the virtual PEDs. The TEBs regarding the energy source and environmental concern could be troublesome for all three forms of PEDs. However, the TEB "energy source" is less relevant if the regulatory framework will change. With regard to the environmental concerns, the question of the extent of harm and the extent of benefit is relevant. Thus, the degree to which the benefits of a PHES as ESS in a PED outweigh the harm to the environment must be considered. This would have to be examined in further studies.

5.1.3 Socio-Economic Drivers

There are three sub-categories which can be assigned to socio-economic drivers (SED). This includes virtual energy storage, certificates, and related concepts, which are explained and discussed in the following with a view to the literature review and the conducted interviews.

Virtual Energy Storage System

There are similarities between the literature and the interview regarding virtual energy storage. Several studies have shown that virtual energy storage system (VESS) is a suitable option to store surplus energy without owing an own ESS (Liu et al., 2017, Oh, 2021). These results corroborate the findings of a great deal of the interviews. To be precise, the results of the interviews further supported the idea of VESS by stating that this is the most economically viable way to use PHES as energy storage in PEDs (I2, I3, I4, I5). This would beyond that include all the advantages of the electricity grid, as the virtual storage is grid-based (Oh, 2021) (see SEB Synchronous Grid of Continental Europe).

The concept of VESS is however only suitable for virtual PEDs as only this form of PEDs is allowed to obtain energy supplier outside the geographical boundaries (Lindholm et al., 2021) (see TEB proximity characteristics and landscape characteristics).

To use virtual energy storage one option could be the use of certificates, which will be explained in the following.

Certificates

If the surplus energy of a PED is to be stored virtually in a PHES, it must be ensured that it is possible to trace how much energy is exchanged on a balance sheet basis. This is important as the energy is transported via the public electricity grid (Liu et al., 2017) in which it is physically not reconstructable where the energy has its origin (I4). To guarantee where the energy comes from one possible solution was mentioned by the interview partners. All interviewees reported that they use certificates in their company to have a proof of origin of the energy they use for pumping (I1, I2, I3, I4, I5). This is done to ensure that they use 100 % RE for maintaining the PHES-plants. The certificates can be generated from every energy generation plant and therefore also from the generation plants within a PED (I4). As such certificates can come from everywhere, e.g. from Norway (I2, I4) the distance between the PHES and the PED is less important.

Since an energy exchange with the public grid is a necessary basis for virtual energy storage or for the use of certificates to trace the energy origin in the balance sheet, these approaches can only be used in virtual PEDs. Dynamic PEDs, could also use certificates to be able to track how much energy has been fed into the grid and how much may be withdrawn. Autonomous PEDs are only allowed to export energy to the grid (Lindholm et al., 2021), therefore it is not possible to import energy from the grid, which makes the solution to use certificates and virtual energy storage not feasible. Nevertheless, it is possible for autonomous PEDs to generate certificates to sell those to e.g. PHES, so that they can prove the renewable origin of the energy used.

Related Concepts

When asking the interviewees if they ever heard of PEDs some answered that they do not know the concept of PEDs, however, already heard of and worked with similar concepts. One concepts that was mentioned several times was the concept of energy communities (I1, I2, I4, I5). Such energy communities are, similar to PEDs, small scaled and geographically limited (I1), and have the main goal to produce energy from renewable sources in a decentralized way (Österreischiche Koordinationsstelle für Energiegemeinschaften, 2022).

The fact that the interviewees heard more about energy communities than PEDs suggests that energy communities are more widespread in Austria than PEDs. However, energy communities could also help to further advance the concept of PEDs by serving as templates and e.g. adopting possible legal adaptations.

Another concept that was mentioned was virtual solar storage. This concept could additionally help to use PHES as virtual storage, by providing e.g. a legal framework which can serve as a foundation for PEDs.

Three SEDs were mentioned above, which can help to use PHES to improve the energy flexibility in PEDs. Certificates can be generated by all energy providers and hence also by PEDs. This is especially supportive for virtual and dynamic PEDs, as they are allowed to interact with the electricity grid in both directions. In contrast, certificates for the guarantee of energy origin within VESS can only be used in virtual PEDs, as virtual energy storage requires virtual generation plants, which are only permitted in the concept of virtual PEDs.

Related concepts, such as energy communities or virtual solar storage, can function as SEDs by helping to further distribute the idea of PEDs and to implements new PEDs in Austria based on the related concepts. Those concepts could function as best-practice examples from which PEDs could learn.

5.1.4 Socio-Economic Barriers

The barriers which relate to socio-economic factors (SEB) are composed of four sub-categories: economies of scale, network-operation, synchronous grid of continental Europe, and social willingness.

Economies of Scale

As mentioned in the literature review, Glasnovic and Margeta (2011) stated that the implementation of small-scaled PHES-plants is often associated with fewer complications, such as the construction site search. However, the findings of the current study do not support this previous research. It might be correct that it is easier to find construction sites for small-scaled PHES-plants (see TEB Landscape Characteristics), however the implementation is less economical than the construction and maintenance of large-scale plants (I4, I5). This is explained by the fact that for the construction of a PHES, irrespective of the size of the plant, numerous components are needed (I5). When these different components are scaled down, the specific costs increase, so that smaller PHESs are due to economies of scale specifically more expensive than larger ones (I5). Beyond that, the energy generated by a PHES has high value in regard to gird stability and balance. Therefore, one interviewee narrated that it is more important to use this high value energy to stabilize the grid than to supply small-scale PEDs.

This finding clarifies that it does not make economic sense to set up or operate a small PHES for a PED. This in turn increases the TEB landscape characteristics as this is amplified when having larger PHES, as Glasnovic and Margeta (2011) explained. This is particularly problematic for autonomous and dynamic PEDs, as those two types are only allowed to generate energy within their geographical boundaries (Lindholm et al., 2021). For virtual PEDs, this SEB is less of a hurdle, as this type is allowed to produce outside the geographic boundaries (Lindholm et al., 2021) and thus has the option of virtual energy generation (see above), where distance plays a subordinate role.

This SEB is strengthened by the following SEB network-operation.

Network-Operation

As already stated, it is less economical and efficient to build a PHES for a PED. This is enforced by the fact that PHESs are always operated in a network, which means that the energy to be pumped is distributed among different power plants so that they all achieve the best possible efficiency (I3). This is confirmed by one interviewee who stated that an exchange of energy between one PHES and one PED is not efficient, due to hydraulic losses and underutilization when having one PHES operating for one customer (I3). Since PEDs are aiming for a high energy efficiency (Erba and Pagliano, 2021), a one-to-one transfer would reduce the overall efficiency and would therefore contradict the ambitions of a PED. Hence, this SEB applies to all three forms of PEDs, as all are pursuing the goal of energy efficiency (Erba and Pagliano, 2021).

Synchronous Grid of Continental Europe

The most frequently reported concern in this research was that PEDs are questioning the synchronous grid of continental Europe. This was justified by the interview partners by the fact that concepts such as PEDs make the energy system smaller and more fragmented, making it less and less reliable (I3). Those aspects are in turn strengthened by the synchronous grid of continental Europe. However, the current trend in the energy system is moving towards a more decentralized energy system, with the result that energy is not further managed in a centralized and therefore top-down approach (Villamor et al., 2020, Aslam et al., 2021). This result is in agreement with the statement of one interviewee who stated that there is a trend towards a more regional and local approach, in which the citizens are more included (I2). This contradiction may be explained by the different backgrounds of the interview partners. Those interviewees, which were supportive for the synchronous grid of continental Europe had a more economical influenced position, whereas the ones that were more technical oriented were less focused on the grid.

Regardless of the functionality of a decentralized system, it must be noted that the grid provides a certain flexibility and thus stability, which is a problematic aspect within PEDs. This lack of flexibility is why ESSs are necessary in PEDs in the first place. However, decentralized energy systems have likewise advantages (Strandberg, 2021). Those two aspects need further elaboration, to give a clear answer, which approach is more efficient, flexible, and future oriented.

Social Willingness

The last SEB is focusing more on the social aspect than the economical aspect. The results of this research indicate that social willingness plays a major role in the energy system. Social willingness can have an influence on the pace of the energy transition and the implementation of new concepts such as PEDs (I2, I4, I5). This also accords with earlier observations of Ali et al. (2021), which showed that public opposition can act as a barrier to the construction and operation of a PHES. This is consistent with the statement of Seetharaman et al. (2019), who stated that a lack of public awareness is often a huge barrier. Building on this statement, one interviewee narrated that awareness and therefore the willingness is mostly increasing when the pressure on the own energy demand is increasing (I5). Therefore, it can be said that there needs to be more enlightenment in regard to the energy sector and its problems. Decentralized concepts such as PEDs, can help to spread the idea of the energy transition further in society and therefore could increase the awareness and willingness to change the system. This would then include PED projects with an increased flexibility due to e.g. PHES.

SEBs are potential hurdles to the use of PHES as energy storage in PEDs. The SEBs economies of scale and network-operation both show that operating or building a PHES-plant for a PED is not sensible due to a reduced efficiency. Economies of scale, however, is only problematic for autonomous and dynamic PEDs, as such are bound to their geographical boundaries. Further research is necessary to determine whether the synchronous grid of continental Europe brings more advantages than a decentralized concept, such as a PED, and if they really question the energy system in the way the interviewees portrayed it.

5.1.5 PHES in autonomous, dynamic, and virtual PEDs

As discussed above there are many factors influencing the use of PHES as energy storage in PEDs. All those techno-environmental and socio-economic factors are influencing each other and are therefore going hand in hand.

Next to this, they are influencing the three different forms of PEDs in a different way. The most limited form is the autonomous PED. This is reflected in particular by the TEB proximity characteristics, as it becomes clear that a distance between PHES and PED is not possible with the autonomous PEDs. However, due to the landscape characteristics (TEB), proximity between a PHES and a PED is not easily possible, which makes the use of PHES in autonomous PEDs difficult or almost impossible, especially where the landscape characteristics are not met. Next to this, the SEB economies of scale is another factor that complicates the implementation of a PHES close to an autonomous PED. This can be explained as the implementation of small PHES is specifically more expensive than the implementation of large-scale PHES. Therefore, an implementation of a small-scale PHES in proximity to an autonomous PED is less economical. However, it is possible to have an off-gird connection between a PHES and a PED if they are in proximity and share the same grid connection point. This solution, nonetheless, is only possible in locations where such a proximity is possible such as in Austria.

Dynamic PEDs are allowed to import and export energy from and to the grid, which reduces the TEB proximity characteristics, due to the reason that including the electricity grid, the distance is less important. Dynamic PEDs likewise to autonomous PEDs are also not allowed to generate electricity outside the geographical boundaries, which makes the use of PHES as virtual storage more complicated. The use of PHES within the geographical boundaries is however contradicted by Lindholm et al. (2021), who explained that it is often more expensive for dynamic PEDs having an own storage method in proximity than using energy form the grid in times of shortage. The possibility to interact with the grid more freely, additionally, brings out the TEB of energy source, as the energy that is imported cannot be 100 % renewable energy as long as non-renewables feed into the gird. This TEB could be solved with the help of the SED certificates, which verify the origin of the imported electricity on a balance sheet. Lastly, it can be said that similar to the autonomous PEDs, the SEB economies of scale is likewise problematic for dynamic PEDs.

Virtual PEDs are not affected by the TEB proximity characteristic, as they are allowed to produce outside their geographic boundaries. This offers the opportunity of VESS. This allows the virtual PED to store the surplus energy in a PHES virtually. With the help of certificates, the amount of exchanged energy can be proved. However, the use of virtual energy storage in virtual PEDs could be problematic due to the TEB energy source, as PHES is currently not seen as RE due to the use of electricity from the grid, which is physically not 100 % RE.

To summarize it can be said that the use of a PHES as energy storage is most suitable and most likely to be implemented in virtual PEDs. The reason for this is that virtual PEDs are less influenced by TEBs and SEBs than autonomous or dynamic PEDs. The most suitable way to implement PHES in virtual PEDs is to use PHES as VESS and to use certificates to prove the origin of the exchanged energy.

6 Conclusion

The contemporary energy system is driven by an energy transition in order to protect the climate by reducing greenhouse gas emissions (Tsantopoulos, 2022). This transition can be achieved by implementing different concepts such as, among others, the in this research considered concept of Positive Energy Districts (PED) (SET-Plan, 2018). Because PEDs generate their energy from renewable sources, energy storage solutions (ESS) are important to maintain energy flexibility. This is why this research was elaborating on the research question, under which condition it is possible to use pumped hydro energy storage (PHES) as an ESS in PEDs and how those conditions vary between the three forms of PEDs, autonomous, dynamic, and virtual.

In order to answer this question, four different supersets of conditions were defined, which in turn contain different sub-items. Those four conditions are techno-environmental drivers and barriers and socio-economic drivers and barriers. The results of this research and thus the answer to the research questions is summarised below.

6.1 Summary of the Results

The defined conditions are influencing the use of PHES as ESS in the three different forms of PEDs in a different way. It can be said that the realisation of this project is mainly possible in virtual PEDs. This is due to the reason that virtual PEDs are less bound to geographical boundaries and are therefore allowed to generate energy within virtual boundaries, which means outside the geographical boundaries. This fact allows a virtual PED to use PHES as a virtual energy storage system (VESS) as the distance between the PHES and the virtual PED is of little significance as the transport losses via a high voltage electricity grid are neglectable. In order to be able to trace how much energy was exchanged between the PHES and the virtual PED, certificates can help. Those certificates provide information about the origin of the energy, so that the energy pumped in the PHES can be allocated to the PED in terms of the balance sheet. However, VESS cannot be implemented in dynamic and autonomous PEDs, as these two forms are strongly bound to their geographical borders, which does not allow them to generate energy outside of those borders. Furthermore, the special landscape characteristics of PHES is a barrier here, as these ensure that PHES can only be built in environments that are more difficult to access, such as the Alps. In order to integrate a PHES into an autonomous or dynamic PED, there must be a spatial proximity between the two and both must share the same network connection point. In this way, the energy transport via the public grid can be avoided and the surplus energy of a PED could be stored directly in the PHES. However, it must be weighed up to what extent this brings economic advantages, or whether the virtual variant is the more cost-efficient solution and thus economically more sensible.

6.1 Scientific relevance

This research contributes to the research field of PEDs. In particular, it tries to overcome the flexibility problems of a PED resulting from the use of RE. Until this research, the possibility of using PHES as energy storage in PEDs was not discussed in detail in the literature. This is also reflected in practice, as there is currently no PED project that uses PHES to compensate for energy imbalances in PEDs. Therefore, this study lays a groundwork for further research into VESS in PEDs and the use of PHES as a storage method.

In addition, the results of this research contribute to the research field by providing a possible solution on how to integrate large-scale ESS into PEDs. The results hence help to further increase the storage possibilities and thus the possibilities to address the problem of energy flexibility in PEDs.

Furthermore, the results can help to foster energy and climate strategies in Austria, such as "mission2030". This can be done with the help of the new emerging concept of PED and the use of the in Austria already widely used PHESs.

6.2 Reflection and Suggestions for Future Research

In this section the strengths and limitation of the research will be considered and how those could be overcome with the help of future research.

The selection of a case study to answer the research question was legitimate, as this reduced the geographical context. However, it is hard to compare this case study to other cases, as the geographical circumstances in Austria are advantageous for the research question and unique in the global context. The Austrian Alps lay between a metropolitan area and hence combine the topography needed for PHES and the urban areas needed for PEDs. It would therefore be interesting to investigate to what extent it is possible to use PHES in PEDs, that are not located in mountainous regions.

Due to the delimitation of the case to Austria, it was hard to find a sufficient amount of interview partners. In Austria there are four companies operating PHES with only a limited number of employees. In order to look at the topic in more detail, it would make sense to also look at the side of the PEDs and to conduct further expert interviews or surveys here. It would be useful to find out to what extent operators and planners of PEDs see the possibility of using PHES as energy storage.

The interview partners mentioned some ideas, which could serve as a basis for further research. On the one hand, participant I4 mentioned that the energy market could be an opportunity to achieve energy flexibility. This is the case, as the surplus energy or the energy that is needed is communicated and traded at the market and anyone who has the capacity can help out in the situation. This does not have to be a PHES but could also be any market participant which has storage capacity. Another idea would be to elaborate on using the idea of virtual solar storage, which is used in parts of Austria to form new regulations for the realisations of using PHES as VESS in PEDs.

One main limitation was the lack of literature about the research topic due to the reason that this topic has not been addressed until now. Therefore, a lot more basic research is needed to build up a strong foundation for implementing this idea. More broadly, this research raises questions about the extent to which the combination of PHES and PEDs must be legally regulated and what this regulatory framework looks like. Therefore, it is advisable to focus on the legal framework in future research, as this would help to put the idea into practice, as the research topic in this study was approached from a more theoretical side.

If, in addition, there will a practical example in the future, it is recommended to work out this practical example as a best-practice example in order to pass on successful aspects, but also potential problems, to other PED projects.

In general, it can be concluded that this research is forming a basic building block for the implementation of PHES into PEDs, and that further research is indispensable if this idea wants to be put into practice. Beyond that, the SET-Plan ACTION n°3.2 also recommends research on innovative technologies for storage solutions in PEDs (SET-Plan, 2018).

Taken together, this research gives insights into the theoretical possibility of using PHES as virtual storage in PEDs. VESS is, based on this research, the most useful solution to the research questions because often a proximity between PHES and PED is not possible due to landscape characteristics of PHES, which would allow a direct connection between a PHES and a PED.

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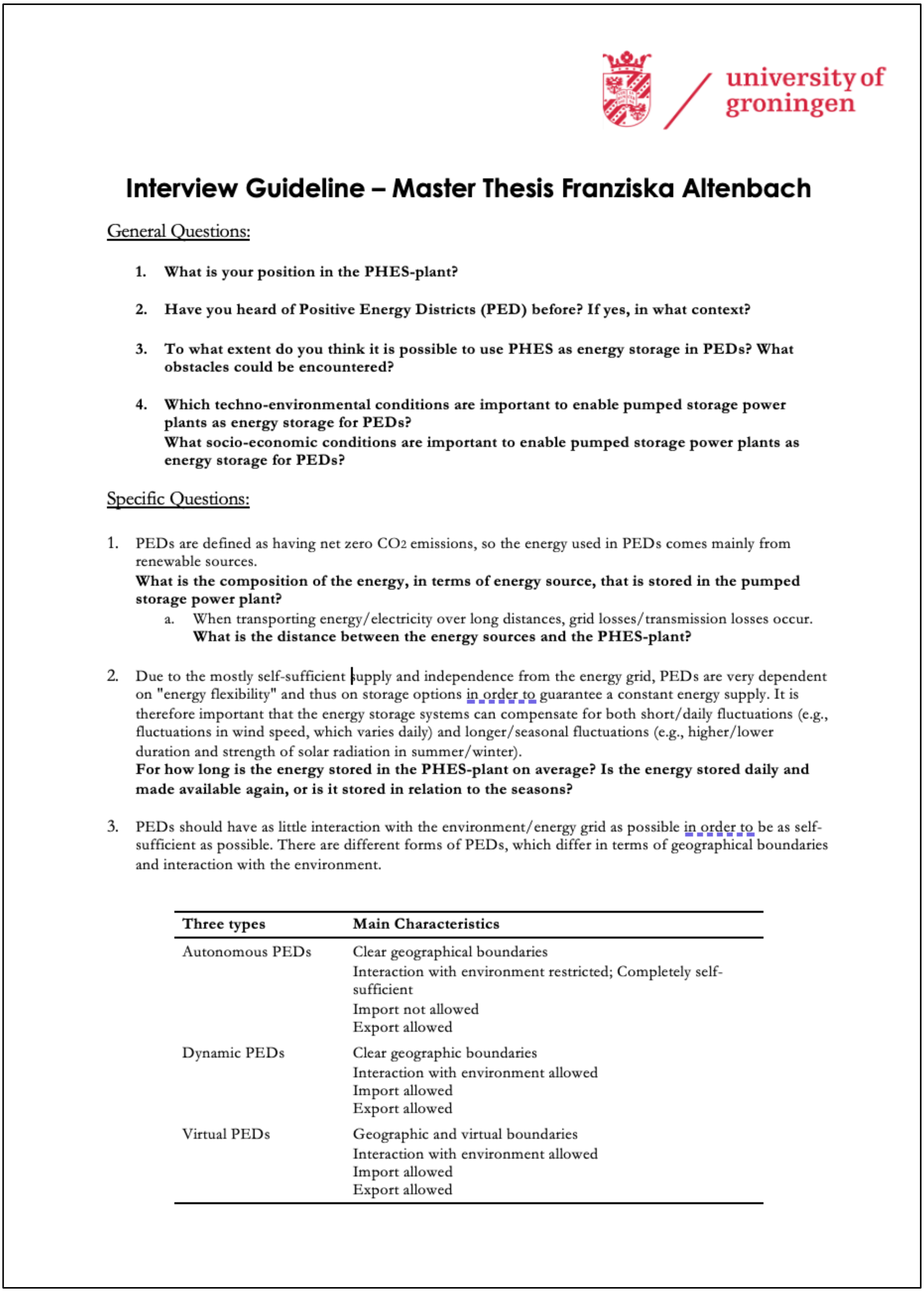
8 Appendix

Appendix 1



Interview Guideline – Master Thesis Franziska Altenbach

General Questions:

1. **What is your position in the PHES-plant?**
2. **Have you heard of Positive Energy Districts (PED) before? If yes, in what context?**
3. **To what extent do you think it is possible to use PHES as energy storage in PEDs? What obstacles could be encountered?**
4. **Which techno-environmental conditions are important to enable pumped storage power plants as energy storage for PEDs?**
   What socio-economic conditions are important to enable pumped storage power plants as energy storage for PEDs?

Specific Questions:

1. PEDs are defined as having net zero CO_2 emissions, so the energy used in PEDs comes mainly from renewable sources.
   What is the composition of the energy, in terms of energy source, that is stored in the pumped storage power plant?
   a. When transporting energy/electricity over long distances, grid losses/transmission losses occur. **What is the distance between the energy sources and the PHES-plant?**

2. Due to the mostly self-sufficient supply and independence from the energy grid, PEDs are very dependent on "energy flexibility" and thus on storage options in order to guarantee a constant energy supply. It is therefore important that the energy storage systems can compensate for both short/daily fluctuations (e.g., fluctuations in wind speed, which varies daily) and longer/seasonal fluctuations (e.g., higher/lower duration and strength of solar radiation in summer/winter).
   For how long is the energy stored in the PHES-plant on average? Is the energy stored daily and made available again, or is it stored in relation to the seasons?

3. PEDs should have as little interaction with the environment/energy grid as possible in order to be as self-sufficient as possible. There are different forms of PEDs, which differ in terms of geographical boundaries and interaction with the environment.

Three types	Main Characteristics
Autonomous PEDs	Clear geographical boundaries Interaction with environment restricted; Completely self-sufficient Import not allowed Export allowed
Dynamic PEDs	Clear geographic boundaries Interaction with environment allowed Import allowed Export allowed
Virtual PEDs	Geographic and virtual boundaries Interaction with environment allowed Import allowed Export allowed

a. **What is the infrastructure regarding energy storage and production (energy cables, connection to the energy grid, etc.) in the PHES-plant? How are the energy production facilities connected to the PHES-plant?**
b. **To what extent is it possible for energy coming from a PED to be returned to the same PED?**
c. **Is it possible to feed surplus energy from PEDs into a PHES-plant without using the energy grid?**
d. **To what extent is the PHES-plant dependent on the energy market? Is it possible to leave it out and transfer the surplus energy of the PED directly to the PHES-plant?**

Additional Questions:

a) According to Glasnovic & Margete (2011), it is less cumbersome to build a small PHES, as it would be possible to install them close to the consumer, thus reducing energy losses during transport.
Is it possible to build a smaller, local PHES-plant for a PED? What needs to be considered? What are possible obstacles?

b) To what extent is it possible for energy from small-scale plants, such as those found in PEDs, to be fed into a large-scale PHES?