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A Review of Possibilities and Challenges of Pit Thermal Energy Storages in Swedish District Heating Networks

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Abstract. The use of pit thermal energy storages (PTES) enables higher solar fraction in district heating networks by counteracting the mismatch between heat demand and production in solar district heating (SDH) installations. Capital costs linked to land areas with site-specific geological conditions are the deciding factors for PTES constructions. This study investigates non-technical and technical factors for the implementation of PTES in Swedish district heating networks. Having several SDH and PTES installations in operation the country of Denmark is used as a reference. This study, based on literature review, discusses the drivers and challenges for the use of PTES in district heating networks.

Keywords: Pit Thermal Energy Storage, District Heating Network, Solar District Heating, Benefits, Challenges

1. Introduction

Currently, thermal energy is constituting half of the total energy use in the world and is therefore regarded as an important target for CO_2 reduction and energy efficient measures. Solar thermal heat production for industrial applications and for district heating enhances the reduction of greenhouse gas emissions, contributes to fuel flexibility and reduce dependency on combustible fuels [1]. According to IEA Net Zero Emissions Outlook, solar thermal (ST) could constitute up to 35% of total hot water production for buildings by 2050 [2] for countries that needs a large quantity of medium-temperature heat for building's space and water heating. The use of ST in district heating production also contributes to Sweden's 2045 climate goals and the European goals on climate neutrality and energy efficiency [3].

The main goals of Sweden's energy policy include increased capacity, flexibility and diversification in the district heating grid. Additionally, Sweden's ambition is to decarbonize district heating by 2030 [4]. The deployment of solar district heating (SDH) in combination with seasonal thermal energy storages could assist in counteracting the mismatch between the period of heat production and the period of having high heat demand in district heating (DH) networks. Such installations in high latitude regions may be viable despite low solar energy intensities and limited solar energy during winter season [5]. Also, such installations could help reduce the dependency on combustible fuels and allow boilers to be operated more gently and optimal. Nevertheless, there have been very few pit thermal energy storages (PTES) constructed in Sweden despite ongoing debates regarding decarbonization of the heat sector [4], [6].

PTES can be constructed in large-scale dimensions underground. Its size enables high charge/discharge power with high flow rates and high operational temperature differences [7]. These characteristics have highlighted the technology as one of the more viable energy storage technologies in combination with SDH installations. Thermal energy storages are classified into short- and long-term storages. The short-term storage normally has a charge and discharge period up to a few days, while the equivalent for long term storages can range up to several months [8].

Through the years, only a few pilot PTES have ever been constructed in Sweden. However, the concept of integrating large-scale PTES together with solar thermal collectors has been applied in several district heating systems in the neighbouring country of Denmark due to favourable policies trigged largely by the limited accessibility to combustible fuels together with the escalation of energy prices [9]. Today, both Sweden and Denmark have well-developed district heating systems with a high proportion of cogeneration plants [10]. PTES are put into operation in Denmark [11] and therefore this country having certain similarities in heat demand patterns and solar resource potential, could be reference to the investigation [12].

The purpose of this study is to give an overview over district heating in Sweden and Denmark to investigate and map out possibilities and challenges for the integration of PTES in Swedish district heating networks. The neighbouring country of Denmark is used as reference due the large number of SDH and PTES installations in the country. The analysis in this paper is based on secondary data from literature studies.

2. District heating: comparison between Sweden and Denmark

2.1 Overview of fuel mix in district heating

At present, there are 285 district heating systems in Sweden's 290 municipalities [13]. The use of fossil fuels for district heat production has decreased sharply from the peak during the 1980s. Nowadays, recycled and renewable energy contributes to over 90% of the fuel mix as shown in Figure 1 [14]. Recycled energy is ranging from flue gas condensation in CHP plants to biomass boiler combustion. With waste and biomass constituting a large part of supplied energy, the two heat sources are fundamental in Swedish district heating with biomass being considered a renewable resource [4].

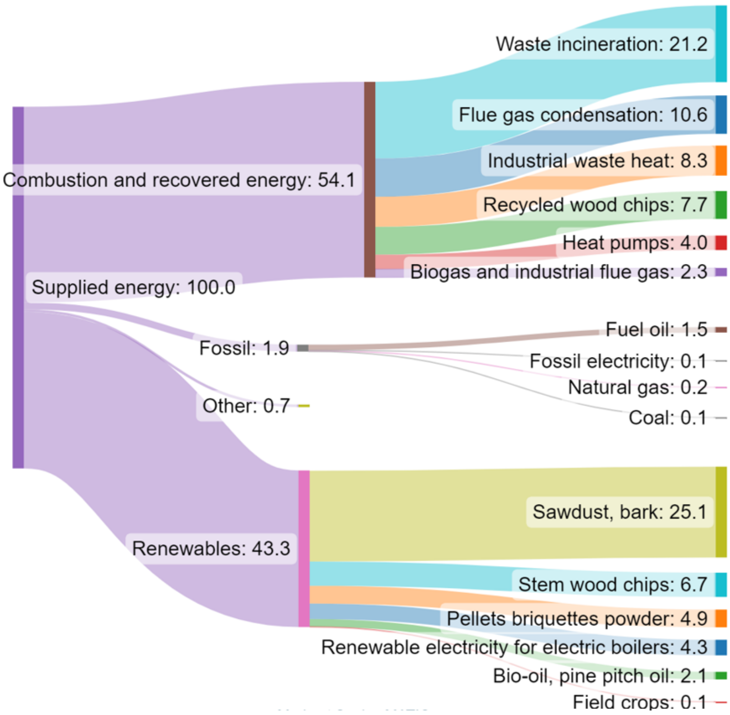

Figure 1. *Supplied energy (%) (2022) for Swedish district heating production [14].*

Fossil-based fuels constitute less than 2% of total heat production in Swedish district heating. Consequently, greenhouse gas emissions from fossil fuel combustion only represent a small part of total emissions from district heating. Waste incineration, constituting approximately one-fifth of the total supplied energy contributes to two-thirds of the total greenhouse gas emissions for the production of district heating [15]. Substituting waste by renewable energy resources or incinerating waste effectively is therefore regarded as a priority to achieve the 2030 goal of a decarbonized district heating sector [4].

With approximately 64% of all households being provided by district heating, the Danish district heating network is in a European context regarded as well-developed. Originating from the 1970 energy crise, the network has been in continuous development to reduce fossil fuel-dependency, improvement of waste management and urban planning [16]. Being nearly 100% energy import dependent during the '70s, the Danish Energy Agency (DEA) was founded in 1976 to increase energy import independency. By developing long-term energy planning and energy policy's, several important steps were taken to achieve this goal. In 1979, The Danish Heat Supply Act enabled planning of collective heat infrastructure. In 1985, nuclear power was downvoted by the government. A couple of years later, the world's first low carbon energy transition plan was published. Finally, Denmark became world-first in banning landfilling of combustible waste in 1990 [10], [16].

Figure 2 [17] shows a substantial share of supplied energy in Danish district heating is still constituted by fossil fuels. In general, the price of Danish district heating has been higher than Sweden, partly due to expensive natural gas [18]. Most of the district heating plants in Denmark are combined heat and power, where surplus heat is generated from electricity production [19]. Since the beginning of 2010, the high price of natural gas initiated the development of SDH systems, mainly due to a competitive heat price [16]. To increase the utilization rate of SDH integrations, the large spread of Danish PTES is a direct consequence to the increased use of solar water heating in the district heating network [10].

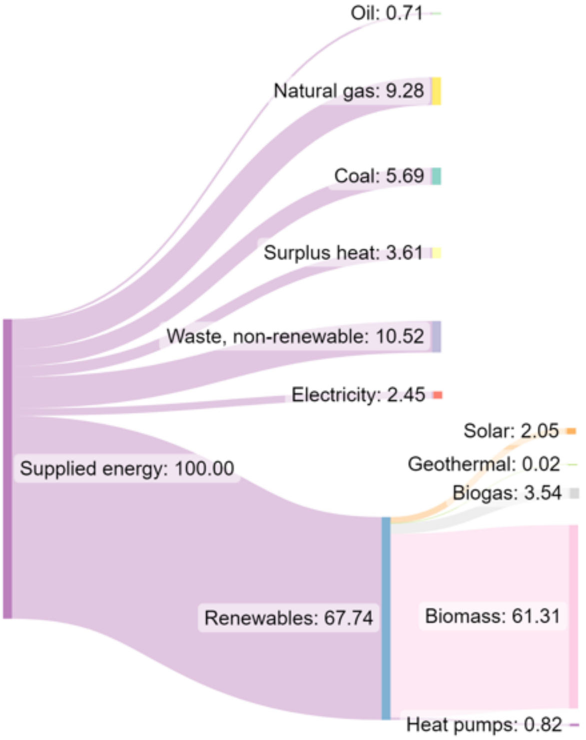

Figure 2. *Supplied energy (%) (2022) for Danish district heating production [16]. Biofuels include the burning of straw, wood chips, wood pellets, waste, bio-oil, biogas and biowaste. Renewables are constituted by solar and geothermal .*

2.2 Policies

Successful integration of PTES in Swedish district heating networks is dependent on several preventive technical and non-technical factors. While Sweden being new to the PTES concept, Denmark have several sites in operation [10]. The main difference between the two countries can be derived from respective country's heat production history. A common denominator and major contributing factor to the development of heat infrastructure and policy's in respective country has been the heat price [10], [16], [20], [21]. The oil crisis in the 70's heavily affected district heating companies in both countries and set a political trajectory away from the direct use of oil in the heating sector [10,24]. The sharp increase in oil prices had devastating effects in the country forcing Danish authorities to long-term energy planning [10]. At present, most of the total heat distribution is produced by CHP. A principle of non-profit regulates the sector [23], where the price of district heating cannot exceed the heat production cost. With the district heating market being regarded as a natural monopoly, the system ensures a customer-warranty against rampant heating prices [16]. Depending on available fuel sources and infrastructure, Sweden's development differs to Denmark's due access and development of waste and biomass incineration [21].

The carbon taxes introduced in Sweden during the 90's resulted in an increased cost of heat production for district heating companies relying on fossil fuels, while companies using biofuels did not have to pay tax [21]. Further, the forest industry in Sweden resulted in large quantities of wood waste creating natural synergies between biomass combustion and wood waste from i.e. forestry and paper mills. Waste incineration has been used in the Swedish district heating sector since the 70's, and was subjected to an increase use due the ban of landfills in the early 2000's [24]. In the case of Denmark, the gas distribution grid is an integrated part of the European gas infrastructure designed to receive gas from the North Sea and Germany [25]. This has allowed the construction of decentralized gas-powered CHP plants throughout the country [10], increasing the potential for construction of nearby PTES bringing benefits to the power production (Table 1).

Denmark has historically had a higher price for district heating [26] in comparison to Sweden due the use of natural gas and fossil fuels. The high tax and large relative share of fossil fuels in the energy mix have resulted in large costs for Danish district heating companies. Accordingly, Denmark has a higher incentive for sustainable and cheap heat production. In addition, favorable national legislations and support policies have been in favor for PTES implementations [11]. Bank loans in Denmark, as stated by Bundgaard, S. [27] let district heating companies finance up to 100% of the cost for investments in renewable energy technologies. In addition, a municipality guarantee can be used for a very low interest rate of 0-3% [27]. Energy saving subsides were in earlier years effective granting PTES in combination with SDH the first year's calculated worth of heat production as subsidy. The subsidy was given by the government to trigger investments in renewable heat production for district heating companies and served as an important incentive for many plants constructed 2010 and onward [10]. The high share of Danish households catered by district heating also assists in reducing the initial investment of SDH systems and PTES. This is due to the district heating companies mainly being owned by the heat-purchase customers willing the invest in renewable heat supplies [20].

3. Thermal storage technologies in Danish and Swedish district heating

3.1 Thermal energy storage

Thermal energy storages are determined to be one of the key elements for successfully integrating renewables in the district heating grid. With the main purpose of bridging the gap between heat production and consumption, it is considered a necessary element for a successful green heat transition [23]. The 5th generation district heating and cooling grid (5GDHC) has a 100% renewable energy target and is determined to maximize the share of renewable energy sources. 5GDHC is based on exchange of thermal energy between buildings with different needs, where heat storages function to counteract fluctuations in supply and demand [40,29].

In Sweden, most of the larger district heating grids are equipped with thermal energy storages. The storages are predominately short-term consisting of steel accumulator tanks to help counteract shorter diurnal load fluctuations [9]. In recent years, the concept of seasonal thermal energy storages has received increased interest due several European installations showing excellent operational data [6]. The Swedish Energy Research Institution Energiforsk [9] stated several benefits for tong-term thermal energy storages. Among the more important factors mentioned was the possibility to exchange expensive heat production during winter months for cheaper during summer. This is predominately the most important factor for Swedish power companies, increasing feasibility for both heat producer and end consumer. Sweden is new to the PTES concept, while Denmark already have several sites in operation [10].

3.2 Pit thermal energy storage

PTES is considered a promising thermal storage technology due to its in principle unlimited sizing and potential for renewable energy integration [30]. It is considered an essential part of SDH systems to increase solar fraction and utility in the district heating grid by storing heat during summer and discharging it during winter, shown in Figure 3 [6]. For district heating companies, several additional benefits follow energy storage implementations such as load fluctuation resilience and dynamic electricity production [9]. The operating temperature for Danish PTES typically range between 40-90 ˚C, making it ideal for future implementation in the low temperature 5GDHC grid [31].

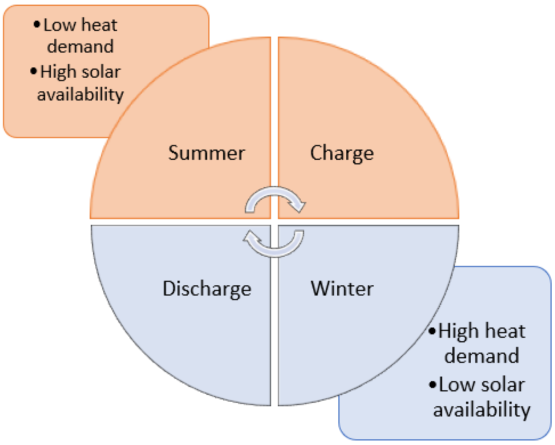

Figure 3. *PTES working principle*

3.2.1 Construction

PTES consists of water-filled excavated ground enclosures covered with waterproof liners [32]. To reach the expected lifetime of 30 years, the material and components used in the construction of PTES play an important part. The choice of components and materials also affect the investment cost and storage efficiency [7]. The components are typically divided into three groups of which each is critical for the function of the storage [11].

The liner is placed on the side walls and bottom of the storage and function to enclose the water volume from the surrounding soil. Typically, investors look for cheap materials with low installation cost such as polymers [33]. Other common materials used include elastomers and steel, where the former are more commonly used due to low material and installation costs. Steel liners are typically more stable and temperature resistant and were used in early installations but were later replaced by polymer materials due to lower installation and material costs [7].

With the highest heat losses occurring through the surface of the water volume, an insulated cover is used on top of a PTES installation. The cover usually consists of two layers of liners on either side of an insulator [7]. With the cover being the most work-intensive and expensive part of the PTES design, continuous research is conducted to improve function and minimize costs [33].

3.2.2 Performance

The performance of PTES is enhanced by stratification where layers of water with different temperatures are formed due to variation in density [34]. A decreasing temperature gradient from surface to bottom is therefore desired to increase the efficiency of SDH installations. In a study made by Fan et. al. [35], a simulated model of the PTES in Marstal, Denmark was constructed to evaluate stratification in the storage volume. The simulation showed a temperature difference of approximately 47 ˚C between the top and bottom of the water volume. A common phenomenon supplying water to hot water tanks are turbulent flows resulting in the mixing of different temperature water volumes [34]. The same principle applies to PTES, why the inlet and outlet design is constructed to counteract turbulence in the storage volume. A diffuser is used to reduce the velocity of water while enabling laminar flow promoting stratification [35].

3.3 Drivers for PTES

PTES are by district heating companies seen as a necessity to increase the utilization and solar fraction of SDH installations [6]. With the cost for storing energy (SEK/kWh) being approximately 400 times cheaper relative electric batteries [16], thermal energy storage is a widely discussed topic for power companies and industries with high demand of energy. As per the report by Swedish Energy Agency there is a potential for 6 TWh of solar-powered district heating in Sweden [18]. However, still a high degree of uncertainty towards SDH and PTES functionality is present in the industry and incentives and proof-of-concepts could facilitate successful PTES and SDH implementations in Sweden [6]. An overview of the technical and non-technical benefits of PTES is provided in the following sections.

3.3.1 Technical drivers for PTES

Technical drivers for implementation of PTES in Swedish district heating networks span outside pairings with SDH installations. In recent years, several district heating companies in Sweden have chosen to construct thermal energy storages as means to make heat and power production more resilient and sustainable [6,18]. However, additional drivers follow PTES integration over which a summary is given in Table 1.

Table 1. *Examples of technical drivers for PTES in district heating networks.*

Factor	Benefit/driver	References
Reliability	The thermal energy in PTES can be used as backup during production breakdowns and maintenance periods. In addition, operational SDH and PTES installations have shown good reliability with very few breakdowns.	[24]
Lifespan	The liner used in a PTES is the main component determining the lifetime of the construction. Liners used in Danish installations are reported to have a lifetime expectancy of 30 years.	[11]
Fuel flexibility	The use of PTES and SDH contributes to diversification in district heating production, making the sector more resilient against fuel price fluctuations and production breakdowns.	[9,26]
Security of supply	The availability of thermal energy is greatly increased with heat storage utilization while also reducing fuel price dependency.	[29,9]
Increased capacity	The heat production capacity is increased with PTES integration resulting in several benefits for power companies. It may to some extent help avoid investments in additional heating sources.	[6,18,9]
Dynamic electricity production	Thermal energy from PTES can be used for dynamic power generation adjusting electricity production to current electricity price.	[18,9]
Load balancing	Startups and stops may be avoided in production facilities while gaining resilience to big load fluctuations in the district heating grid.	[9,26]
Lower service temperature	A lower service temperature in the district heating grid increases the energy utilization of PTES.	[18], [38], [38]

Integration of renewables	Thermal energy storage is regarded as a promising technology for integration of renewable energy sources, assisting in counteracting the intermittency of solar and wind power.	[31], [39]
5GDHC ready	Heat storages constitute fundaments in 5th generation district heating having a 100% renewable energy target.	[31], [38], [40]
Peak shaving	PTES help reduce the dependency of fossil fuels and other expensive fuels during periods of high heat demand. CHP plants may be operated more smoothly increasing lifespan and limiting wear of the plant.	[9]
STS synergy	PTES may be used as short-term storages in systems where such operational strategies are used frequently.	[7]
Synergy between isolated energy systems	The use for PTES may extend past district heating systems and work to connect heat-intensive industries as well as being subject to innovational use in the future.	[7], [41]

3.3.2 Non-technical drivers for PTES

The price of fuels, such as wood pellets, used in Swedish district heating plants have nearly doubled in recent years [42]. This, in addition to increased customer-awareness on sustainability and environmental responsibility has made district heating companies look for less price-dependant, more sustainable heat sources [6]. While economy and decarbonization may be the factors carrying most weight for Swedish energy utility companies, several non-technical aspects follow PTES integration (Table 2).

While drivers given in Table 1-2 may be on a more regional scale directed towards power companies and consumers, implementations of PTES may be put in a larger context. With the current fuel mix in Swedish district heating having big potential for reductions of greenhouse gas emissions, construction of PTES may also contributes to climate goals of Sweden[15],

Table 2. *Examples of non-technical drivers for PTES in district heating networks.*

Factor	Benefit/driver	References
Ecological sustainability	Reduction of emission-intensive fuels. Indirect environmental impacts include i.e. reduction of transports and fuel processing.	[10], [31], [43]
Employment	Construction of PTES may create local job opportunities.	[43]
Sustainability trademark	Use of energy storages could help power companies increase their sustainability and “green label” trademark.	[6]
Use of otherwise wasted energy	Industrial waste energy and surplus solar energy during summer may be stored and used to substitute conventional fuel use during periods of high heat demand.	[7], [43], [44]
Cost savings	The energy costs for consumers may be reduced by limiting the use of expensive fuel use during production peaks. Power companies reduce fuel-dependency and associated costs.	[9,45]
Low operational cost	The operational costs and maintenance requirements for PTES are relatively low.	[35,48]

Reduction of fuel-poverty	Reduction of the risk for fuel-poverty for end-consumers.	[43]
Adding benefits to area reputation	The value of an increased area reputation may easily be overlooked. Construction of thermal energy storages may attract new customers and result in unexpected consequences such as research collaborations and media exposure.	[43]
Integration of renewables	Reduction of emission-intensive fuels. Indirect environmental impacts include reduction of transports and fuel processing.	[7], [41], [49]

3.4 Challenges for PTES

Despite numerous drivers presented in Table 1-2, the construction of PTES in Swedish district heating networks faces several challenges. With limited experience, PTES concept and technology is regarded with uncertainty by power companies [6]. As frequently discussed in literature, one of the major deciding factors is the substantial capital cost (Table 3) related to soil excavation and pit construction [23]. Sifnaios et al. [31] investigated specific investment costs for eight operational PTES in Denmark. The study shows a strong correlation between storage size and specific investment cost. A trend from the results is shown in Figure 4.

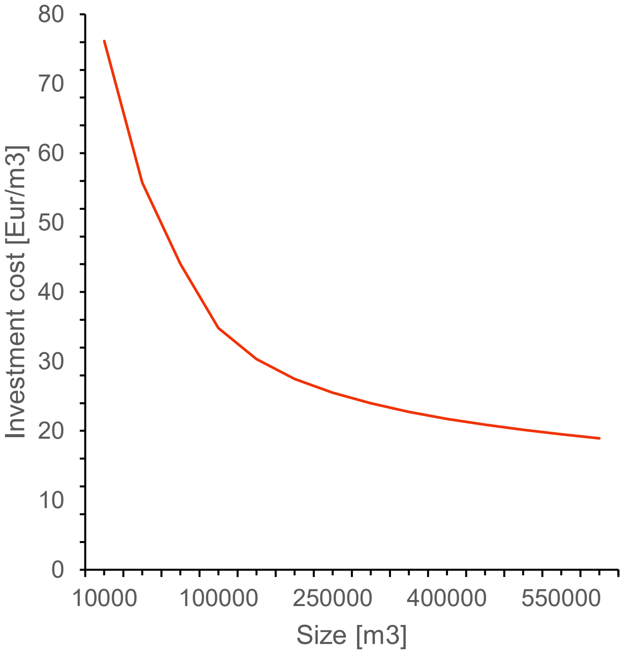

Figure 4. *Specific investment cost as a function of storage size as adapted from [31]***.**

The figure shows a rapid decrease in investment cost with increased storage volume. This heavily influences decision-making and planning for energy utility companies while putting additional delimitations on placement and feasibility. With lower payback time following increased storage volume, available surface area becomes a deciding factor for power companies. Moreover, capital cost and potential heat losses are increased with the distance between PTES and the source of heat production [48]. Most of the installed PTES are large and designed for seasonal heat storage carrying large discharge capacities [31]. With most of the large networks being associated with cities, large plots of land may be a scarce commodity. PTES construction may therefore be limited to outskirts or suburbs, where both the availability and price of land usually is more affordable [49]. Additionally, surface area requirement is frequently mentioned in literature as one of the main challenges for power companies (Table 3). In summary, these factors may have strong delimitating effects on the prospecting phase prior PTES constructions. Mentioned obstacles and challenges for PTES implementations may be divided into technical and non-technical categories and are shown in Table 3.

Further delimitating the placement of PTES is the presence and flow of groundwater. Studies show up to 40% heat losses from sidewalls of the storage in the presence of flowing groundwater [7]. In addition to heat losses water flows may also compromise stability of surrounding geology limiting storage side slope angles. To avoid complications during construction and reduce heat losses, areas with shallow ground water tables are best avoided during the prospecting phase [48].

Table 3. *Examples of technical and non-technical challenges for PTES in Swedish district heating networks.*

Factor	Impact	References
Technical		
Surface area requirement	The surface area requirement is one of the main challenges for power companies.	[7], [30], [31], [48]
Stable ground conditions	Thorough geotechnical studies are necessary to evaluate ground conditions prior PTES constructions. The geology may limit the design of the storage.	[30], [48]
Absence of groundwater	Both still and moving groundwater result in substantial heat losses from the storage. Extensive hydrogeological studies are necessary prior construction.	[7], [48]
Production proximity	Heat losses and capital expenses are reduced by constructing PTES close to heat production sources,	[48]
Bedrock depth	The capital cost and difficulties related to ground excavations are affected by the bedrock depth.	[48]
Grid bottlenecks	An increased production capacity due PTES construction may create bottlenecks where parameters like pipe diameters may be insufficient.	[9]
Construction improvement areas	Some main construction improvement areas from commissioned Danish installations include lid design, liner material and rainwater handling.	[11]
DH supply temperatures	The PTES store temperature is often limited to 90˚C due to the polymer liners. PTES may therefore not be viable in district heating networks with high supply temperatures.	[31], [50]
Non-technical		
Capital cost	The capital cost for PTES is high and is usually considered as one of the deciding factors for power companies.	[6], [18], [31], [9]
Competitive technologies	Other heat storage technologies compete with PTES regarding capital cost and heat storage obligatory	[6], [31]
Global warming	Global warming and increasingly efficient isolation in buildings may reduce the interest for thermal storage in the future.	[6]
Subsidies	Lack of subsidies for thermal energy storages may reduce incentives for power companies to invest in PTES.	[6], [51]

Size requirement	Investment cost (euro/m^3) decreases rapidly with increased storage volume, considerably reducing feasibility for small storage volumes.	[31]

An additional factor easily overlooked is the district heating companies' attitude towards new concepts and technologies. The Swedish district heating sector, having had limited changes in the fuel mix since the 1980s [21], may be perceived as sceptic towards new concepts and initiatives [6]. While the concept of thermal energy storage is well known, water-filled ground enclosures associated with PTES are brand new concepts bringing skepticism and caution for decision makers. With SDH systems often being considered part of the solution during PTES project planning, such installations are likely to invoke further skepticism [6,9] due to risks and uncertainties associated with new technologies.

4. Conclusion

While many site-specific factors may prohibit PTES constructions, the main challenges for power companies today are associated with surface area requirements and capital cost. In addition, there is a high demand for "proof-of-concept" regarding functionality and reliability at power companies in Sweden.

The distinction in PTES implementation between Sweden and Denmark can be derived from favorable Danish support policies, lack of alternative heat sources and high taxes on fossil fuels. With fossil fuels such as natural gas constituting a large share of the Danish fuel mix, the demand for cheap and sustainable heat production has been great. Additionally, large investments in renewable heat sources are more easily implemented in Denmark relative Sweden due end-consumer business models.

With district heating contributing to Sweden's total greenhouse gas emissions, an important driver for PTES implementation is the reduction of combustible fuels used in the district heating sector. Substitution of waste incineration, biomass and fossil fuels (peak loads) to stored heat in PTES could contribute to the 2030 goal of a decarbonized district heating sector. The feasibility of PTES is strongly related to its size and type of operating profit following the construction [9]. With the main operating profit being substitution of expensive heat production during winter to cheap stored heat during summer, the feasibility of PTES is dependent on the current price of fuels in the fuel mix.

Data availability statement

Data will be made available on request.

Underlying and related material

No underlaying material other than stated in the paper was used during this study.

Author contributions

Writing- original draft: Frej Fogelström
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Supervision- Itai Danielski, Truong Nguyen, Gireesh Nair

Competing interests

The authors declare no competing financial interests or personal relationships that could influence the work reported in this article.

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