

École polytechnique de Louvain

Techno-Economic Assessment of Pit Thermal Energy Storage in Low-Temperature District Heating Systems

A Case Study of the Athena-Lauzelle Project in
Louvain-La-Neuve

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Abstract

Pit Thermal Energy Storage (PTES) has emerged as the most promising large-scale storage solution, driven by increased knowledge and proven efficiency in existing implementations. Enhancing the thermal efficiency of buildings to limit carbon emissions and reduce primary energy consumption encourages the design of low-temperature and renewably powered district heating networks. This thesis, conducted in collaboration with Resolia, assesses the relevance of PTES in low-temperature district heating systems through a real-life case study: the Athena-Lauzelle project in Louvain-La-Neuve. A two-step method is developed to understand the technical and economic dynamics of PTES integration at the system level and to analyze factors such as size, operating strategy, stratification, and interactions with the local environment at the component level. Results indicate that for the case study and its associated load pattern, PTES fails to deliver the significant impact expected from such a large-scale installation due to its poor utilization rate and negligible economic gains. However, the study confirms the benefit of incorporating a smaller energy storage buffer, such as a tank storage, within the system.

Keywords: Pit Thermal Energy Storage (PTES), low-temperature district heating, Athena-Lauzelle

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List of Notations

TES	Thermal Energy Storage
PTES	Pit Thermal Energy Storage
DH	District Heating
CHP	Combined Heat and Power unit
HP	Heat Pump
ASHP	Air-Source Heat Pump
COP	Coefficient of Performance
STC	Solar Thermal Collector
PV	Photovoltaic Panels
LCOH	Levelized Cost Of Heat
SLU	System Land Use
GDF	Grid Dependency Factor
HSUR	Heat Storage Utilization Rate
MoSDH	Modelica Solar District Heating library

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Introduction

The idea for this research came from a personal interest in Resolia's mission to decarbonise the Belgian heat sector through district heating and cooling technology. Indeed, it is widely recognised as a promising solution to reduce both primary energy consumption and local emissions.

In 2015, Belgium consumed 214 TWh for heating and cooling purposes. With only approximately 2% of this total provided through district heating, Belgium lags behind other European countries. Recent studies indicate there is a potential to cover about 37% of needs related to the built environment [1]. Moreover, the development of the district heating and cooling concept has reached its fifth generation. It is characterised by low-temperature supply, bi-directional operation (i.e. it can provide heating and cooling simultaneously), decentralised energy flows and heat sharing [2]. New decarbonized district heating systems often rely on storage technologies. In pioneering countries, large-scale storage is widely investigated. However, in Belgium, these technologies are not yet included in current project plans due to relatively poor expertise.

The Pit Thermal Energy Storage (PTES) technology, recognized for its significant potential and already demonstrated by efficient pilot plants, is of particular interest to Resolia. Under the supervision of Hervé Jeanmart, the collaboration with Resolia began with the ambition to better understand the main challenges around PTES technology and to investigate its integration into a concrete low-temperature district heating system.

Resolia was tasked with studying decarbonized heat supply solutions for a new residential area in Louvain-La-Neuve, known as the Athena-Lauzelle project. This innovative project provides the opportunity to consider PTES integration within a real low-temperature application setting.

This work's ambition is to contribute to the development of knowledge around PTES within the Belgian industry and assess the relevance of integrating PTES into low-temperature district heating systems based on the Athena-Lauzelle case study.

The study follows a structured framework: Chapter 1 provides a background on Long-Term Energy Storage, elucidating its main drivers. The PTES concept is introduced,

detailing its structure, and operations. Additionally, it provides a description of some existing implementations. In Chapter 2, the 2-steps research methodology is described with their respective objectives, model assumptions and associated tooling. Chapter 3 presents the case study and conducts an analysis of the obtained results. Following this, Chapter 4 summarizes the key learnings from the case study together with our recommendations. Ultimately, Chapter 5 concludes the study, also provides reflections and perspectives going beyond the scope of the present work.

Preliminaries and backgrounds

The literature is indisputable: thermal energy storage (TES) systems could become a major actor in future energy systems. It is even claimed that energy systems with TES could achieve carbon neutrality by 2050, unlike systems without TES[3]. In this context, large-scale thermal energy storage (LTES) stands as a prominent research area within the energy sector.

1.1 Large-scale Thermal Energy Storage (LTES)

While small-scale storage systems are widely recognized and utilized, LTES technologies remain less understood and are the subject of extensive research. LTES has the potential to play a significant role in highly interconnected, carbon-reduced energy systems by addressing the limited flexibility and dispatchability of renewable sources at a seasonal level. LTES systems also accelerate decarbonization through increased cost efficiency thanks to the economy of scale. Note that with quite low exergetic content ($<100^{\circ}\text{C}$), conversion is complex and therefore employing LTES necessitates the existence of a district heating (DH) network or industrial processes.

1.1.1 The four LTES concepts

LTES four technological declinations identified in the literature are tank, pit, borehole and aquifer TES. With the help of LTES technologies advancement reviews conducted in 2019[4] and 2020[5], a brief description of each is given as well as their main pros and cons shown in Figure 1.1.

The aquifer TES utilizes a mixture of natural water and ground (e.g. rock) to store the collected heat in an underground layer. [4] Unfortunately, it is very dependent on specific local geological properties and is therefore not one of the technologies with a

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great deployment potential.

The borehole TES stores the excess heat utilizing soil and/or rock; so, the ground layer itself is the storage medium. Therefore, multiple vertical boreholes are usually used to store the collected heat and, commonly, water is utilized as heat carrier in those borehole heat exchangers that transfer the heat between water and the ground. Despite the low installation cost, it is observed that due to the large interface area between the horizontally oriented pipes and the ground, storage heat losses might increase. Another drawback is the low supply temperatures BTES can provide.[4]

The tank TES is an artificially made reinforced pre-stressed concrete or stainless steel and, commonly, water is seen as favourable storage medium. It is a well-known and performant technology but suffers from high construction costs.

Pit thermal energy storage (PTES) is relatively young but is perceived as the most promising due to its affordability and scalability. Consequently, this study will concentrate on PTES and its integration into a wider energy system.

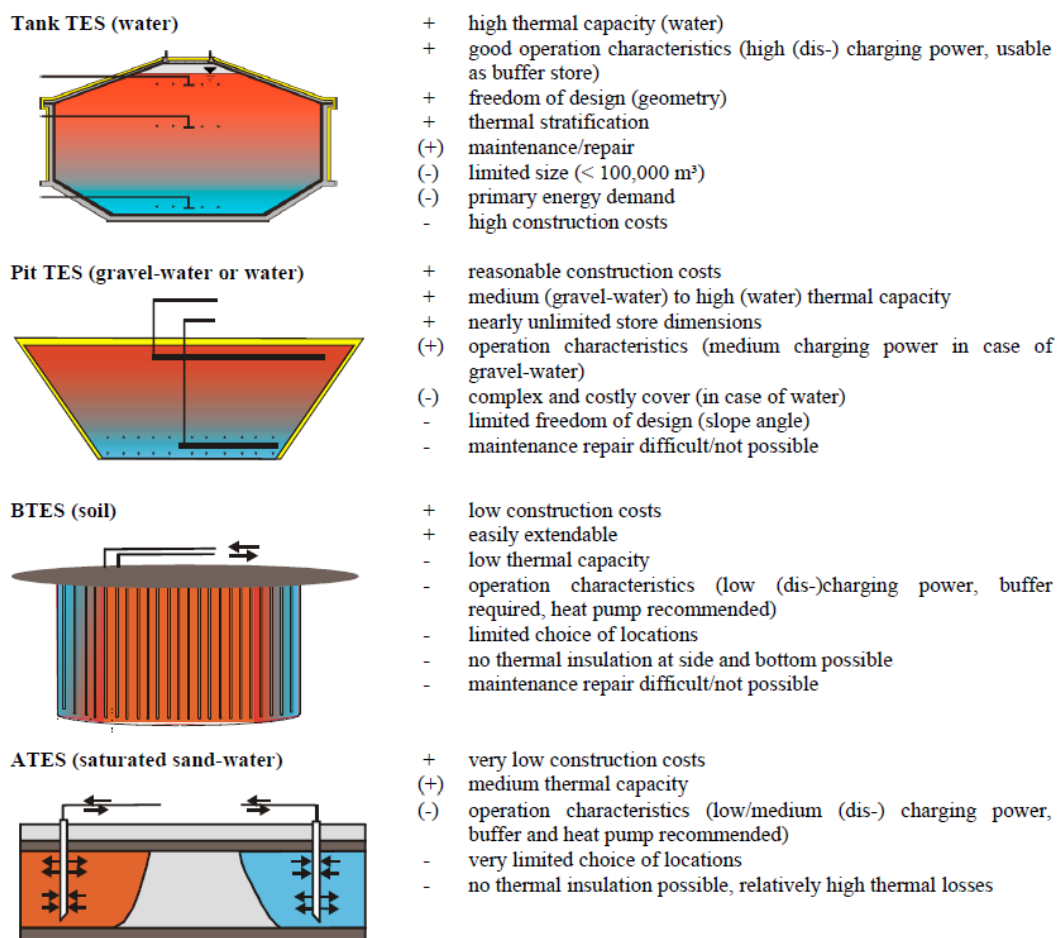


Figure 1.1 Construction concepts for LTES systems with their advantages and disadvantages [4]

1.1.2 A pivotal technology

LTES must be considered and studied as part of a wider energy system with multiple heat generation sources. Different combinations with production or conversion units and their different operation strategies are addressed in this part. A diagram illustrating potential synergies is shown in Figure 1.2.

LTES makes it possible to partially decouple production from consumption over time. Initially designed for seasonal decoupling, it can in complementary also be used as a short-term buffer. Therefore, integrating LTES should be carefully sized and managed to optimize self-consumption and enhance flexibility.

The thermal energy is stored in a low to medium temperature range ($<100^{\circ}\text{C}$) because of supply sources and storage technology limitations.

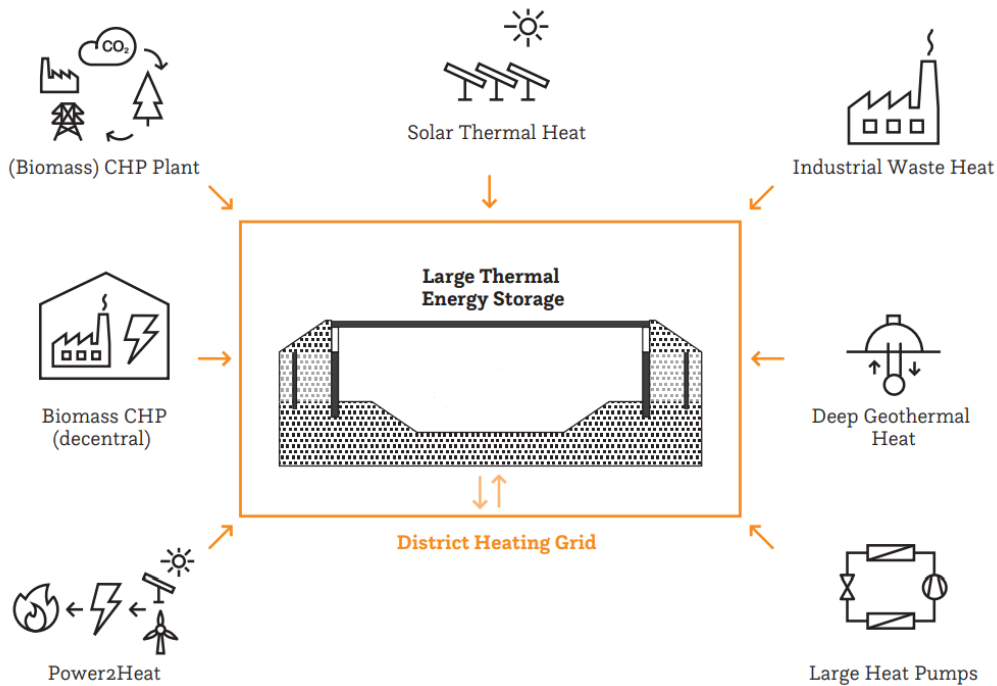


Figure 1.2 LTES as a pivotal technology in district heating systems (adapted from [6])

System integration drivers

In the context of the urgent energy transition, LTES constitute fundamentals in 5th generation district heating having a 100% renewable energy target.[7] Indeed, LTES technologies offer a possible solution to reduce drastically fossil fuel-based heat production. In addition, LTES offers ancillary services to the system in which it's integrated. Some important drivers are listed in table 1.1.

Factor	Driver
Integration of renewables	LTES is regarded as a promising technology for the integration of renewable energy sources, assisting in counteracting the intermittency of solar and wind power.
Sector coupling	LTES can become a key feature for large-scale highly interconnected heat and electricity systems. Thermal storage has been identified in the literature as a useful component to allow sector coupling technologies such as heat pumps (HP), electric boilers, and Combined Heat and Power (CHP) to provide intra-day balancing and frequency support.
Security of supply	The availability of thermal energy is greatly increased with heat storage utilization while also reducing fuel price dependency.
CHP economics optimization	CHP facilities produce both electricity and heat simultaneously. LTES systems can provide flexibility to these facilities by producing electricity when the market price is high and storing excess heat for later use. This flexibility can optimize the operation of CHP facilities, improving overall efficiency and economic viability.
Waste Heat recovery	Industries often produce waste heat that is released into the environment. Heat storage systems can capture and store this waste heat for heating use. This not only reduces waste but also improves the energy efficiency of industrial processes.
Peak load shaving	LTES helps reduce dependency on fossil fuels and other expensive fuels during periods of high heat demand by replacing the need for high-emitting peak generators.
Heat Source for Industrial HP	In certain operational strategies, LTES systems can serve as the heat source for industrial HPs. Using stored heat as a source can increase the Coefficient of Performance (COP), enhancing their efficiency and reducing energy consumption.
High and sudden demand change affordability	LTES systems can respond quickly to high and sudden changes in heat demand. This responsiveness allows them to meet fluctuating demand effectively, ensuring consistent heat supply even during peak demand periods.
Fluctuating prices	In an interconnected energy network, thermal storage systems can produce heat when electricity prices are low. This strategy can help optimize energy costs by utilizing cheaper electricity to produce heat, saving money for end-users.
Short-Term Storage	Thermal energy storage can be used partly as short-term storage for heat. This capability allows for the temporary storage of excess heat or the provision of additional heat during peak demand periods, enhancing system flexibility and reliability.

Table 1.1 Examples of drivers for LTES in DHN [8, 3, 9, 7]

1.2 Pit Thermal Energy Storage (PTES)

Given that PTES technology is relatively new and not all operating systems are fully reliable, with operating parameters and performance varying across installations, it's crucial to draw from current practical experiences. This section is therefore supported by a comprehensive compilation of worldwide operational and planned PTES systems, as detailed in Table 1.2.

1.2.1 Evolution and advancements in PTES technology

The PTES technology started to be developed in the 80s in Germany. Relatively small storages (up to 10,000 m³) were constructed with mostly a mixture of gravel and water as the storage medium. In the 90s, Denmark started R&D on PTES and has now become a worldwide pioneer in large-scale PTES (up to 210,000 m³ in operation) .

As it can be deduced from Table 1.2, since 2012, water has become the unique heat carrier for most PTES. Water was chosen for its higher energy density, better thermal stratification, ease of maintenance and high charge and discharge power. The construction complexity (especially the cover lid) and the impossibility of using the upper part of the storage as part of a residential area constitute a drawback compared to the gravel and water mixture. The focus is nevertheless kept on water-filled PTES.

Ramboll Danish company has since the first 10,000 m³ PTES was established in Marstal in 2004, been involved in the majority of the planned and constructed PTES in Denmark and abroad. Today, more countries show interest in that technology. China with the help of Danish expertise constructed its first PTES. Germany, Norway, Austria, Estonia and Denmark have huge pit projects that are currently under feasibility and design study. [10]

Recent implementations and future planned systems are increasingly focusing on larger storage volumes. This trend arises from the benefits of a reduced air-to-volume ratio, which minimizes losses. Additionally, the primary advantage of PTES lies in its cost-effectiveness, which scales non-linearly with size. [11]

1.2.2 The operation principle

The general operation characteristics are similar to tank TES. The storage operates as a closed-loop system, maintaining a consistent water level year-round. In the charging phase, the cold lower fluid is heated up and replaced on top. Vice versa for the discharge phase. In some installations, a third inlet/outlet is placed in the middle of the pit to increase operating opportunities.

To understand the operation and structure constraints on PTES presented in the next section, let's introduce the key concept: thermal stratification.

Thermal stratification inside a storage facility is critical. The better the stratification the lower the losses are and the higher the maximal temperature stays. This vertical temperature gradient is due to density differences caused by temperature variations. Thermal stratification is enhanced by increasing the temperature difference between the top and bottom, lower inlet velocities and higher aspect ratios. Weather conditions, inlet and outlet flow arrangements, geometry parameters, and levels of thermal insulation all impact the thermal stratification of the storage. A thermocline region is formed between the hot water at the top and the cold water at the bottom. This thermocline region acts as a natural buffer between the hot and cold regions, preventing mixing. In general, the thermocline layer should be as thin as possible as this allows for a greater volume of hot water within the storage indicating reduced mixing. [5]

1.2.3 Structure of PTES

Based on pilot and actual operating plants, the structure of PTES improved over the past years. The main technical characteristics based on the actual state of knowledge are detailed below.

Geometry

To limit thermal losses as much as possible, geometries that allow the best thermal stratification and have the lowest outer contact surface-to-volume ratio (A/V) are considered.

Large-scale PTES are proportionally less subject to losses due to their low surface-to-volume ratio. In that way, wide and deep pits are constructed. In addition, the deeper the water pit, the more obvious the thermal stratification. [13]

From the standpoint of reducing heat loss, improving thermal stratification, and reducing costs, the highest possible slope angle is chosen. But to prevent sidewall collapse, a non-null slope angle has to be chosen. The slope angle is around 30 for PTES larger than 10,000 m³. [12]

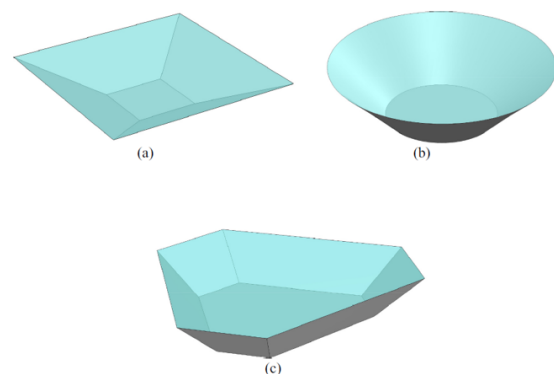


Figure 1.3 Geometries of PTES: (a) truncated pyramid stump; (b) truncated cone; (c) complicated pyramid stump [12]

In Figure 1.3, three distinct geometric configurations employed in current systems are

presented. The truncated pyramid stump is more common due to conventional construction. A complex pyramid stump was created and used in today's biggest PTES in operation: the Danish Vojens plant.

Geological conditions

Buried, partly buried and underground storage have to deal with the surrounding ground. In fact, the ground influences the fluid behaviour inside the PTES. It acts as a thermal capacitance. It is responsible for around 40% of the overall storage losses [12] but can restore some heat with a wise operation strategy. It's important to note that PTES surrounding ground needs multiple years of operation to reach a steady-state regime.

PTES constructed in geology with groundwater suffer from large thermal losses through the bottom and wall layers. To avoid this the excavation depth of the storage pit is selected so that the excavation bottom is above the groundwater level and the excavated material can be used as embankment fill on site. The shallow construction in Fig 1.4 is mainly carried out in Denmark.

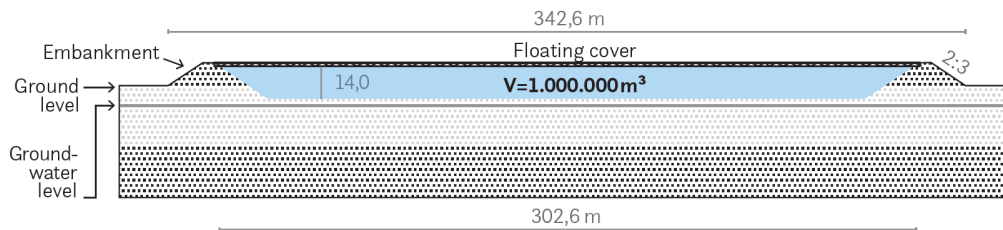


Figure 1.4 Schematic of a shallow pit, example of 1,0 Mio m³ [6]

In terms of available space and high floating cover cost, the excavation depth must sometimes be increased. The impact of moving groundwater is then reduced thanks to cut-off walls and cantilever walls can be added to increase volume for the same cover-needed surface as can be seen in Figure 1.5.

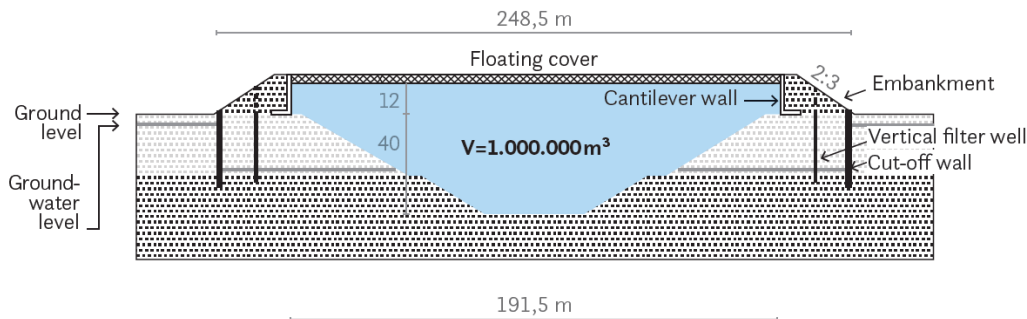


Figure 1.5 Schematic of a hybrid pit / deep pit with cut off wall, example of 1,0 Mio m³ [6]

Insulation of the bottom wall is recommended when it is close to groundwater. But

usually, the side and bottom walls of PTES are not insulated because the surrounding soil can act as a heat reservoir and transfer heat back to the PTES during discharge. Still, the influence of soil types on the thermal performance of the storage is significant. Study shows that for a PTES surrounded by dry soil, the storage efficiency can reach 90%, while for a PTES surrounded by wet sandy gravel, the storage efficiency decreases by 7%.^[14]

Inlet and outlet design

As previously signified, thermal stratification is critical. Charge and discharge flow speed has to be wisely balanced with the turbulence it produces. The design of inlet and outlet diffusers is therefore important. The radial diffuser design, as can be seen in Figure 1.6, is the most commonly used.

Note that in large TES, multiple inlet/outlet diffusers are used to charge or discharge at different temperatures depending on production availability and demand requirements.

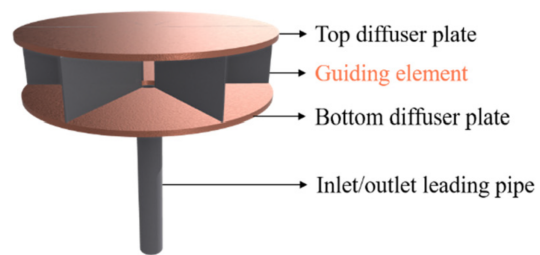


Figure 1.6 Schematic of a radial diffuser used for in and out flows ^[12]

Floating cover

Based on the lessons learned from operating projects, most heat losses occur at the top of the PTES. Taking Danish Dronninglund PTES as an example, heat loss from the cover contributes to around 60% of the annual thermal losses while the sidewall and the bottom contribute 38% and 2% respectively.^[14]

The cover is often made out of two waterproof polymeric layers that surround an insulation material. In addition to its critical insulation function, it is also the most difficult technology to install and to keep performing over the long term.

At present, the maximum temperature of PTES is generally controlled below 85 °C because of a significant decrease in the lifetime of liner materials with temperatures higher than 85 °C.^[12]

One of the challenges is to remove the moisture inside the cover. Moisture may result from the implementation phase of the cover, water diffusion through the liner, or damage to the liners. In this case, the insulation material will be degraded, resulting in increased thermal conductivity and reduced service life. Setting a ventilation gap between the liner and the insulation is a practical construction to remove moisture. At the same time, ventilation hoses are connected to the gap to help suck the moisture out in time. ^[12]

Evacuate rainwater presents another challenge. Because of this, the cover is typically constructed with a 2% slope towards the center of the cover where the water is pumped out. A new cover design was conceived by Aalborg CSP and can be seen in Fig 1.7. The principle is to divide the cover into smaller sections, each with an individual drop towards the centre pump. This makes it considerably simpler to direct rainwater away from the surface and makes it possible to build larger PTES. Moreover, sectioning of the lid construction makes it easier to detect leakage and reduces the impact on the lid insulation in case of one.

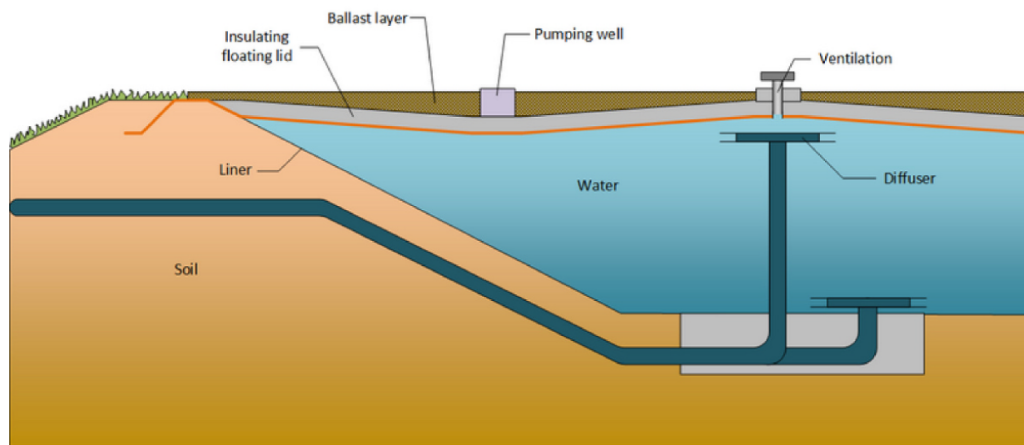


Figure 1.7 Principle sketch of a new cover solution developed by Aalborg CSP [12]

The next cover liner generation should stay long-term durable for temperatures higher than 90 °C. These liners could allow recovery of more heat from CHP units or industrial waste heat. To store more energy per m³ (e.g. solar thermal production peaks in the summer) and to keep higher temperatures for a longer period of the year. In addition, higher temperatures will improve the possibilities for application. Most PTES of today are in combination with solar thermal collectors (STC). In the future large-scale PTES in the large district heating systems would require more hours with temperatures of 90°C because they store heat from waste incineration and industries and work as buffer storages for CHPs adding flexibility to the electricity production.

City	Country	In service	Year installed	Volume [m ³]	Heat capacity [MWh]	Temperature range [°C]	Heat store material	Area [m ²]	Surface to volume ratio (A/V)	Buffer tank volume [m ³]	Main heat source	Auxiliary energy (type/capacity/number)	Solar collector field area [m ²]	Heat pump (type/capacity/kW)	Heat demand [MWh]	Geometry-slope angle [°]	References
Lambohov	Sweden	y	1980	10,000		10-65	Gravel, water	1,750		-	Solar thermal	Gas Boiler/-/1	2,700	Compression/-	900	90	[12]
Stuttgart	Germany	y	1985	1,050		0-30	Gravel, pebbles, water	835	0.840	1	Solar thermal	Co generation plant/-	211	Compression/66	100	45	[12]
Herlev	Denmark	n	1991	3,000		10-85				10	Solar thermal	Gas boiler/-/1 Gas CHP/-/1	1,050	Compression/-	-		[12]
Otrupgård	Denmark		1995	1,500	43.5	35-60				-	Solar thermal	-	560	-	43.5		[12, 11]
Julich	Germany	y	1996	2,500		-	Water	-	-	1	Solar thermal	Gas Boiler/750 kW/1	1,200	-	590	-	[12]
Augsburg	Germany	y	1996	6,500		-	Gravel, water	-	-	-	Solar thermal	-	2,000	-	-	90	[12]
Steinfurt	Germany	y	1999	1,500		15-60	Gravel, water	1,305	0.870	1000	Solar thermal	Gas Boiler/-/1	510	-	325	50	[12]
Chemnitz	Germany	y	2000	8,000		7-85	Gravel, water	3,375	0.430	-	Solar thermal	Gas Boiler/-/1	2,000	-	1200	90	[12]
Eggerstein	Germany	y	2008	4,500		10-80	Gravel, water	1,925	0.428	30	Solar thermal	Gas boiler/600 kW/2	1,600	Compression/60	1400	26 (top) 35 (bottom)	[12]
Marstal	Denmark	y	2012	75,000	6,000	20-80	Water	20,298	0.233	2100	Solar thermal	Biomass boiler/4MW/1 Bio-oil boiler/8.3MW/1 ORC/750 kW/1	33,300	Compression/1500	32000	32.78	[12, 11, 15]
Dronninglund	Denmark	y	2014	60,000	5,500	10-85	Water	17,076	0.288	None	Solar thermal	Bio-oil boiler/5MW/1 Bio-oil boiler/10MW/1 Gas boiler/8 MW/1 Gas CHP/1.6 MW/1 Electric boiler/10MW/1	37,573	Absorption/4700	40000	26.6	[12, 11, 15]
Gram	Denmark	y	2015	125,000	12,125	20-90	Water	28,893	0.237	2300	Solar thermal	Gas boiler/5.5 MW/1 Gas CHP/5 MW/6MWh/1 Industrial surplus heat/2 MW	44,000	Compression/900	30000	20	[12, 11]
Vejers	Denmark	y	2015	210,000	12,180	40-90	Water	-	-	-	Solar thermal	Electric boiler/10MW/1 Gas boiler/5.5 MW/1 Gas CHP/5 MW/6MWh/1 Industrial surplus heat/2MW	70,000	Absorption/5100	22000	-	[12, 11]
Toftlund	Denmark	y	2017	85,000	6,885	20-90	Water	19,204	0.274	-	Solar thermal	Electric boiler/3MW/1 Gas boiler/4.5 MW/1	27,000	Absorption/5100	28000	27	[12, 11]
Langgazi Tibet	China	y	2018	15,000	1,000	35-65	Water	6,748	0.447	None	Solar thermal	Electric boiler/1.5MW/2 biogas/gas	22,275	-	37300	27	[12, 16]
Meldorf	Germany	y	2023	43,000	1,500	7-90	Water			2xsteel tank (660MW)	Waste heat (printing plants) Waste/surplus heat/HP/CHP		0				[17]
Høje-Taastrup	Denmark	y	2023	70,000	3,300	7-95-110	Water	12,960					0				[18]
Graz	Austria	p	-	4,500,000							Solar thermal						[10]
Tallin	Estonia	p	-	5x400,000							Gas/waste/bio CHP						[10]
Aalborg	Denmark	p	-	2,500,000							Waste/surplus heat/HP/CHP						[10]
Odense	Denmark	p	-	500,000							Bio CHP/HP/Waste/gas						[10]
Bærum	Norway	p	-	55,000							Solar thermal						[10]
Neumünster	Germany	p	-	800,000							CHP						[10]
Roskilde	Denmark	p	-	200,000							Waste/surplus heat/HP/CHP						[10]
Esbjerg	Denmark	p	-	400,000							Waste/HP						[10]

Table 1.2 Global compilation of characteristics of existing, and planned systems incorporating PTES.

1.2.4 Global PTES implementations

Beginning with small-scale test systems, PTES has been implemented in large-scale DH systems since 2012, enhancing operational flexibility. PTES systems were predominantly developed to support solar collector plants by storing excess heat generated in the summer and supplying customers during colder winter months. Their primary design objective is to achieve the highest possible solar fraction in heat generation.

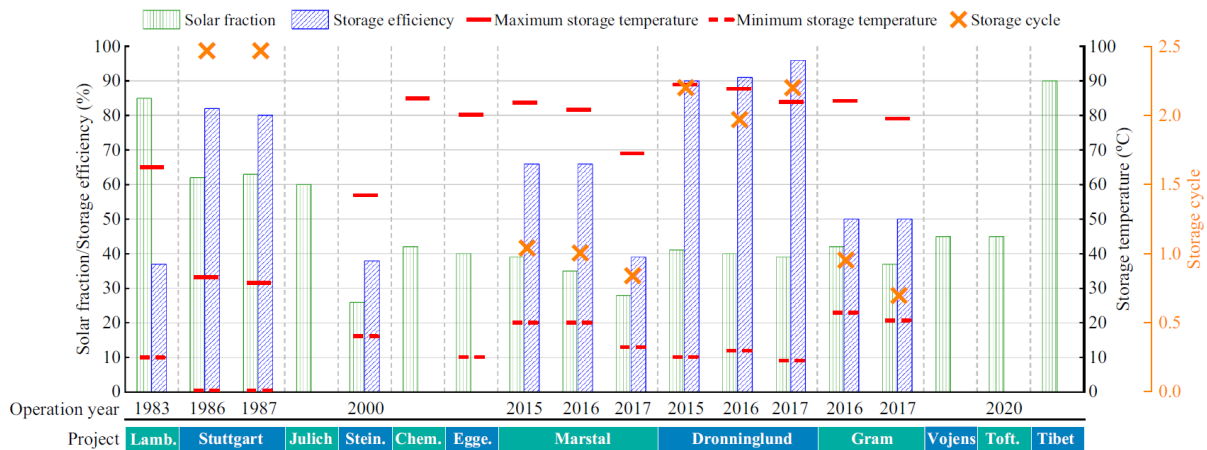


Figure 1.8 Comparison of performance metrics of existing PTES systems [12]

As illustrated in Figure 1.8, the majority of projects exhibit solar fractions between 30% and 50%, with the Lambohov and Langkazi Tibet projects exhibiting solar fractions exceeding 60%. Solar fraction is defined as the percentage of the total thermal load satisfied by solar energy. Therefore, the operational strategy and component design will both affect solar fraction. In the Stuttgart and Tibet projects, the solar collector fields are slightly oversized, resulting in the waste of additional heat during certain summer months. Notably, the Marstal project's solar fraction in 2017 fell below 30%. This can be attributed to the ingress of rainwater through leakage, which has increased the humidification of the cover and further increased the heat loss through the cover.

Regarding storage efficiency, there's a noticeable disparity among the projects. To clarify, storage efficiency is defined as the ratio of the total discharged and internal energy changes to the charged energy. For the Dronninglund PTES, there has been a gradual annual increase in storage efficiency, reaching a peak of 96% in 2017. This superior efficiency compared to Marstal and Gram can be partially attributed to the storage cycle. The storage cycle is the ratio of discharged heat to the maximum heat capacity of the PTES. As shown in Figure 1.8, the storage cycles for Marstal and Gram are below 1, whereas Dronninglund's typical storage cycle is 2. Furthermore, efficient operation at Dronninglund maintains the minimum PTES temperature at approximately 10°C, thereby reducing heat losses from its side and bottom walls. This relationship between storage cycle and storage efficiency is further evidenced in the Stuttgart projects. Despite the storage temperature being capped at around 30°C due to unglazed collectors,

the HP effectively leverages the storage capacity, resulting in a substantial temperature differential.

To integrate with the production or distribution grid, PTES systems use heat exchangers when the stored temperature exceeds the supply target or utilize a upgrader HP to achieve the required temperature. To minimize mixing within the PTES, which affects thermal stratification, buffer tanks are occasionally incorporated to provide intra-day balancing.

All systems have their own generation hub but in general gas, electric, and biomass peak load units help the PTES system to match the DH heat demand. In some cases, other sources supplement heat production. Industrial surplus heat and gas CHP are the most common ones.

The following describes two systems which are representative of state-of-the-art knowledge and give an idea about future expectations.

Solar Dronninglund PTES system

Dronninglund PTES is one of the pilot Danish installations constructed in 2014 and created a precedent in seasonal storage by reaching a storage efficiency above 90% between 2016 and 2019. Figure 1.9 gives an overview of the DH system in Dronninglund. The pit is supplied in heat only via solar collector fields and is discharged with the help of an absorption HP if necessary into the DH grid.

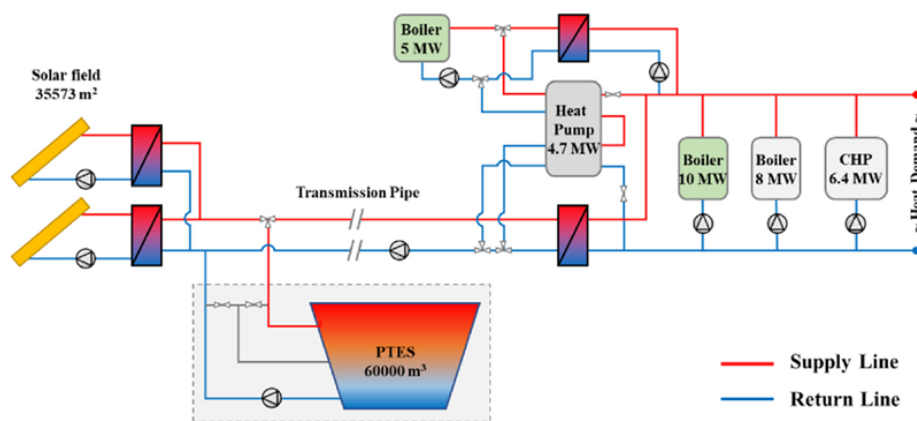


Figure 1.9 Principle diagram of DH system with PTES in Dronninglund [15]

Compared to previous pit storage operations, Dronninglund PTES acts as a short and long-term storage. The number of storage cycles is around 2 so the energy turnover is higher.

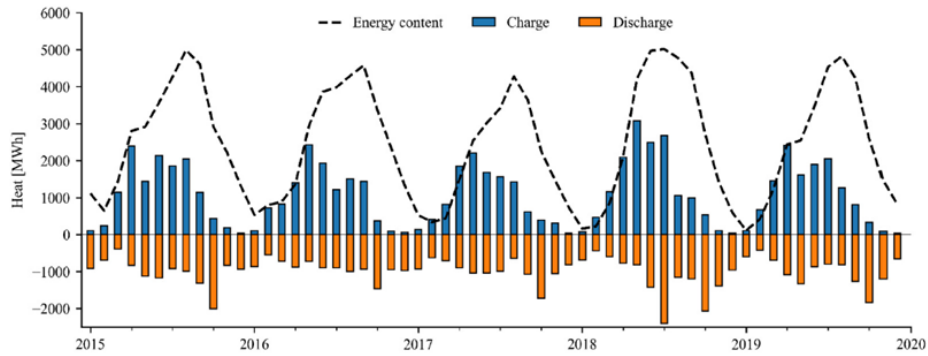


Figure 1.10 Monthly charged/discharged energy and energy content for PTES in Dronninglund [15]

To reach such a high efficiency, thermal losses are very low. This is due to the high stratification in the pit, the well-functioning thermal insulation cover and also to the wise utilization of the HP. When the storage temperature was lower than 75 °C, the system was used as a heat source for a HP. The HP was only operated in winter and cooled down the storage to approximately 10 °C. In particular, in 2017, the energy used as heat source for the HP accounted for 5398 MW. An analysis of the temperatures in the storage shows, that in 2017 the lower part of the storage had temperatures below 15 °C for about more than 2200 hours. In these periods the temperatures in the surrounding ground are higher than the temperatures inside the storage (see Figure 1.11). This leads to a heat transfer from the underground into the storage in the lower parts of the storage and thus to negative heat losses [19].

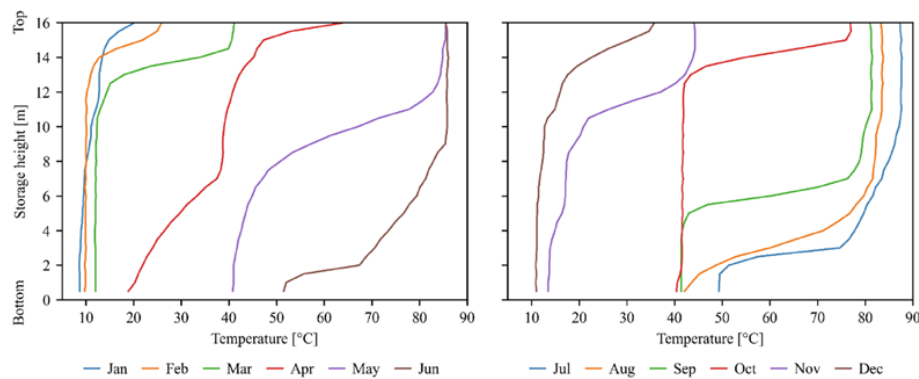


Figure 1.11 Temperature profile inside the Dronninglund storage on the 1st day of each month in 2018 [15]

Highly interconnected Høje-Taastrup PTES system

Traditionally, PTES had been used only for seasonal heat storage in conjunction with large-scale solar heating plants. However, in 2023, two new PTES without solar sources were commissioned. The operation in Meldorf, Germany, stands out because the predominant source of heat is the recovery of waste heat from a printing plant. In Høje-Taastrup in Denmark, the PTES is meant to act as a short-term (two-week cycle) storage and is directly connected to the Copenhagen DH network without the use of a HP. [18]

The purpose of this PTES is to store heat when production costs are low and distribute it when costs are high, thereby providing economic optimization services to a wide system including buffers, waste and surplus heat sources, HP, and CHP units. In total, PTES serves 26 local district heating companies in the Copenhagen metropolitan area.

Several PTES integrated with diverse heat systems, synergizing with various generation hubs configurations (see bottom of Table 1.2), are currently under design and feasibility studies in Austria, Estonia, Denmark, Norway, and Germany. As sector coupling is increasingly recognized as essential for maximizing carbon-free production, complex operations and interconnected configurations are now being more explored.

1.3 PTES numerical modelling and simulation

The substantial expenses linked to implementing PTES continue to be a significant obstacle to its large deployment. Experimental investigations in the design phase are limited due to the size of these storage technologies and the long time periods in question. Therefore, numerical simulations from the component to the system level are used throughout the whole design process, from the feasibility phase to the detailed design. [21]

The complexity of the processes and interactions involved emphasises the need to use simulation tools in the design of these systems. To optimise PTES, it is essential to use flexible and detailed models capable of exploring different geometries, isolation levels, ground thermal behaviour and boundary conditions, such as the presence of ground-water (GW).

The various existing tools used for PTES modelling are presented in Figure 1.12 according to their respective scope: from the pure fluid domain to the system level. The global PTES review [12] written in 2022 highlighted that simulation approaches

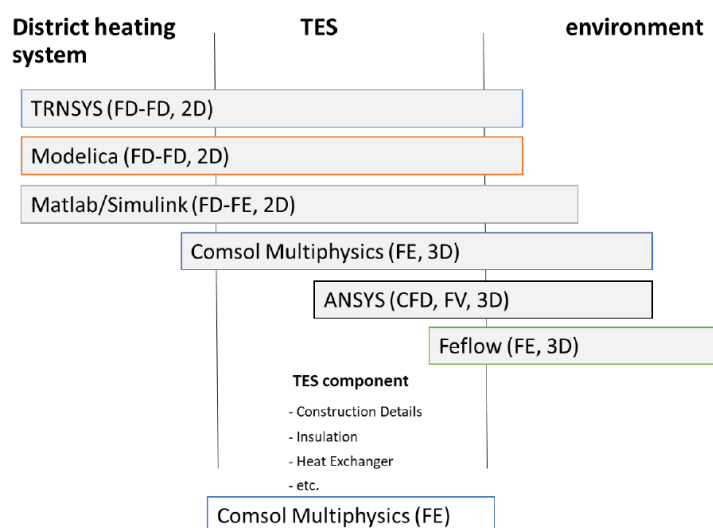


Figure 1.12 Representation of simulation levels with the allocation of several tools according to their scope [20]

for system integration are less studied and suffer from significant differences in performance indicators from the actual projects due to the simplification of the operation strategy. Furthermore, system modelling is considered necessary to integrate PTES in the energy system with different system structures and operation strategies.

To date, for PTES systems, TRNSYS is the most widely used simulation tool for storage and system design questions in the private sector as well as for scientific studies.[21]. In recent years, Modelica models have been increasingly investigated. A number of new studies and new Modelica models are being carried out in the context of the IEA Task 39 "Large scale thermal energy storage for district heating"¹.

Modelica tool seems to be playing a greater role in PTES modelling in the research since Modelica's equation-based, object-oriented, and multidomain modeling approach inherently facilitates high reusability, expandability and adaptability of the produced models.

To give an overview of current advances, a PTES model with cylindrical geometry was developed by Fournier [22] and validated against the Dronninglund PTES measurement data. More recently, Kirschstein [23] developed a Modelica PTES model with a conical geometry, which is available as part of the Modelica Solar District Heating (MoSDH) library. Based on these previous Modelica models limited in functionality and flexibility, Reisenbichler [21] built an efficient and flexible modelling and simulation library (LargeTESmtk). Figure 1.13 shows the library's range of possibilities.

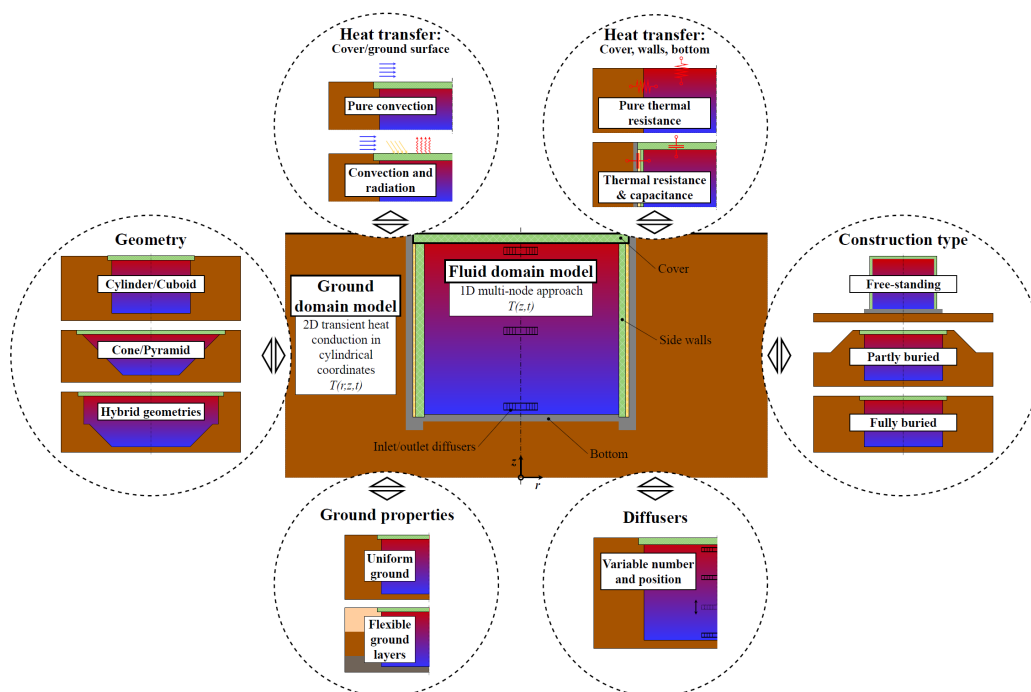


Figure 1.13 Overview and features of the LargeTESmtk library [21]

¹<https://iea-es.org/task-39/>

1 | Preliminaries and backgrounds

The PTES models developed on various tools (COMSOL Multiphysics, TRNSYS, Modelica and MATLAB/Simulink) were cross-compared in [20] and generally must all be validated against real data. Figure 1.14 analyses the Modelica LargeTESmtk model performance with the measured Drinninglund data which gives an idea of the accuracy of current models.

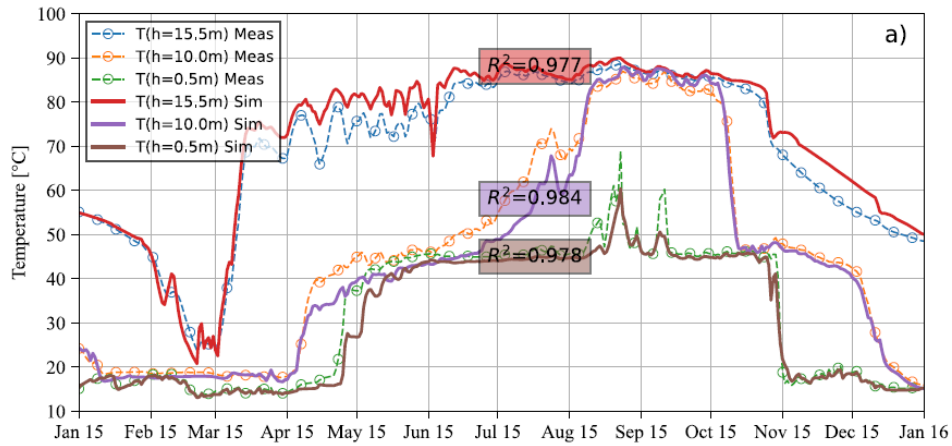


Figure 1.14 Comparison between simulated and measured storage temperatures of the PTES in Dronninglund for the year 2015 in daily resolution at the three inlet and outlet diffuser heights; In the corresponding colored boxes, the coefficient of determination values (R^2) for the entire year are shown. (Adapted from [21])

The validation case study related to this figure showed that the storage temperatures as well as the charge and discharge energies could be accurately represented (with deviations in the range of 1%) compared to the measured data. Slightly higher deviations from the measured data (in the range of 10%) were observed only for the simulated total thermal losses, in particular the side and bottom thermal losses. This is probably due to the differences in geometries between the simulated and measured storage.[21]

2.1 Research approach

The work aims to evaluate the significance of PTES system integration in a low-temperature network. The appropriate design and operational strategies for given heat load patterns are addressed. To achieve this objective, the study delves into two successive steps that gradually address the complexity of PTES in the broader system. Figure 2.1 summarises the two steps as well as the main variables and parameters involved.

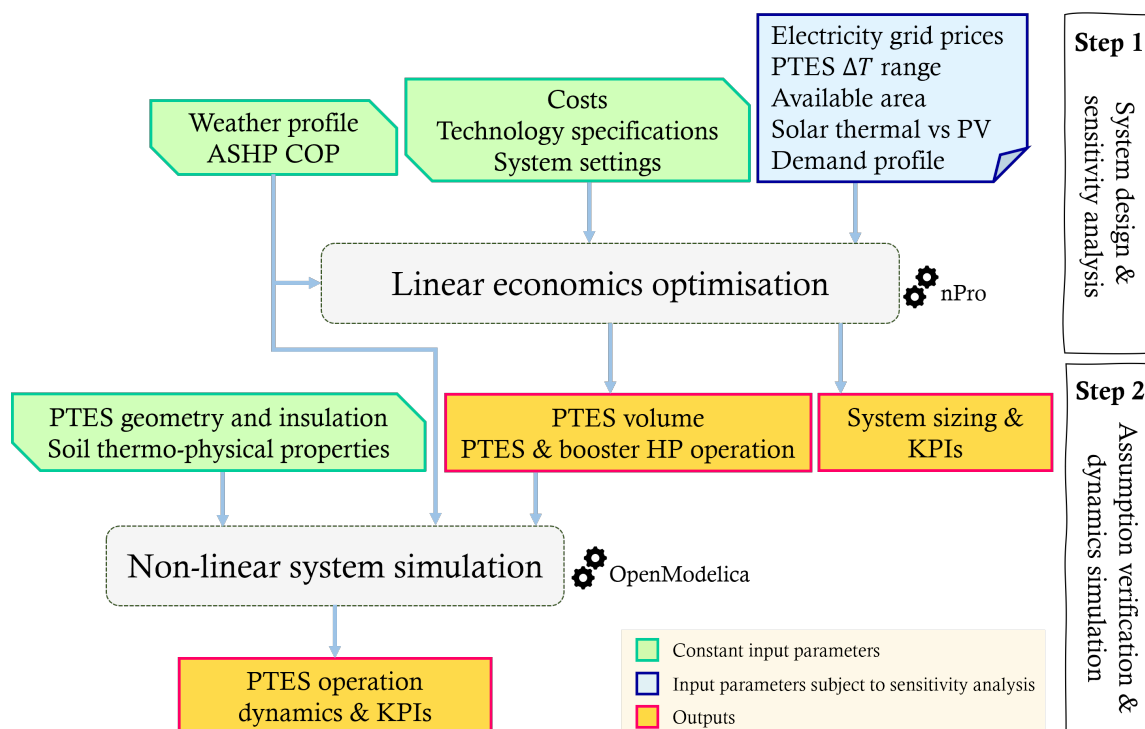


Figure 2.1 Scheme of the executed method

2.1.1 Step 1: Heating system design - economics optimisation

The first step involves a comprehensive energy system analysis focused on economic efficiency. By utilizing a linear optimization tool (nPro), we can determine the optimal technology configurations and sizing, as well as their corresponding operation throughout the year. The integration of PTES into the system is depicted in Figure 2.2.

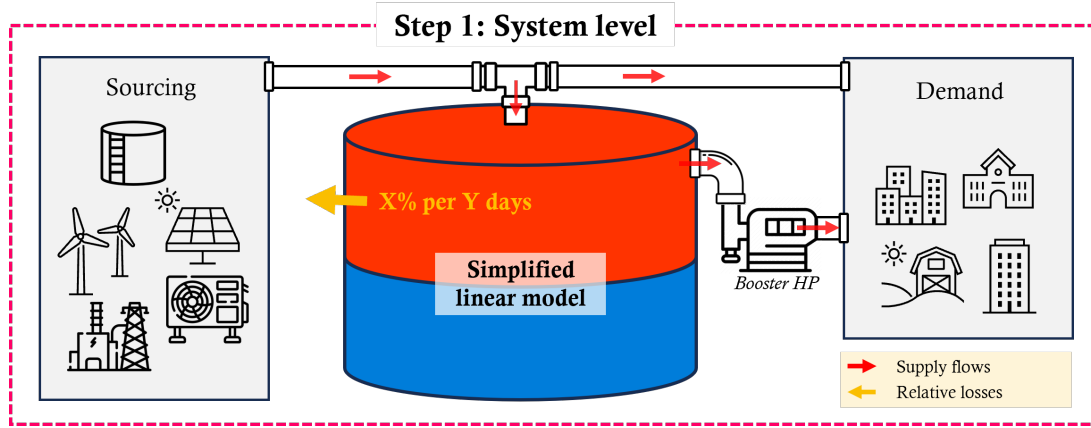


Figure 2.2 Step 1 scope and configuration. PTES is modelled as a pure accumulator. The positive energy content is considered at a constant temperature and the PTES loss model is explicit.

Due to the necessity for simplified modeling to facilitate linear optimization, these scenarios serve as preliminary assessments for a specific DH system and require robustness analysis. By varying optimization parameters and constraints based on relevant assumptions, multiple scenarios are generated and evaluated based on economic and system Key Performance Indicators (KPI). Some representative scenarios can be forwarded to the next step for further analysis. The considered KPIs are presented below.

The Levelized Cost Of Heat (LCOH) is a metric used to assess the cost of producing heat over the lifetime of a heat production facility, typically expressed in €/kWh_{th}. The equation 2.1 for LCOH calculation is detailed below.

$$\text{LCOH} = \frac{\text{annual cost}}{\text{annual heat consumption}} = \frac{\text{NPV} / N}{Q_{th}} \quad (2.1)$$

NPV (Net Present Value) represents the total costs associated with heat production, including capital costs, operating costs, maintenance costs, and other expenses, discounted to reflect the value of future cash flows. Q_{th} is the annual quantity of heat consumed. N is the number of years over which the analysis is conducted.

System Land Use (SLU) involves the management and modification of natural environment or wilderness into heating system units and is expressed in m². Equation 2.2 combines the area occupied by PV and STC installations, as well as the upper surface area of the PTES. This metric gives an underestimation of real land use but is used to

compare different scenarios.

$$SLU = A_{PV} + A_{STC} + A_{PTES} \quad (2.2)$$

The area used for PTES installation is estimated as a square with side corresponding to PTES upper diameter : $A_{PTES} = (2 \cdot R_{top})^2$. The PTES geometry is simplified to a cone where R_{top} is the top radius and is expressed as a function of its volume, and the angle θ (where θ is the angle between the side wall and the horizontal and is a constant given in the data description section). Starting with the volume equation of a cone :

$$V = \frac{1}{3} \pi R_{top}^2 h$$

and knowing the following relation : $h = R_{top} / \tan(\theta)$. The PTES top radius can be expressed as follow :

$$R_{top} = \sqrt[3]{\frac{3V \tan(\theta)}{\pi}}$$

The Grid Dependency Factor (GDF) allows for the analysis of self-sufficiency and grid price fluctuation impact among different heat systems. It is determined by normalizing the total energy imported from the grid by the total heat consumption. This normalization, as described by equation 2.3, enables the comparison of systems with varying heat demands. The GDF is expressed in kWh_e / kWh_{th} , indicating the ratio of electrical energy imported from the grid to thermal energy consumed.

$$GDF = \frac{\text{annual imported electricity from the grid}}{\text{annual heat consumption}} \quad (2.3)$$

Heat Storage Utilization Rate (HSUR), expressed as a percentage, quantifies the proportion of heat passing through a storage system relative to the total heat demand (Equation 2.4). This metric is crucial for assessing the role and effectiveness of a storage within the overall heat system.

$$HSUR = \frac{\text{annual heat discharged from storage}}{\text{annual heat consumption}} \quad (2.4)$$

Number of storage cycles (N_{cycl}) represents the number of cycles based on the discharged thermal energy (Q_{out}) divided by the maximum thermal energy storage capacity (Q_{cap}).

$$N_{cycl} = \frac{Q_{out}}{Q_{cap}} \quad (2.5)$$

This equation provides a measure of how many complete cycles a storage undergoes based on the ratio of the energy taken out from the storage system to its maximum energy capacity. This indicator is often used to understand the cycling behaviour, which is important for evaluating their performance and durability. Typically, storages acting as pure seasonal energy shifters have a N_{cycl} of 1.

2.1.2 Step 2: PTES operation simulation

The systems identified as significant and representative during step 1 will undergo a detailed analysis, focusing on the PTES sizing and its operational performance which are outputs of step 1. A sophisticated non-linear modeling tool is necessary for this analysis to assess stratification quality, thermal losses, efficiencies, operating temperatures, and fluxes. The scope of step 2, presented in Figure 2.3, involves a detailed model of the PTES to represent the physical dynamics of fluid and environment interactions as well as energy exchanges within the system. This model captures the intricate behaviors of the PTES, including thermal stratification, implicit heat transfer processes, and the impact of external environmental conditions.

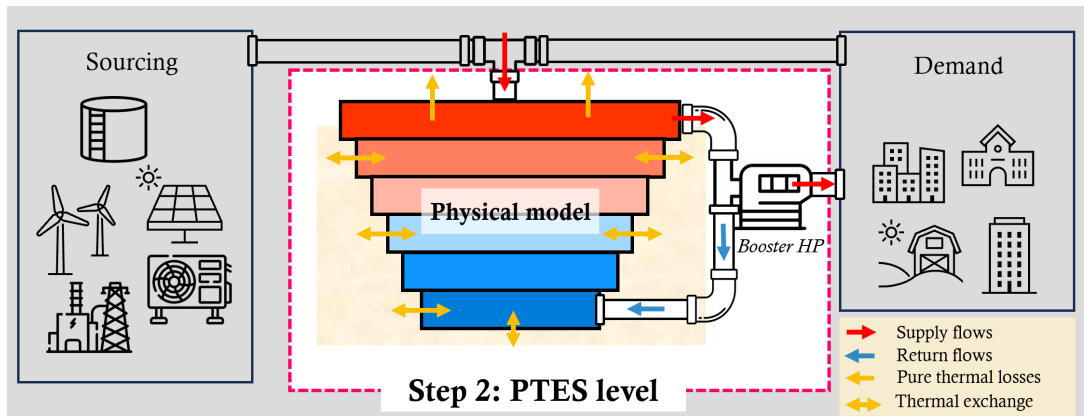


Figure 2.3 Step 2 scope and configuration. The PTES model physically represents fluid and environment dynamics and energy exchanges.

To ensure valuable results, the maximum parameters and solution outputs from step 1 are retained and used as inputs for the simulation. Below is a comprehensive list of the data transferred to the simulation tool:

1. The demand directly supplied to the final consumer is excluded from the analysis, as it does not affect the PTES operation. Only the heat produced by the various units charging the PTES is considered relevant and is aggregated into a single heat source.
2. The PTES volume is directly taken from the optimization output. The initial state of charge is transformed with Equation 2.10 into a perfectly stratified temperature gradient with the same energy content.

3. Additionally, a booster HP is simulated, as it directly affects the PTES flows and temperatures. The COP and load power time series are taken from step 1. The booster HP evaporator return temperature is assumed to be the temperature threshold at which the PTES is considered empty.

The data provided by the optimisation is supplemented by a bunch of parameters giving a concrete and realistic physical aspect to the PTES. The parameters are listed in Figure 2.1.

The PTES operates in a closed loop, energised by a heat source raising in temperature the fluid coming from the bottom port to be reloaded on top. During the discharge phase, the booster HP drives the heat from the top layer, upgarding the temperature on the DH side and sending the cooler fluid to the bottom layer.

The following KPIs will help to understand the main issues concerning PTES design and operation.

Thermal performance indicators

The storage efficiency (η) of a storage is usually defined as the ratio between the useful output and the input to the system.

The energy balance of a thermal storage system can be expressed as:

$$Q_{out} = Q_{in} - Q_{loss} - \Delta Q_{int}$$

where Q_{out} is the discharged energy from the storage system, Q_{in} is the charged energy, and Q_{loss} is the energy lost due to heat losses. ΔQ_{int} represents the change in the internal energy of the storage system, which is the difference between the internal energy at the start and end of the period under consideration. In this study, the efficiency is expressed as:

$$\eta = \frac{Q_{out}}{Q_{in} - \Delta Q_{int}} = \frac{Q_{out}}{Q_{out} + Q_{loss}} \quad (2.6)$$

Stratification indicators

The MIX number is a dimensionless indicator for evaluating storage stratification by comparing the temperature profile of the storage system with that of fully mixed and fully stratified reference systems [24]. Ranging between zero and one, the MIX number signifies a perfectly stratified and fully mixed storage, respectively. It is calculated based on the moment of energy, as presented in Eq. 2.7.

$$MIX = \frac{M_E^{stratified} - M_E^{actual}}{M_E^{stratified} - M_E^{mixed}} \quad (2.7)$$

The moment of energy for each scenario is computed by summing the moment of energy for each layer. The moment of energy for each layer is determined by multiplying the energy content of the layer by its distance from the bottom of the storage:

$$M_E = \sum_{i=1}^N \rho \cdot V_i \cdot C_p \cdot (T_i - T_{\text{ref}}) \cdot z_i \quad (2.8)$$

Where N is the number of storage layers, ρ represents the water density, V_i is the water volume of layer i , C_p is the specific heat, and T_i is the water temperature of the i th layer. The distance from the centroid of the layer to the bottom of the storage system is denoted as z_i , and T_{ref} is the reference temperature, i.e., the temperature at which the storage system is considered empty.

The moment of energy for the fully mixed (Equation 2.9) and fully stratified (Equation 2.10) storage systems is calculated such that they have the same energy content Q_{th} as the actual storage system.

$$T_i^{\text{mixed}} = \frac{Q_{th}}{\rho \cdot C_p \cdot V} + T_{\text{ref}} \quad (2.9)$$

$$T_i^{\text{stratified}} = \begin{cases} T_{\text{max}} & \text{if } i > N - f_{\text{int}} - 1 \\ T_{\text{ref}} \cdot (1 - f_{\text{dec}}) + T_{\text{max}} \cdot f_{\text{dec}} & \text{if } i = N - f_{\text{int}} - 1 \\ T_{\text{ref}} & \text{otherwise} \end{cases} \quad (2.10)$$

Where T_{max} is the temperature of the charged fluid at the top of the storage, f_{int} and f_{dec} are, respectively, the integer and decimal part of the proportion of storage layers filled at T_{max} .

The stratification coefficient St quantifies the degree of thermal stratification by measuring the deviation of the storage temperature profile from the mean temperature. The expression taken from [15] is presented below:

$$St = \sum_{i=1}^N \frac{m_i \cdot (T_i - T_{\text{avg}})^2}{m_{\text{total}}} \quad (2.11)$$

where T_i is the temperature and m_i is the mass of the i th layer, T_{avg} is the average storage temperature, and m_{total} is the total mass of the storage system.

Note that, similar to the MIX number, the value of the stratification coefficient has no physical meaning on its own. However, it can be used to compare different storage systems or various storage operations.

2.2 Step 1: Linear economics optimisation tool - nPro

The first method step involves estimating the demand and investigating the sensitivity of key parameters on the overall cost and design of the heating system. To calculate

energy loads and elaborate heating system scenarios, the company I collaborate with, Resolia, employs the linear optimization nPro tool. Consequently, this study utilizes nPro app¹.

2.2.1 Basic principles

The nPro app is a web-based tool aimed at simplifying the early planning stage of district solutions. The tool covers the three main calculation steps for district energy system planning: load profile generation, thermal network calculation, and energy system design optimization.

nPro runs a linear optimization algorithm over a cost function based on user-defined variables, constraints, and parameters. All available technologies and their corresponding interconnections in the latest (2.2) version of nPro can be consulted in the documentation².

2.2.2 Planning method in three steps

A mathematical optimization model, such as the one employed in nPro, comprises thousands of equations that represent the physical relationships within the energy system. Each equation is formulated of static or dynamic parameters and one or multiple variables to be designed. To do so nPro tool is divided into two calculation modules that are processed one after the other as presented in Figure 2.4. In Module I, load profiles and the thermal network are calculated. In Module II, the energy hub design optimization and operation simulation are conducted. This section provides a comprehensive understanding of the two modules.

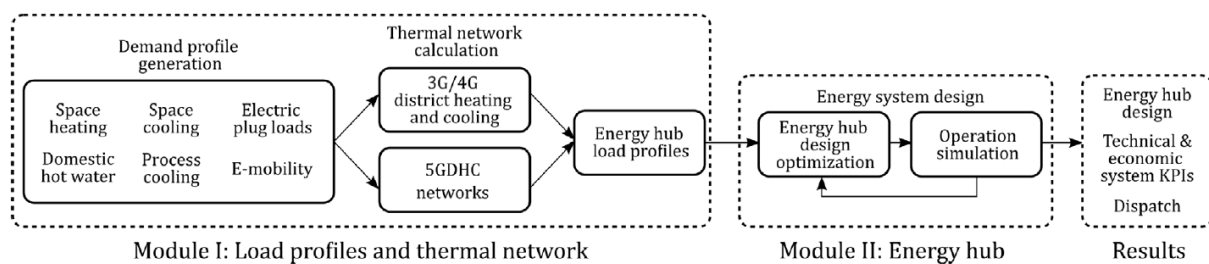


Figure 2.4 Design workflow for planning district energy systems in nPro [25]

Demand profile generation

The nPro tool generates energy demand profiles for various purposes, including space heating, domestic hot water and electricity demands. These demand profiles are created at an hourly resolution considering imported project weather profiles combined

¹<https://app.npro.energy/en>

²<https://www.npro.energy/main/en/help/all-tool-features>

with provided buildings connected to the district.

For domestic hot water and electricity demands, a base profile is supplemented by daily profiles. These day profiles are available for different building types and for three typical days of the week: Weekday (Monday to Friday), Saturday, and Sunday. The base profiles can either be constant or they can account for seasonal fluctuations observed, for instance, in domestic hot water demand (which tends to decrease during summer months).

For space heating, the base demand depends on ambient air temperature, calculated using a degree-day approach. This method assumes that space heating demand increases linearly with the temperature difference between outdoor and indoor set temperatures. The heating base temperature represents the outdoor temperature below which a building requires heating to maintain its set temperature.

For low-temperature heat networks, decentralized upgrade units such as booster HP can be considered. The heat network becomes the cold source for the booster HP. This allows for low distribution thermal losses and high HP performance. At least if the district supply temperature falls under the sanitary limit of tap water, decentralized heat generation is necessary.

District heating network calculation

The heat imported from the network is derived as follows. All heat demands from buildings are aggregated together. The waste heat recovered in the ventilation as well as the part of the heat demand that is covered by the decentralized HPs reduces the amount of heat that needs to be imported from the heat network by the buildings. To determine the effective energy generated by the energy hub and supplied to the district heating network, it's necessary to account for network heat losses.

In addition to the heat losses and gains, a diversity factor can be considered for a given thermal network. The diversity factor considers the scenario where the collective peak demand of a group of buildings is less than the sum of the peak demands of individual buildings. This leads to a less restrictive and more representative load profile for the building group.

Energy hub design optimization

The design optimization process is conducted using a linear program and operates at an hourly resolution for all time series data. This approach enables the tool to determine the optimal configuration and sizing of technologies. The objective function of this optimization is the minimization of total annualized costs (TAC). Focusing only

on cost types relevant to this work, the objective function can be expressed as follows:

$$\min C_{\text{capex}} + C_{\text{opex}} + (C_{\text{grid}} - R_{\text{grid}}) \quad (2.12)$$

where C_{capex} corresponds to the annualized investment costs. C_{opex} represents the annual expenses related to maintenance and repair. C_{grid} reflects the expenditure on electricity procured from the power grid, while R_{grid} denotes the revenues generated from feeding electricity back into the grid.

2.2.3 Storage linear model

To understand the analysis conducted in this study, it is necessary to detail the storage model provided by nPro. This component used to represent the PTES is modeled in a simplistic manner, with only two parameters that can be defined.

1. The temperature range describes the temperature difference between a fully charged and a fully discharged storage. It expresses the energy density.
2. The standby losses are defined by a relative loss per time and describe how fast the state of charge decreases over time due to thermal losses.

The storage settings open up the possibility of a seasonal operation. If a seasonal operation of storages is enabled, storages are modeled as follows:

The state of charge $S_{n,t}$ of a storage technology for each day of the year $n \in N_{\text{year}}$ with $N_{\text{year}} = \{1, 2, \dots, 365\}$ and every time step $t \in T$ is:

$$S_{n,t} = S_{n,t-1}(1 - \phi_{\text{loss}}) + P_{\sigma(n),t}^{\text{ch}} - P_{\sigma(n),t}^{\text{dch}} \quad n \in N_{\text{year}}, t \in T : t \neq 1 \quad (2.13)$$

Here, ϕ_{loss} is the stand-by loss coefficient. P^{ch} and P^{dch} denote charging and discharging energy flows. The function σ is the assignment between the days of the year n and design days d :

$$\sigma : N_{\text{year}} \rightarrow D, \sigma(n) = d \quad (2.14)$$

2.3 Step 2: PTES operation simulation tool - OpenModelica

To implement the second step of the method, a modelling and simulation tool is required. The domain is in constant evolution and novel and performant tools, such as the Modelica LargeTESmtk library presented in Section 1.3, are not yet available and will soon arrive on the market or made open-source.

For the purpose of this work, an Modelica open-source, user-friendly system-level modelling and simulation library was chosen. The Modelica Solar District Heating

library (MoSDH) [26, 23] was developed by Julian Formhals and suggested by Michael Reisenbichler, a researcher at AEE INTEC, Austria and part of the Large Thermal Energy Storages for District Heating Task 39 within the International Energy Agency Technology Collaboration Programs.

Initially created for solar district heating simulation with borehole TES, the library has been extended to include all existing sourcing technologies and water thermally stratified storage technologies (tank and PTES). Although this library doesn't offer as much flexibility as the LargeTESmtk library, it is based on the same fluid and soil modelling approaches and is therefore sufficient for the purposes of this work.

2.3.1 Library basic principle and components

MoSDH is a complete and autonomous library that includes all the components needed to implement and simulate a complete district heating network. Secondary components such as pumps and interface connections are already included in the main ones.

The library contains thermal energy sources, storage technologies, distribution features, load and weather profile blocks and additional utilities such as a control unit. This section will give more details on the modelling of applicable components for renewably sourced DH study cases this work will deal with.

Thermal load, weather, distribution and system control

The implemented heat demand module extracts the load curve data from a text file. It necessitates the definition of a reference return temperature, which acts as a pivotal parameter regulating the volume flow rate. Should the temperature difference between supply and return drop below a design minimum, the actual extracted heat deviates from the predefined load curve and the load is not fully supplied.

Consequently, the weather data module serves the purpose of extracting climate records and defining calendar specifications.

Moreover, the control system component allows dynamic switching between two DH supply temperatures depending on the ambient temperature. The distribution components such as pumps, heat exchangers, mixing valves or the return-flow mixing component for lowering supply temperatures help the system to operate with all the suitable properties.

Heat source components

The HP model is categorized as either a compression air-source or water-source. Its performance is defined through tables illustrating the coefficient of performance (COP) corresponding to different evaporator and condenser temperatures. The model includes multiple operation modes, each necessitating the specification of three control variables: the load side temperature and heating power, as well as the source side volume flow rate, temperature difference, and cooling power.

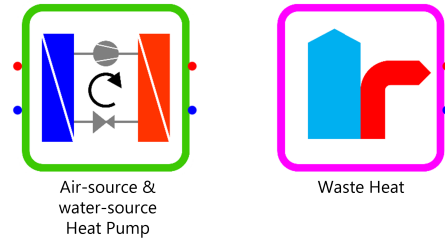


Figure 2.5 HP and waste heat components icons of the MoSDH library [23]

The waste heat model is simply a heat generation component. Generally, the heat supply is defined by the supply temperature, the volume flow rate and the thermal power, of which two values have to be defined by control variables, depending on the current mode. This component can also be used to import thermal production data time series from an external file.

2.3.2 PTES modelling approach

The PTES modeling is the very purpose for which the MoSDH library is utilized, and as such, it is elaborated upon below.

The PTES model combines interconnected meshed elements modeling the stratified water volumes, the ground and the floating lid. Due to the chosen geometry being a truncated cone, the PTES model is axisymmetric and is represented as a 2D meshed half-section of the considered system. The key geometry parameters of the model are illustrated in Figure 2.7. Notably, the lid is meticulously modeled due to its previously identified significance in PTES systems. To account for a user-defined number of insulation layers, thermal resistances and capacities are employed, incorporating temperature-dependent values for thermal conductivity. Three fluid ports are established, connecting to the top layer, the bottom layer, and a user-defined mid layer, facilitating the integration of the PTES component into the broader system model.

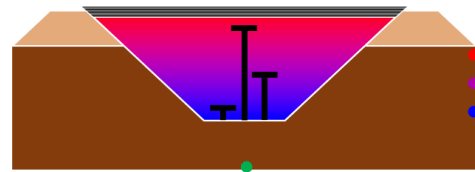


Figure 2.6 PTES component icon of the MoSDH library [23]

One aspect that undergoes simplification in the model is the geometry of the pit wall. To that purpose, rectangular elements are employed, giving rise to the step shape depicted in Figure 2.7. Heat transfer from the pit layer elements to the adjacent ground elements is exclusively taken into account in the radial direction.

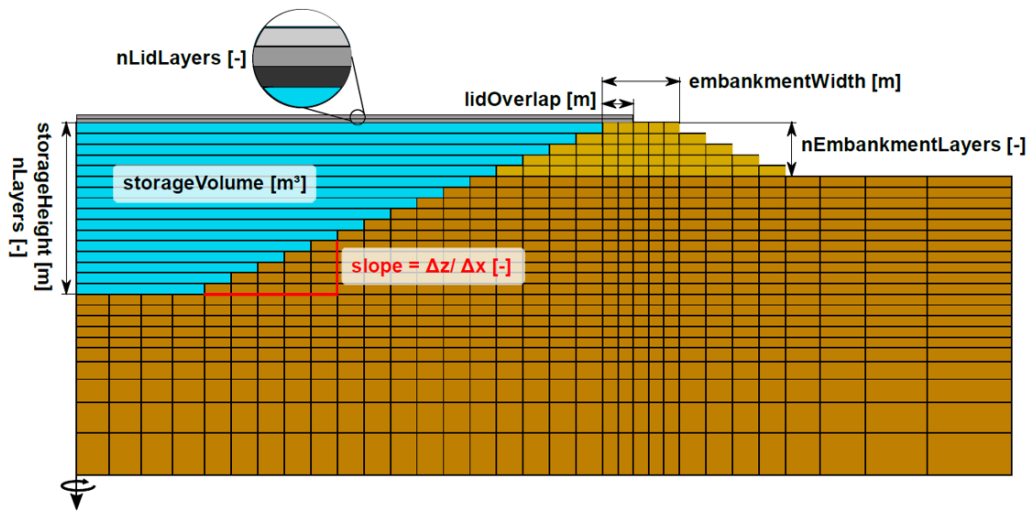


Figure 2.7 Exemplary mesh and main parameters of the PTES model of the MoSDH library [23]

Fluid modelling

The PTES dynamic fluid domain is represented using the StratifiedStorageVolume sub-model. This model segments a cylindrical fluid volume into multiple layers, each with the same volume, as depicted in Figure [23]. Each layer includes two fluid ports for injecting and extracting fluid, located on the load and source sides (indicated by black points). Additionally, there are conductive ports in each layer to consider heat losses through the walls, along with additional ports positioned at the top and bottom of the storage volume (marked as red and white squares). Heat losses through the storage top lid are determined using the dynamic ambient temperature defined by the PTES weather port. Insulation levels for the storage top, wall, and bottom can be specified using respective parameter values.

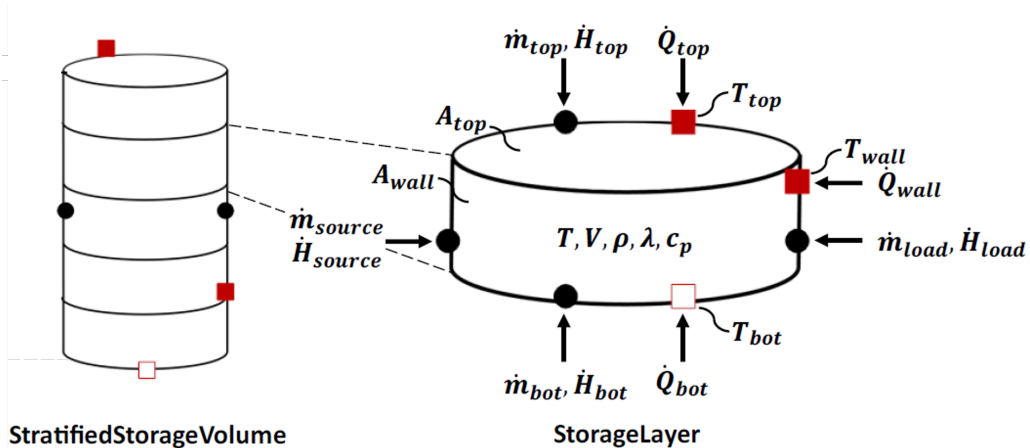


Figure 2.8 Fluid domain structure and physical fluxes and quantities of one single volume element model (Adapted from [23])

Within each layer, a constant temperature is assumed, and both mass and energy balances are taken into account following Equations (2.15) and (2.16) respectively. The

energy balance for each volume element can be expressed as the sum of all incoming and outgoing enthalpy flows $\dot{H}$ and heat fluxes $\dot{Q}$ equal to the change in internal energy U or, in the case of constant thermophysical properties of the storage fluid (water), the change in temperature T of the element with time t .

$$\dot{m}_{top} + \dot{m}_{bot} + \dot{m}_{source} + \dot{m}_{load} = 0 \quad (2.15)$$

$$\rho V c_p \frac{dT}{dt} = \dot{H}_{top} + \dot{H}_{bot} + \dot{H}_{source} + \dot{H}_{load} + \dot{Q}_{top} + \dot{Q}_{bot} + \dot{Q}_{wall} \quad (2.16)$$

Conductive heat transfer between adjacent storage layers is determined by Equation (2.17), where $\dot{Q}_{port}$ represents the heat flux to either the layer below (bot), the layer above (top), or the shell surface (wall). A_{surf} denotes the corresponding contact surface area, λ signifies the thermal conductivity of the medium, and h is the segment height.

In cases of thermal inversion, where a lower temperature exists within the upper layer, natural convection effects are incorporated by artificially increasing the thermal conductivity. The term $\lambda_{buoyancy}$ is calculated using Equation (2.18), where β_w represents the thermal expansion coefficient of the storage medium, and κ denotes the Kármán constant.

$$\dot{Q}_{port} = (T_{port} - T) \frac{2A_{surf}}{h} (\lambda + \lambda_{buoyancy}) \quad (2.17)$$

$$\lambda_{buoyancy} = \begin{cases} \frac{2}{3} \rho \kappa h^2 \sqrt{|-g \beta_w \frac{(T_{port} - T)}{h}|} & \text{if } T_{top} < T_{bottom} \\ 0 & \text{otherwise} \end{cases} \quad (2.18)$$

The modeling techniques described for the stratified fluid domain storage model have been validated in the original literature [27] by comparing the model's results with those obtained from existing buffer storage models.

Ground modelling

The heat is transferred to the ground through the storage side walls and bottom, which requires another modeling approach. The ground model handles the heat diffusion processes between the ground elements surrounding the storage. The ground is divided into multiple meshes facilitating their respective specific connections with other elements, see figure 2.9 example.

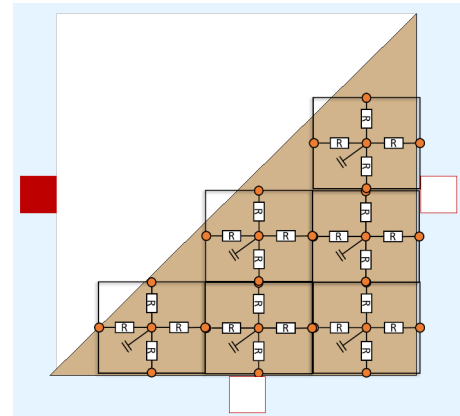


Figure 2.9 Exemplary mesh of the left embankment region connecting with the side storage side wall (red port) and with the right and bottom ground meshes (white ports) [23]

Note that the bordering elements are connected to

boundary conditions being the soil reference temperature for the ground borders and the fluctuating outside temperature and top ground ports.

Each of the meshes comprises several unique cylindrical ground elements, each governed by the energy balance described in Equation 2.19.

$$\rho V c_p \frac{dT}{dt} = \dot{Q}_{top} + \dot{Q}_{bot} + \dot{Q}_{outer} + \dot{Q}_{inner} \quad (2.19)$$

The ground element is modelled by four thermal resistances R connecting to the surrounding elements (top, bottom, inner and outer radius) which are characterized by the equation: $\dot{Q} = \frac{\Delta T}{R}$. The model also includes a thermal capacity C modeling the ground's ability to store heat and is characterized by the equation: $\dot{Q} = C \cdot dT$. The temperature is assumed to be uniform for the entire volume. Furthermore, note that the heat capacity is considered constant (independent of temperature). The resistance and capacitor value are expressed respectively in [K/W] and [J/K]. Their calculations are detailed below.

$$R_{top,k} = R_{bottom,k} = \frac{h_k}{2 \cdot \pi \cdot \lambda_{gr} \cdot (r_{o,k}^2 - r_{i,k}^2)} \quad (2.20)$$

$$R_{outer,k} = \frac{\log\left(\frac{2 \cdot r_{o,k}}{r_{o,k} + r_{i,k}}\right)}{2 \cdot \pi \cdot h_k \cdot \lambda_{gr}} \quad (2.21)$$

$$R_{inner,k} = \frac{\log\left(\frac{r_{i,k} + r_{o,k}}{2 \cdot r_{i,k}}\right)}{2 \cdot \pi \cdot h_k \cdot \lambda_{gr}} \quad (2.22)$$

$$C_k = \pi \cdot h_k \cdot \rho_{gr} \cdot C_{p,gr} \cdot (r_{o,k}^2 - r_{i,k}^2) \quad (2.23)$$

Where h_k is the height of the k-th ground element and $r_{o,k}$ and $r_{i,k}$ are the outer and inner element radii respectively.

Floating lid modelling

The floating lid can be divided into multiple layers each divided into several radial elements. Each element is modeled by a convective solid-fluid thermal resistance and a thermal capacitor. The conservation equations characterizing the thermal behaviour are the same as the ground model.

$$R_{i,j}^{lid} = \frac{t_i^{lid}}{2 \cdot \lambda_{ins}} \quad (2.24)$$

$$C_{i,j}^{lid} = \pi \cdot t_i^{lid} \cdot \rho_{ins} \cdot C_{p,ins} \cdot (r_{j+1}^2 - r_j^2) \quad (2.25)$$

Where t_i^{lid} is the width of the i-th lid layer and r_j is the j-th radial element radius.

2.4 Data description

To draw relevant conclusions from the optimization and simulation results, it is essential to use state-of-the-art and trustworthy information. This section summarizes the main parameters values.

2.4.1 Optimization parameters

For the energy building simulations, EnergyPlus weather files are provided in the nPro app, which describes a typical weather year for a given location. Similarly, all technical operating and economic data for selected technologies consists of default values validated and sourced from nPro's documentation [28].

For air-sourced heat pumps (ASHP) systems, the performance factors are sourced from existing product data, such as Dimplex and Carrier. For booster HP systems, particular attention must be paid to small temperature lift applications. From an analysis developed in paper [29], the correlation between the lift temperature and the COP is depicted in Figure 2.10

Regarding PV and STC systems, south-facing panels with a tilt angle of 30° are considered optimal for year-round efficiency in the central Europe geographical region.

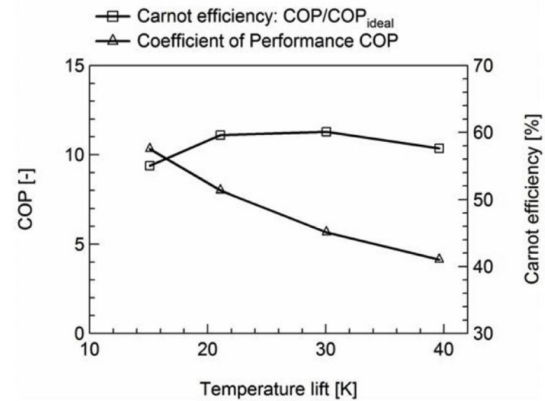


Figure 2.10 Booster HP (water-sourced) characteristics dependence on temperature lift [29]

The cost (CAPEX and OPEX) as well as the lifetime of technologies given by nPro are listed here [30] and the most relevant ones for this research in Table 2.1. For the PTES costs, a deeper investigation was performed. After cross-referencing sources [31, 11, 15, 32], the lifetime is considered close to 30 years and the cost range varies from 20€/m³ to 50€/m³ for large-scale systems. The commonly used linear value is 30€/m³ for large PTES. From the same sources, the cost of the buffer tank is fixed at 200€/m³, as it is assumed to be larger than 500m³.

The heat loss accounted for the buffer storage and the PTES is highly dependent on sizing and operation factors. As previously stated in this chapter, this value must be expressed as a relative loss per number of days. The number of days is primarily affected by the operation time scales. Based on nPro documentation, for the buffer, the

heat losses can be estimated at 10% per 10 days, given its operation over the short term. For the PTES, to allow for seasonal operation, the reference value is fixed at 35% per 365 days. The orientation value provided by nPro, which can be cross-checked with the analysis of the existing Marstal installation in Denmark, indicates a loss of 35%. This aligns with the 34% losses observed at Marstal for a cycle number of 1.1 in 2016 [19]. From the same source, the Dronninglund installation in Denmark demonstrated an annual loss factor of 10%. Consequently, the validation of this design parameter will be studied in the second step of the method.

Another two significant parameters affecting the results are the electricity grid supply and feed-in tariffs. In Belgium, considering distribution, transmission, and other taxes, a reasonable estimate for the past decade has been around 35c€/kWh for consumption [33], and 4c€/kWh for electricity sold to the grid.

	Specific investment costs	Lifetime	Annual maintenance costs
PV	1100 €/kWp	20 years	1% of investment
STC	400 €/m ²	20 years	1.5% of investment
Booster HP	900 €/kWth	20 years	2.5% of investment
ASHP	1200 €/kWth	20 years	2.5% of investment
Low temperature PTES	30 €/m ³	30 years	1% of investment
Buffer tank	200 €/m ³	30 years	1% of investment

Table 2.1 Technology costs parameters

2.4.2 MoSDH PTES model parameters

PTES geometry

As seen in the first chapter, the inclination angle of the pit must be maximized but is limited by construction constraints. It is fixed at 26.56° here. The embankment height and width are arbitrarily set to 1m and 1.5m respectively. The depth is wisely defined to minimize the air-to-volume ratio. Note that the mid-port is not utilized in this study.

Fluid characteristics

Inside the PTES the fluid medium is water and its properties are taken at 30 °C and 1 bar. To model buoyancy, the water thermal expansion coefficient β_w is $350 \cdot 10^{-6}$ [K/m].

Local geology characteristics

The ground is considered as a homogeneous layer with uniform properties. To facilitate comparison with existing pits, data from Dronninglund has been selected for this study. Soil investigations there revealed that the surrounding soil type is primarily fine sand with a few clay layers which gives an soil density of 1500 kg/m³. The soil properties are given in 2.2. In addition, the initial average soil temperature is uniformly fixed at 12°C.

	units	value
Density ρ_{gr}	kg/m ³	1500
Thermal capacity $C_{p,gr}$	J/(kg.K)	720
Thermal conductivity λ_{gr}	W/(m.K)	1.5

Table 2.2 Dronninglund soil properties [14]

Insulation characteristics

In Dronninglund, the lid insulation consisted of three 80 mm thick layers of closed-cell structure polyethylene (PE) foam with an operating temperature of up to 95 °C.

Except for the top surface, the storage is only covered with 2.5 mm HDPE (high density polyethylene) water-tight liner and 1 mm layer of geotextile. The insulation details are given in 2.3.

Finally, according to [14], the heat transfer ground/lid-to-air coefficient of 25 W/(m²K) was chosen.

	units	value
Wall and bottom thickness	mm	3.5
Wall and bottom thermal conductivity	W/(m.K)	0.445
Top lid density	kg/m ³	200
Top lid thickness	mm	240
Top lid thermal conductivity	W/(m.K)	0.047
Top lid thermal capacity	J/(kg.K)	2300

Table 2.3 Dronninglund insulation properties [34]

Case Study: Athena-Lauzelle Context and Results Analysis

In order to apply the method described in the previous chapter, a Belgian real case is investigated: The Athena-Lauzelle project. The site for the new constructions is illustrated in Figure 3.1.

The project aims at creating an exemplary neighbourhood of 30 hectares across various domains [35], but the relevance of this project for the current study lies in its ambition to generate and distribute low-carbon, environmentally friendly energy for around 2500 well-insulated housing units.

The development of the new district is in line with the European "Green Deal" policy and with the Negawatt approach that consists firstly of reducing needs through sobriety in the individual and collective use of energy. Efficiency then makes it possible to reduce the amount of energy needed to satisfy these needs.



Figure 3.1 Athena-Lauzelle district site [36]

The ambition of the district is to make maximum use of renewable energy sources and to come as close as possible to carbon neutrality without, however, aiming to be an off-grid island. Other sources of renewable energy outside the district exist at different scales.

The project managers commissioned Resolia company to produce an estimate of the demand and suggest different energy

systems scenarios on an observation period of 50 years and an imputed interest rate of 2% used to annualized investment costs.

Because this study case is based on real project data, it guarantees a practical and relevant low-temperature DH application for investigating PTES integration.

3.1 System profiles & features

3.1.1 Energy demand estimation

Before diving into the thesis method application, it is necessary to properly define the demand profiles. These come from Resolia's work.

Only heat and electricity loads for operating the DH are considered. Cold, plug loads and e-mobility are not considered in this research. These are derived by summing up the estimated demand for each building type considered. The different types and their corresponding annual demand and their peak load are presented in table 3.1. The outdoor ambient temperature limit for space heating is set to 19°C for most of them. It means that buildings will be heated even in the summer season.

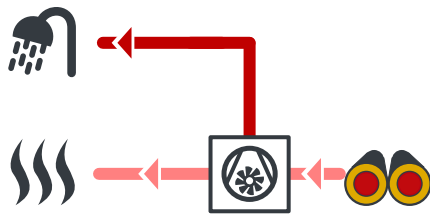


Figure 3.2 nPro heating system in buildings [28]

The operating power comes from the operation of decentralized booster HPs installed in each building. The booster HPs use the heat network as a heat source and cover the heat demands that cannot be covered directly by the heat network due to insufficient network temperatures (see Figure 3.2). This is the case for the sanitary hot water (SHW) of all buildings and the space heating for existing buildings with a less-performing heating system since the DH is operated at a supply temperature of 40 °C and a return temperature of 30 °C. This decentralised heat generation reduces the amount of heat that needs to be imported from the heat network by the buildings.

Name	Usage type	Number	Floor area	Heat	Operating power
Single-family homes	Residential	166	26,560 m ²	721 MWh	11.8 MWh
Bunk houses	Residential	279	39,060 m ²	1,420 MWh	39.6 MWh
Multi-family	Residential	309	37,080 m ²	1,449 MWh	43.9 MWh
Communal	Residential	533	42,640 m ²	2,073 MWh	76 MWh
Existing offices	Office	3	10,996 m ²	1,316 MWh	281 MWh
New offices	Office	13	8,760 m ²	776 MWh	37.9 MWh
School	School	1	7,848 m ²	171 MWh	4 MWh
Existing farm	Office	1	2,334 m ²	368 MWh	65 MWh
Sum		1305	175,278 m²	8,294 MWh	560 MWh
Max. power					2,729 kW

Table 3.1 Building demand summary

The heat load covers the space heating and DHW consumption. The thermal energy delivered by the decentralized HPs and the waste heat recovered in the ventilation system are deducted from the summed-up annual heat and peak power. Consequently, the electricity necessary to run the building's energy systems must be counted.

Finally, to determine exactly how much production is needed to meet the building demand profiles, assumptions on the heat network behaviour are fixed:

- * The relative heat losses of the heat networks is fixed at 5 % of the heat provided by the energy hub
- * The pump work is estimated at 2% of the heating generation provided by the energy hub and is considered in the electricity load profile.
- * The diversity factor is set to 0.7 and describes how the peak load at the energy hub is reduced.

In order to take into account the full diversity of consumption patterns, the number of design days has been set at its maximum, i.e. 365.

The detailed calculations for heat and electricity profile generation considering all assumptions described before are developed in Table 3.2 and 3.3. Note that the heat consumption quantity used to calculate the various KPIs is the end-user net heat consumption.

	Annual energy	Peak power
Space heating	4,697 MWh	1,947 kW
Domestic hot water	3,598 MWh	859 kW
Total	8,294 MWh	2,729 kW
Heat recovery (ventilation)	– 2,584 MWh	
End-user net heat consumption	5,710 MWh	
Electricity input for network heat pumps	– 560 MWh	
Heat import from heat network	5,150 MWh	1,493 kW
Heat losses	+ 258 MWh	29.4 kW
Heat feed-in at energy hub	5,408 MWh	1,070 kW

Table 3.2 Thermal load profiles calculations

	Annual energy	Peak power
Operating power of all buildings	560 MWh	
Pump work	108 MWh	21.4 kW
Electricity demand district	668 MWh	240 kW

Table 3.3 DH operating electricity load profile calculations

Figure 3.3 provides the profiles of thermal and operating electricity demands. The heat load curve showcases the exceptional thermal efficiency of the newly planned buildings within the district. There's less than a factor of 2 between the lowest demand for one month (July - 323 MWh) and the highest (January - 594 MWh). This number is considered low for a seasonal change and emphasises the large part of SHW consumption in the load profile.

3 | Case Study: Athena-Lauzelle

Context and Results Analysis

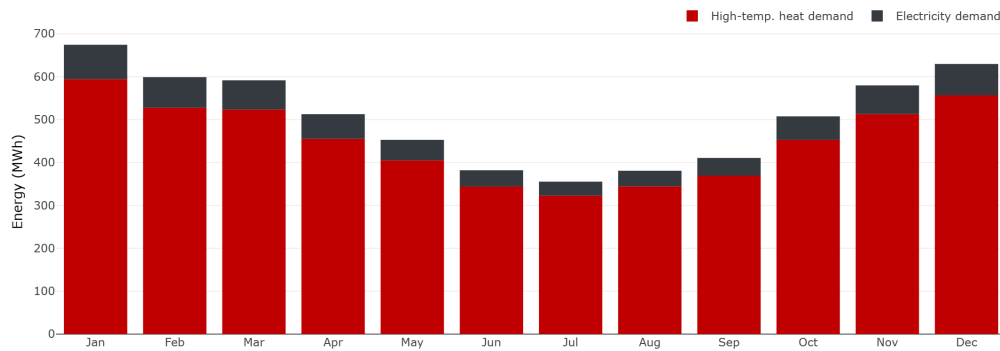


Figure 3.3 Athena-Lauzelle heat and electricity feed-in at energy hub

The heat demand profiles and their composition (space heating and SHW) are hugely varying depending on the type of building. Figures 3.4a and 3.4b show the two extremes in heat profile composition.

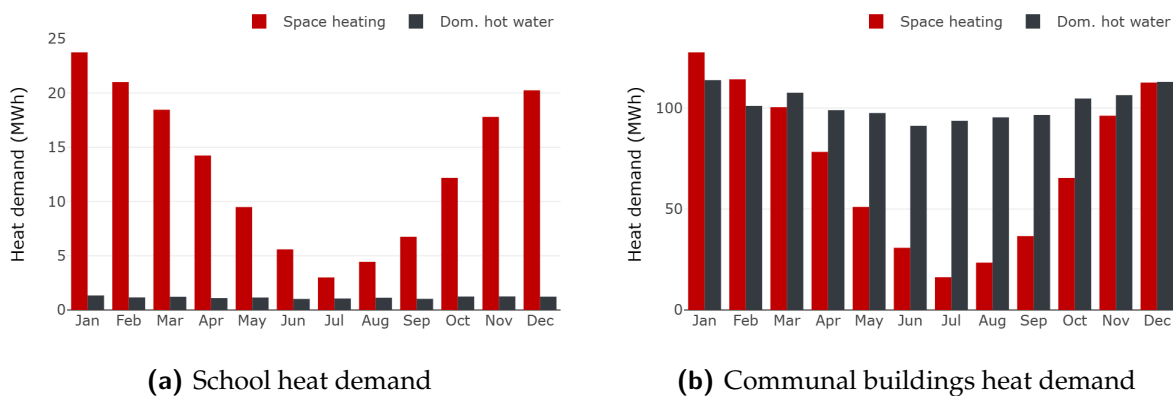


Figure 3.4 Examples of Athena-Lauzelle heat demand composition

3.1.2 Heating system sourcing

Because of the low-carbon ambition of the Athena-Lauzelle district, only renewable energy production units are chosen to be sized by optimization. Biomass energy is not considered as it is part of other scenarios investigated by Resolia and geothermal sources seem incompatible with PTES. The considered units for the energy system are listed below and are depicted as well as their interconnections, in Figure 3.5.

- **Solar thermal energy**, as indicated in the inventory table 1.2, demonstrates a strong synergy when combined with PTES systems.
- **Photovoltaic panels** as is could be more efficient to run the HPs with self-produced solar electricity compared to relying on the grid. In addition, the thermal generation system cannot be thought of independently from the electricity supply since the heating system has some power needs for the decentralized HPs and the circulation pumps.

- **ASHP** as it can reach high performance with warm ambient temperatures and can act as a peak load heat generator.
- **Booster HP** as it can upgrade the storage temperature when it falls below the supply heat network temperature and is widely used in existing systems.
- **PTES**, as it is at the heart of what this work aims to study. In nPro it takes the form of a heat storage that is allowed to operate on the long-term scale.
- **Buffer heat storage** as it helps the networks to face short-term fluctuations and make sure the PTES should not also act as a daily buffer.
- **Electricity grid** serves as the electricity supplier for the remaining load and allows injection for any excess PV generation.

nPro operation limits

To understand the system configuration and potential fluxes, it is necessary to know some limitations inherent to the used tool.

For the heating system, nPro can afford two temperature levels. In order to be able to use the booster HP, the entire heat demand profile is considered as high-temperature heat demand.

The nPro energy fluxes model doesn't include a by-pass connection from the PTES directly to the heat demand. All discharged energy must flow through the booster HP. Therefore, is the PTES forced to be studied with filling temperature equal or below the DH supply temperature (40°C).

Since nPro is a linear optimization tool, the heat storages are modeled as pure accumulators (i.e. charge and discharge temperature are equal). As a result of this simplification, the booster heat pump operates at a constant COP and is estimated at 8 with the help of Figure 2.10 and an estimated mean temperature lift of 20°C.

Note that the ASHP and the STC produce heat at 40°C regardless of towards where the heat flows.

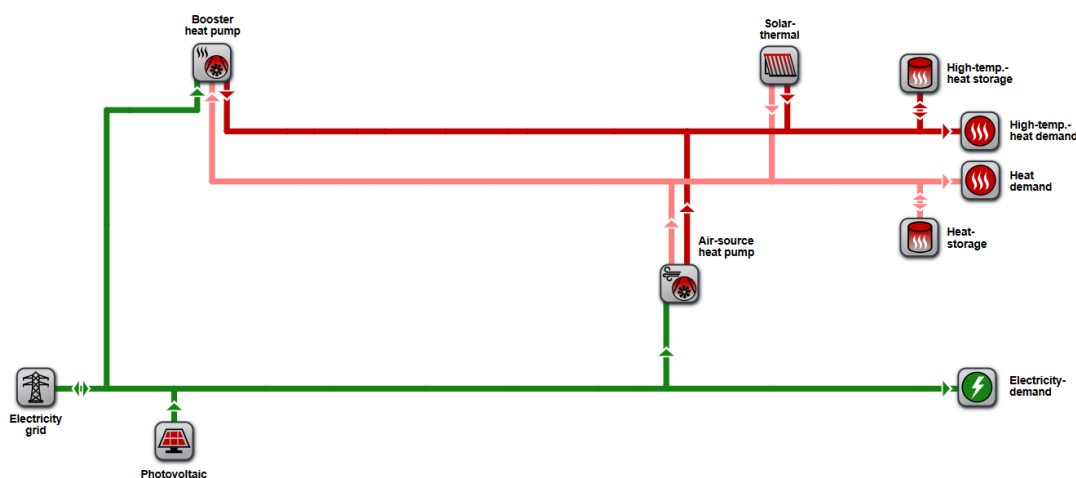


Figure 3.5 Athena-Lauzelle energy hub subject to optimisation (nPro).

The potential area available for STC or PV panels is in competition. Initially, the project estimated the roof area suitable for installing panels to be around 20,000 m². In this study, only half of this area is considered reserved for the heating system. This proportion is high but, considering the potential to install panels on top of the PTES, 10,000 m² is the chosen reference available surface for the DH system. This value corresponds to 3.3% of the area allocated to the district.

To fully understand the sizing dynamics of the PTES, no volume limits are given.

3.2 Step 1: heating system design

This section investigates PTES integration into the Athena-Lauzelle district at a system level. Sensitivity to the grid, the available area, the sourcing configuration, the demand pattern and the PTES modelling parameters are addressed. The results are evaluated using the earlier presented KPIs, focusing on understanding the technologies' design. Each scenario (with prefix *ref*) presented in the table 3.4 will always be compared to its corresponding scenario without PTES installation. This comparison is crucial to address the main question regarding Athena-Lauzelle: whether it is relevant to integrate PTES. Ref_F1, rendered with the reference parameters given in section 2.4.2, constitutes the reference scenario on which the following sensitivity analysis is based.

Scenarios	PTES ΔT range [K]	PTES relative losses [%/year]	Grid supply cost [€/kWh]	Grid feed-in tariff [€/kWh]	Solar area available [m ²]	Comments
Ref_F1	20	35	0.35	0.04	10000	
Ref_F2	20	35	0.35	0	10000	
Ref_F3	20	35	0.39	0.04	10000	annual price increase 0.5%
Ref_F4	20	35	0.44	0.04	10000	annual price increase 1%
Ref_F5	20	35	0.49	0.04	10000	annual price increase 1.5%
Ref_G1	20	35	0.35	0.04	10000	No PV allowed
Ref_J1	10	35	0.35	0.04	10000	booster COP = 10
Ref_J2	30	35	0.35	0.04	10000	booster COP = 6
Ref_L1	20	35	0.35	0.04	5000	
Ref_L2	20	35	0.35	0.04	2500	
Ref_L3	20	35	0.35	0.04	1250	
Ref_M1	20	35	0.35	0.04	10000	existing district

Table 3.4 nPro scenarios overview of parameters subject to changes

3.2.1 Sensitivity to grid prices fluctuations

In a project of such scale, the grid price external factor can be important in system sizing. The price of electricity is subject to fluctuations due to the availability and cost of primary energies, which are unpredictable in the current economic climate. To account for this uncertainty and represent global inflation, three different annual

increase percentages (ranging from 0.5% to 1.5%) over the design period of 50 years are studied. Additionally, one scenario (Ref_F2) sets the non-self-consumed electricity injection price to 0, representing a boundary case where the grid is oversaturated and the grid operator has no interest in purchasing private-sector production. This first study analyses the robustness of the system against various future economic conditions and grid constraints.

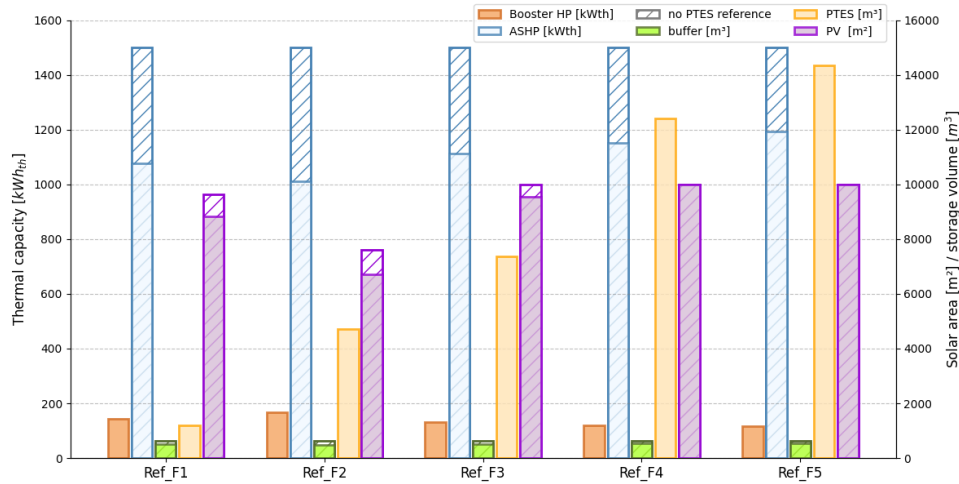


Figure 3.6 System design comparison for different grid supply and feed-in tariffs. In each scenario, the sizing is compared to those without PTES integration. Note that no STC are installed.

The capacities installed are depicted in Figure 3.6. In the scenarios without PTES (represented by hatched bars), it's understood that no booster heat pumps are installed either. In the absence of large-scale storage, the nominal capacity of the installed ASHP must be adjusted to meet the peak load. The PV-installed area is revised upwards as it synergizes with the ASHP. Additionally, the capacity of the buffer is slightly increased and operates at a higher cyclic frequency.

While PTES volume increases as the external economic conditions become worse, the associated booster capacity reduces. This behaviour can be understood by looking at the dynamics focusing on PTES which are presented in Figure 3.7.

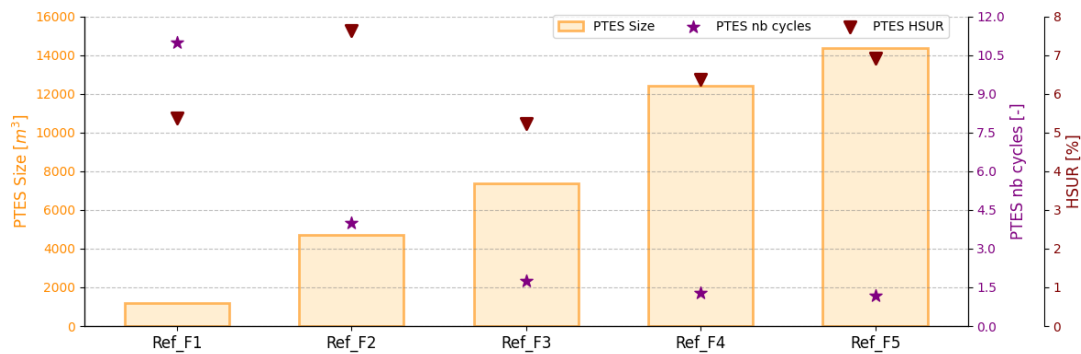


Figure 3.7 PTES characteristics comparison for different grid supply and feed-in tariffs.

3 | Case Study: Athena-Lauzelle

Context and Results Analysis

The PTES operation time scale strategy, represented by the number of complete annual cycles, tends to shift towards seasonal storage as the grid supply price increases. In scenarios such as Ref_F4 and Ref_F5, where the cycles approach one complete cycle, the storage usage becomes almost purely seasonal. This trend corresponds to the notion that storing a larger proportion of self-produced electricity becomes economically more advantageous. Consequently, the operation of the PTES becomes more closely aligned with the annual cycle of solar energy production.

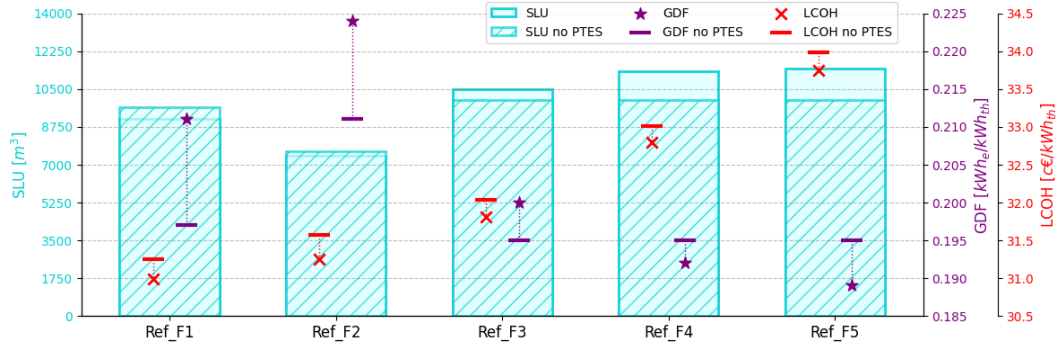


Figure 3.8 System KPIs comparison for different grid supply and feed-in tariffs. In each scenario, KPIs are compared to those without PTES integration.

Analyzing the KPIs depicted in Figure 3.8, the most substantial variance in LCOH between scenarios with and without PTES integration is observed in the non-feed-in scenario. In other scenarios, a consistent difference of 0.2€/kWh in LCOH is noted. This indicates that while PTES integration generally shows cost efficiency across all scenarios, its impact is most pronounced in situations where the ability to sell excess electricity is restricted.

The system dependency on the grid decreases with the increase of grid supply prices. This observation, supported by Figure 3.9, highlights that PTES in this heating system is not designed to reduce grid consumption. On the contrary, it serves to optimise the performance of the ASHP by choosing operating hours that maximise its COP. Consequently, more thermal capacity is installed to accommodate fewer operating hours. To support the expanded ASHP capacity, additional PV panels are installed.

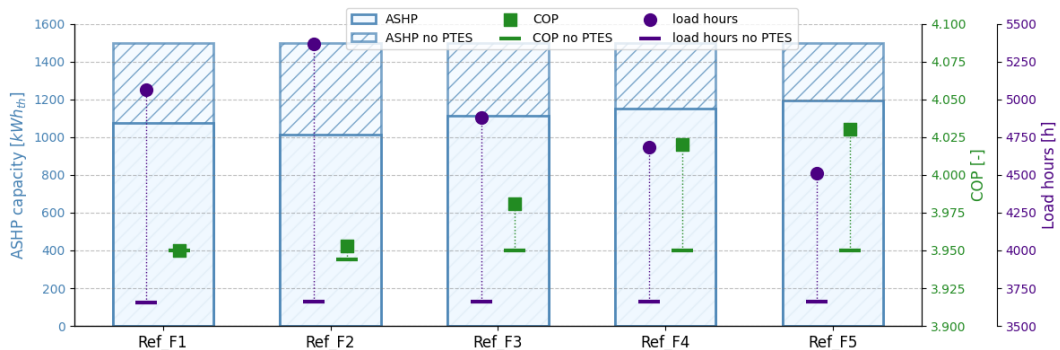


Figure 3.9 ASHP characteristics comparison for different grid supply and feed-in tariffs. In each scenario, KPIs are compared to those without PTES integration.

3.2.2 Sensitivity to PTES temperature range

As previously mentioned in section 3.1.2, the PTES is restricted to storing heat below the network supply temperature, which is 40°C. The reference temperature threshold, above which the stored water is considered to contain usable energy, can vary based on the return temperature of the booster HP at the evaporator outlet. Three different PTES ΔT ranges, representing the difference between fully charged and discharged states, are investigated. The impact of increasing ΔT on the average performance of the booster HP is considered, as depicted in Figure 2.10.

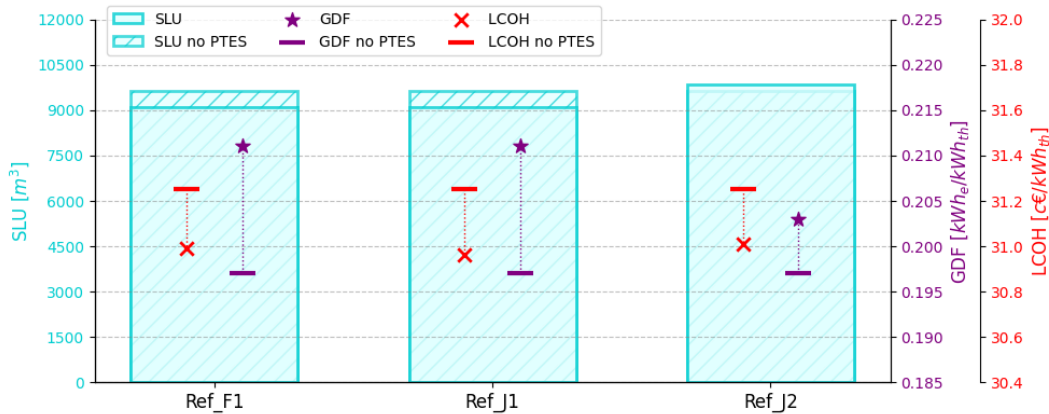


Figure 3.10 System KPIs comparison for different PTES ΔT ranges. In each scenario, KPIs are compared to those without PTES integration.

Figure 3.10 illustrates that changes in cost as a function of the energy density of the PTES are relatively minor. However, Ref_J2 shows a lower dependency on grid prices. Specifically, as depicted in Figure 3.11, scenario Ref_J2 indicates an increase in PTES volume, which is accompanied by an increase in solar power capacity and a higher self-consumption rate.

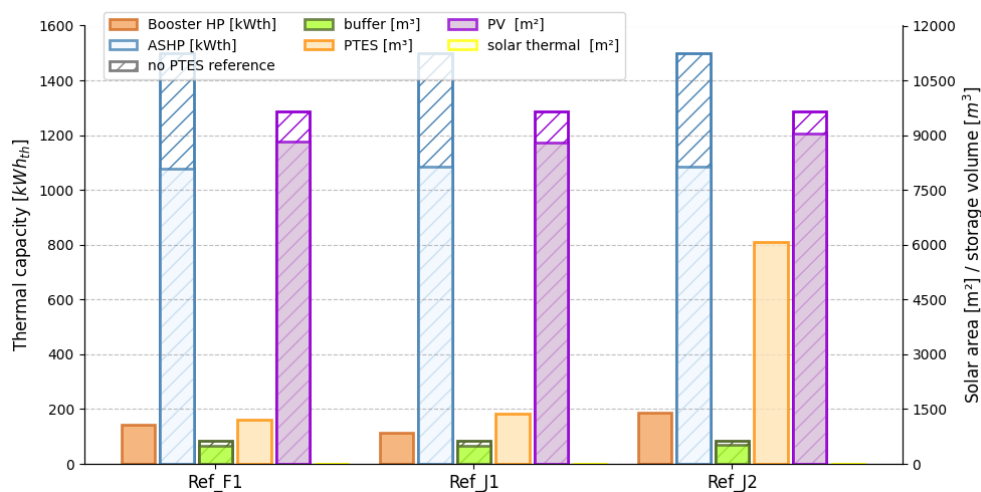


Figure 3.11 System design comparison for different PTES ΔT ranges. In each scenario, the sizing is compared to those without PTES integration. Note that no STC are installed.

3 | Case Study: Athena-Lauzelle

Context and Results Analysis

In Figure 3.12, a consistent HSUR is observed, indicating that the amount of heat that must transit through the PTES to optimize cost remains stable. The operation time scale adjusts itself according to the installed PTES volume and energy density.

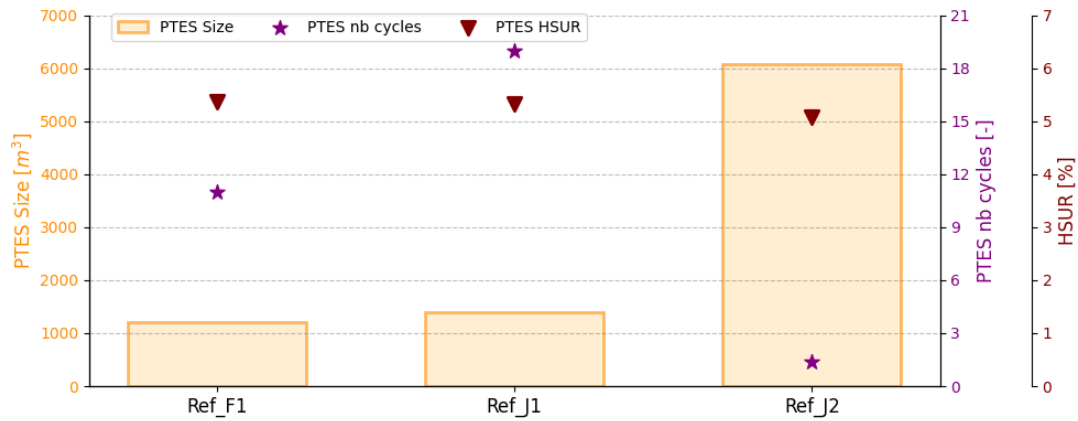


Figure 3.12 PTES characteristics comparison for three different PTES ΔT ranges between a fully charged and discharge storage.

3.2.3 Sensitivity to solar area allocation

Athena-Lauzelle is a large and dense urban district, and determining which spaces should be allocated exclusively to the heating system poses a challenge that requires thorough investigation. Additionally, the design of the building's roof is not yet finalized, despite its significant impact on the feasibility of installing roof-mounted solar panels, whether they are STC or PV panels. Therefore, since Resolia's prediction is somewhat smaller than the initial space, this section examines the system's response to a decrease in the space allocated to solar production.

Figures 3.13 and 3.14 exhibit a clear trend. As the area allocated to solar energy diminishes, the system responds by augmenting the capacity of the PTES and the associated booster HP. Concurrently, the capacity of the ASHP decreases, yet it operates more frequently at a lower COP. This adjustment occurs because the synergy with the solar panels, driven by the economic advantages of self-consumption, diminishes, no longer elevating the maximum supply power of the ASHP.

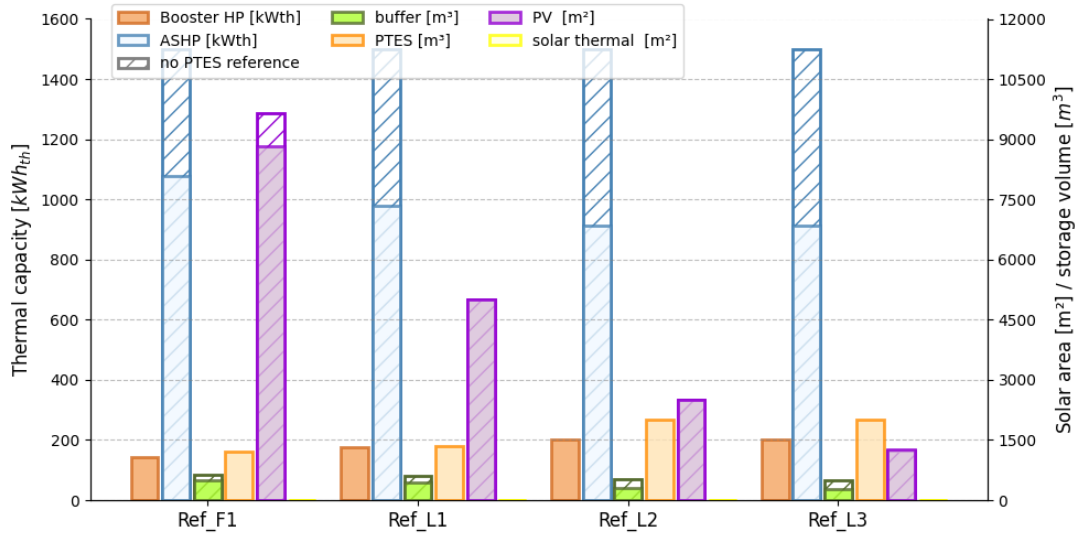


Figure 3.13 System design comparison for different area allocations for solar energy. In each scenario, the sizing is compared to those without PTES integration. Note that no STC are installed.

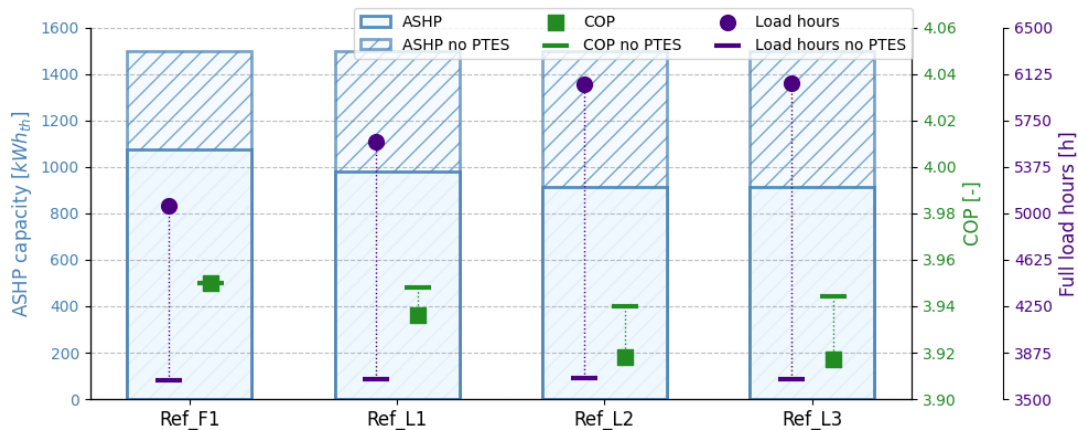


Figure 3.14 ASHP characteristics comparison for different area allocations for solar energy. In each scenario, KPIs are compared to those without PTES integration.

It is noteworthy that there are minimal variations in the design and operation of the heat system when the installed PV panels are below 5000m². The primary difference lies in the amount of energy imported from the grid, resulting in increased costs for energy consumption. This behavior is evident in Figures 3.15 and 3.16.

The economic benefits of installing a PTES system increase as the proportion of intermittent solar decreases. This is confirmed by the low level of HSUR, which indicates that the system design relies predominantly on the ASHP. In the absence of STC, the ASHP acts as the sole heat source and the influence of the PTES on the system is minimal.

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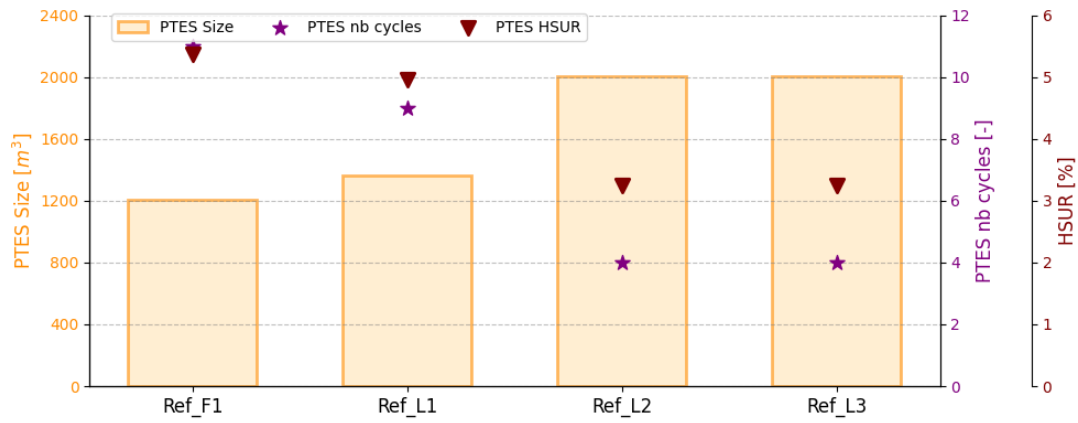


Figure 3.15 PTES characteristics comparison for different area allocations for solar energy.

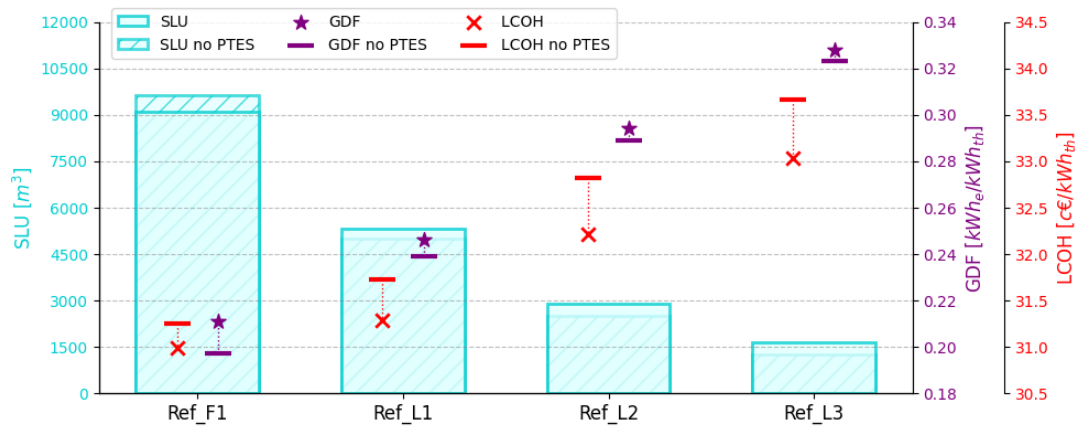


Figure 3.16 System KPIs comparison for different area allocations for solar energy. In each scenario, KPIs are compared to those without PTES integration.

3.2.4 PV vs. solar thermal

No STCs have been installed in any of the scenarios so far, despite their demonstrated synergy with PTES in the literature. The reason for this absence is investigated here by configuring the system so that no PV panels are installed.

Figure 3.17 shows that the approximately 9000m² PV installation is replaced by a smaller, approximately 3000m² PV installation combined with a larger PTES. This modification allows for a reduction in the capacity of the ASHP.

According to Figure 3.18, the system is considerably more expensive with STCs compared to PV panels. The inability of STCs to export the generated heat necessitates storing all the generated heat, making it less cost-efficient. Even with cost savings from the reduced capacity of the ASHP, PV remains more cost-efficient than solar thermal. This is due to the synergy between PV and the high performance of the ASHP, as

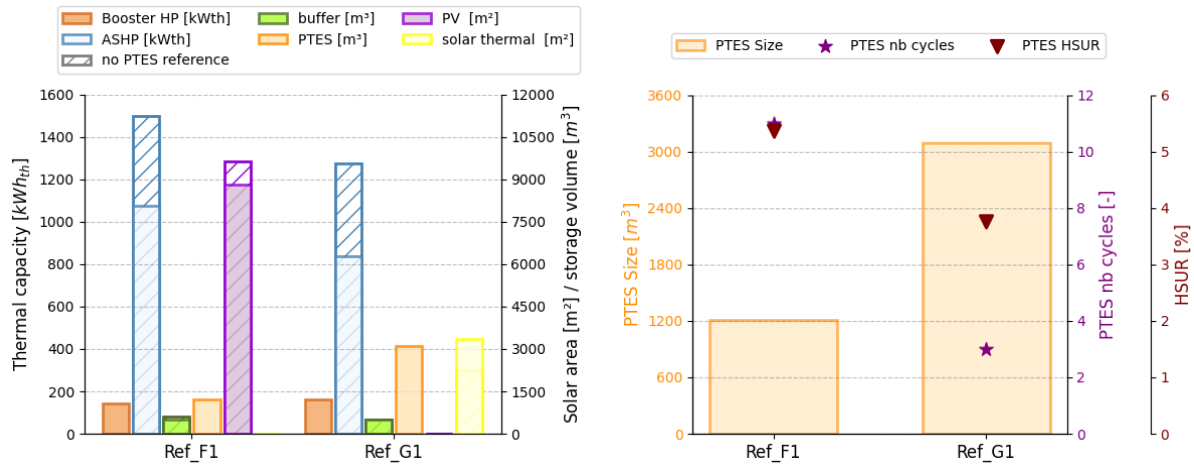


Figure 3.17 On the left: system design comparison between the reference and the no PV scenarios. In each scenario, the sizing is compared to those without PTES integration. On the right: PTES characteristics comparison between the reference and the no PV scenarios.

well as the lower installation cost of PV systems.

STC systems are more dependent on the grid due to the lower performance of their ASHP. However, unlike PV systems, this dependency decreases with the integration of PTES.

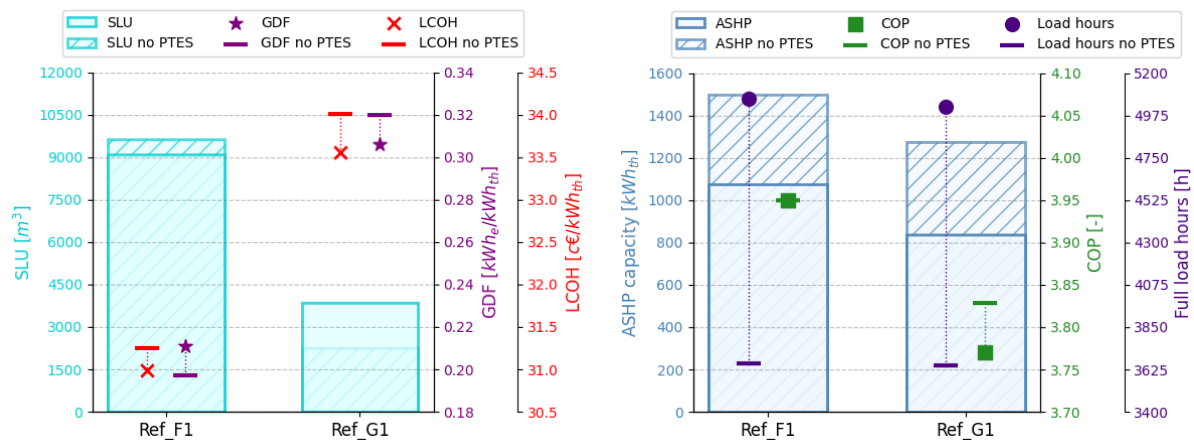


Figure 3.18 On the left: System KPIs comparison of the reference and the no PV scenarios. In each scenario, KPIs are compared to those without PTES integration. On the right: ASHP characteristics comparison between the reference and the no PV scenarios. In each scenario, KPIs are compared to those without PTES integration.

3.2.5 PTES in an existing DH network

Referring to Figure 3.3, the heat load seasonal variation for the new district is low because the buildings are well insulated. Because PTES could be installed in existing DH

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systems supplying consumers at high temperatures, it would be worth examining another load pattern.

This alternative district calculates its demand by maintaining the same building types and diurnal profiles of heat consumption as the Athéna-Lauzelle district under consideration. The only differences are in the energy demand, building supply and return temperature. This scenario uses classic consumption data of an existing DH network provided by nPro. The total annual electricity demand reaches 4512 MWh, while the heat demand is increased by 474% and reaches 27082 MWh. The monthly distribution shown in Figure 3.19 exhibits higher seasonal variation in the base load compared to the new district demand illustrated in Figure 3.3. Note that the supply temperature of the DH remains constant (40°C), but more work is required from the decentralised booster HPs.

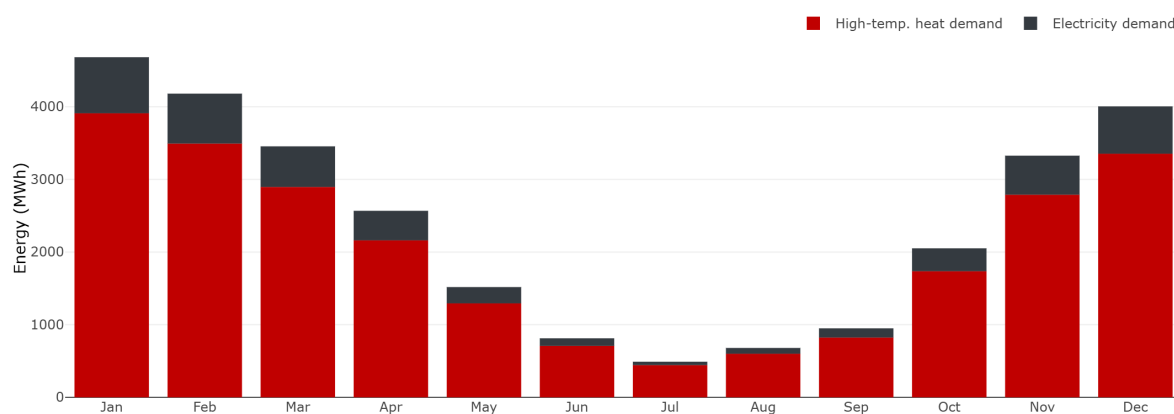


Figure 3.19 Existing Athena-Lauzelle district heat and electricity feed-in at energy hub

Figure 3.20 reveal that, in this new scenario, PTES is largely installed and saves by more than half of ASHP capacity compared to the scenario without PTES. The PTES is operated with a higher HSUR (around 13%), highlighting the importance of the PTES operation within the system dynamics. This characteristic is reinforced by the cost-effectiveness of PTES integration shown in Figure 3.21.

Even though all the energy produced by the PV is converted directly into heat, Ref_M1's ASHP operates with lower performance which increases the system dependency on the grid. This increased dependency is due to the difference in the share of self-consumption. For instance, this ratio is approximately 42% for Ref_F1, compared to only 14% for Ref_M1.

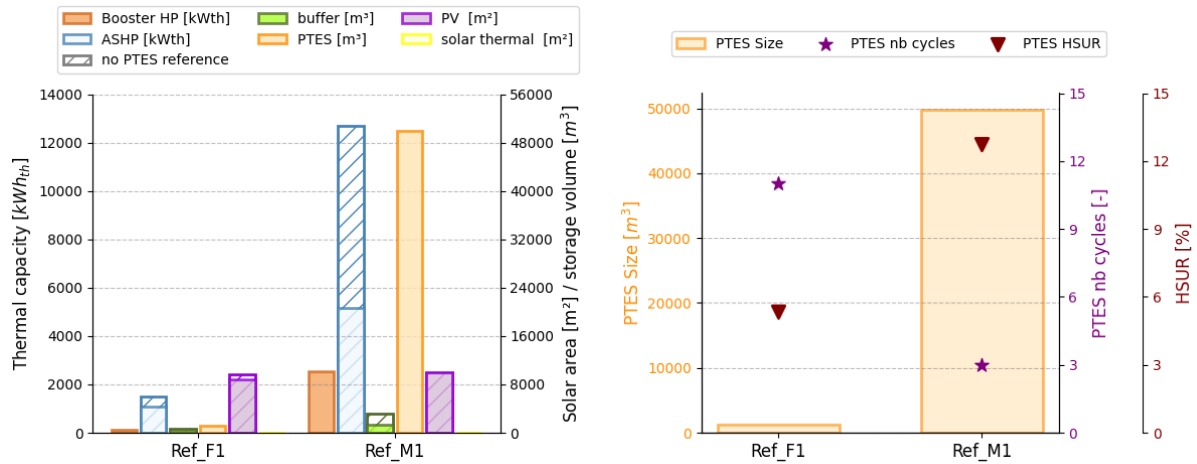


Figure 3.20 On the left: System design comparison between the new and the existing district. In each scenario, the sizing is compared to those without PTES integration. Note that no STC are installed. On the right: Comparison of PTES characteristics between the new and the existing district.

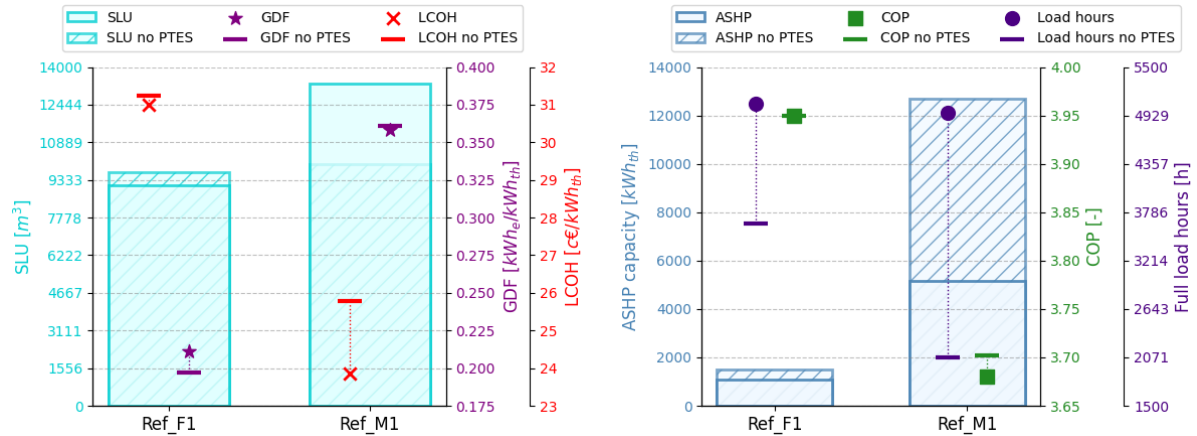


Figure 3.21 On the left: System KPIs comparison between the new and the existing district. In each scenario, KPIs are compared to those without PTES integration. On the right: ASHP characteristics comparison between the new and the existing district. In each scenario, KPIs are compared to those without PTES integration.

3.3 Step 2: PTES operation simulation

As mentioned previously, the storage loss model in nPro is linear and not representative of reality. Furthermore, numerous parameters and variables are interdependent and are not represented in the linear optimisation model. In order to complement and/or challenge the optimisation results, a detailed study of the PTES is required. It is based on the OpenModelica system model scheme from Figure 3.22.

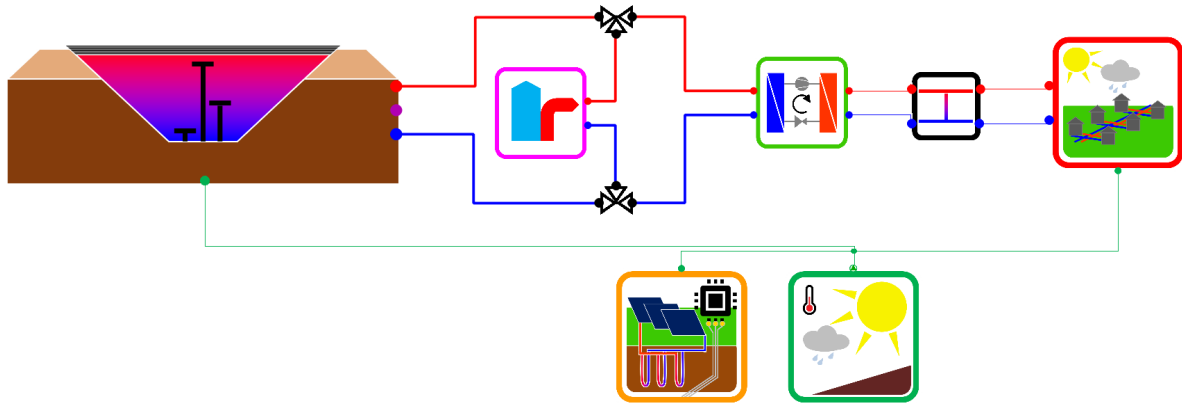


Figure 3.22 OpenModelica model scheme for step 2 simulation

3.3.1 The optimal operation strategy by nPro

In order to understand the outcomes of further analysis using detailed PTES modelling, a deeper overview of data sent to the simulation tool is needed.

The results showed the central role of the ASHP for optimal energy production and that all other equipment is complementary to optimise ASHP performance and limit its installed capacity. The two storage facilities are the assets giving flexibility to this unique source of heat. Their utilisation rate is summarized in Table 3.5

	Ref_F1	Ref_F2	Ref_F3	Ref_F4	Ref_F5	Ref_G1	Ref_J1	Ref_J2	Ref_L1	Ref_L2	Ref_L3	Ref_M1
PTES HSUR [%]	5.4	7.6	5.2	6.4	6.9	3.8	5.3	5.1	5.0	3.2	3.2	12.8
Buffer HSUR [%]	30.3	27.2	32.4	34.3	35.6	23.4	30.3	31.5	24.7	18.3	18.0	13.2
Buffer HSUR (no PTES) [%]	44.4	42.1	44.4	44.4	44.6	37.0	44.4	44.4	43.4	40.6	41.1	43.7

Table 3.5 Review of PTES and buffer HSUR levels of the different scenarios compared to those without PTES integration.

These HSUR values show the importance of short-term storage in the current system. The use of the buffer decreases slightly with the reduction of the installed solar panels, but its main action is to optimise the diurnal ASHP performance subject to cold source temperature variations. Indeed as can be seen in Table 3.5, when the flexibility provided by PTES is removed, the use of buffer storage increases and reaches an approximately constant value for all scenarios.

These HSUR values are closely linked with the storage volume and energy density but also with the number of full-load storage cycles that express the charge and discharge operation time scales. The table 3.6 summarizes them all.

	Ref_F1	Ref_F2	Ref_F3	Ref_F4	Ref_F5	Ref_G1	Ref_J1	Ref_J2	Ref_L1	Ref_L2	Ref_L3	Ref_M1
PTES nb cycles [-]	11	4	1.75	1.27	1.2	3	19	1.38	9	4	4	2.3
Buffer nb cycles [-]	298	284	311	316	319	239	303	293	271	296	308	244
Buffer nb cycles (no PTES) [-]	352	330	352	351	347	372	352	352	362	394	402	328

Table 3.6 Review of PTES and buffer number of storage cycles of the different scenarios compared to those without PTES integration.

In the scenarios studied, three levels of PTES operation timescales can be distinguished: **Ref_F5**, **Ref_M1**, **Ref_F1**. The following scenarios are representative of the variety of operational strategies and PTES volumes installed and will be the subjects of this section.

Ref_F5: Seasonal operation - Medium capacity

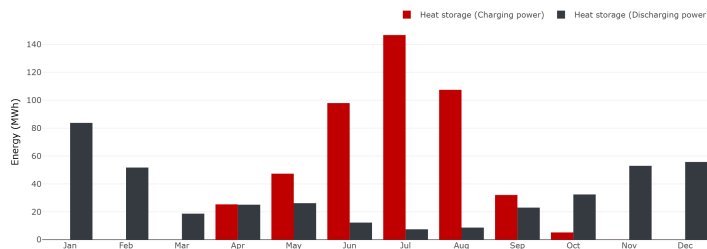


Figure 3.23 PTES monthly charged and discharged energy example for scenario **Ref_F5** storage operation.

Figure 3.23 illustrates an almost seasonal variation. Despite minor short-term usage during the inter-season, the PTES functions effectively as a solar energy shifter, storing solar energy during the summer and releasing it during the heating season.

Ref_M1: Hybrid operation - Large capacity

Figure 3.24 depicts a hybrid usage of the PTES. In summer, it is charged according to the solar curve to store cheap energy. In November and December, the performance conditions are variable, requiring assistance on some days but allowing the other days to be charged in preparation for the next two months. In fact, the base and peak loads are higher in January and February.

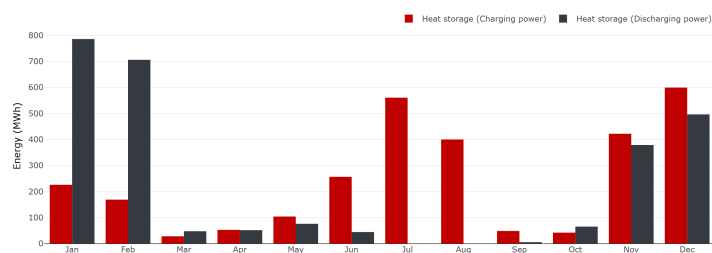


Figure 3.24 PTES monthly charged and discharged energy for scenario for **Ref_M1** storage operation.

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Ref_F1: Short-term operation - Small capacity

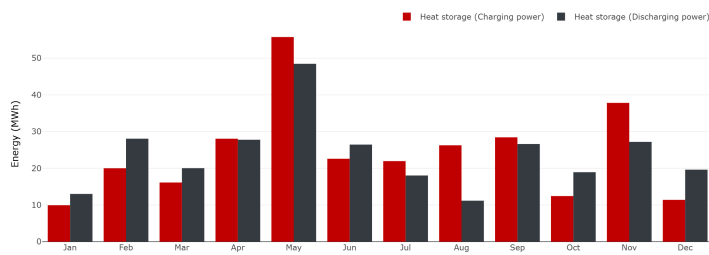


Figure 3.25 PTES monthly charged and discharged energy for scenario **Ref_F1** storage operation.

Figure 3.25 depicts the short-term usage of the PTES. This operation takes minimal advantage of the abundant solar energy available in the summer due to its small size, serving as a buffer for heat generation and load balancing at a monthly time scale.

3.3.2 Thermal energy performance

Reference data

The three scenarios presented in the previous section are simulated over a period of three years by periodically repeating the year-only optimisation data. Their theoretical annual operation quantities provided by the optimisation are summarised in the table 3.8. Notes that the fluid, soil and insulation thermo-physical parameters are constant across all three scenarios. The difference between them lies in the PTES geometry and the operating data provided by the optimisation.

The geometry is partly defined by the embankment height and width, as well as the pit slope described in section 2.4.2. This is complemented by the PTES volume and depth, with the latter being fixed to reduce the surface-to-volume ratio without tending towards the perfect cone. The PTES surface area encompasses the top surface, sidewalls, and bottom surface. Table 3.7 summarises the three.

	Ref_F5	Ref_M1	Ref_F1
Surface-to-volume ratio [1/m]	0.48	0.28	0.97

Table 3.7 Surface-to-volume ratio for scenarios Ref_F5 and Ref_M1, Ref_F1.

Based on this reference data and on the evolution of PTES behaviour with the years, the performances of the three different PTES systems and their corresponding operation are compared using the optimisation outputs performance indicators detailed in section 2.1.2.

	Ref_F5	Ref_M1	Ref_F1
Capacity [MWh]	333	1158	28
Number of cycles [-]	1.2	2.3	10.2
Charged energy [MWh]	462	2913	291
Discharged energy [MWh]	398	2661	285
Absolute losses [MWh]	64	252	6
Relative losses [%]	13.9	8.7	2.1

Table 3.8 Review of the optimisation reference PTES annual operation performance provided by nPro for scenarios Ref_F5 and Ref_M1, Ref_F1.

Simulation results

Table 3.9 presents the global efficiency and the evolution of annual simulated PTES thermal energy flow for the three scenarios. To provide an understanding of the magnitude of these variations, three additional ratios are included:

- Relative losses ratio: This is the ratio between absolute losses and the energy charged.
- Load error ratio: This corresponds to the proportion of energy that was expected but could not be supplied to the DH system by the PTES.
- State of charge error ratio: This accounts for the difference in energy content between the last day and the first day of a given year, normalized by the storage's maximum capacity.

Note that the simulated compared to the reference charged energies deviate by less than 0.8%, likely due to simulation approximations.

	Ref_F5			Ref_M1			Ref_F1		
	year 1	year 2	year 3	year 1	year 2	year 3	year 1	year 2	year 3
Efficiency [%]	60.2	60.3	62.2	81.6	85.4	86.2	81.4	83.2	83.3
Energy charged [MWh]	456	455	455	2910	2908	2908	281	280	280
Energy discharged [MWh]	334	263	278	2505	2451	2502	235	233	234
Lid losses [MWh]	92.8	85.9	87.3	228.4	228.6	229.8	19.5	19.1	19.1
Wall losses [MWh]	122.7	84.1	79.1	335.5	188.8	168.3	33.7	27.6	27.3
Bottom losses [MWh]	5.5	3.3	2.7	2.2	1.6	1.4	0.6	0.4	0.3
Absolute losses [MWh]	221	173.4	169.1	566	419.1	399.5	53.9	47	46.8
Relative losses [%]	48.5	38.1	37.2	19.5	14.4	13.7	19.2	16.8	16.7
Load error [%]	14.38	31.88	28.05	5.72	7.68	5.83	13.91	14.22	13.87
State of charge error [%]	-31.1	4.5	1.3	-14.3	3.4	1	-31.5	0.5	0.2

Table 3.9 Review of three years PTES simulated operation results for scenarios Ref_F5 and Ref_M1, Ref_F1.

Looking at the yearly state of charge error evolution, the simulated three years can be considered part of the transient phase, although the third year appears to be approaching steady-state regime.

The global efficiencies need to be considered in conjunction with their respective percentages of load error and relative losses. The periods where the load cannot be met

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are represented by red shaded vertical lines in Figures 3.26, 3.27, and 3.28. The load shortages occur when the PTES is empty. The first year is biased by the initial PTES energy content, which allows the PTES to adequately respond to the demand during the first two months of the year while it is more complicated for the two following years.

Taking the last simulated year's relative loss values to compare with the reference ones, Ref_F1 suffers for the highest difference followed by Ref_F5 and Ref_M1. This ranking can be explained by the respective surface-to-volume ratio, which is likely the most significant factor not accounted for by the linear loss coefficient.

In all three scenarios, we observe a high level of side wall losses in the first year of operation, particularly during the first two months. This indicates the charging of the ground's thermal capacity. After the first year, wall losses continue to decrease but at a slower rate, whereas lid losses remain approximately constant. Scenario Ref_M1 is the most representative of existing PTES systems in terms of size and the distribution of losses among the lid, side walls, and bottom surface, as outlined in Section 1.2.3.

When the PTES energy content is depleted or discharges rapidly, the ground may restore some energy. This behaviour is observed in all three scenarios, visible in Figures 3.26, 3.27, and 3.28, but in different proportions. In scenario Ref_M1, with a fast discharge (i.e. with a huge temperature drop), proportionally more energy can be recovered from the ground.

By analyzing the loss time series of each operation, it becomes apparent that the linear loss model generally suffers from an offset proportional to the surface-to-volume ratio. It also lacks representativeness in short-term operations, particularly during the transition phase between the heating and the summer season. When the state of charge is low, the losses calculated by the linear model are negligible. However, the heat charged at 40°C into the top layer experiences significant lid losses.

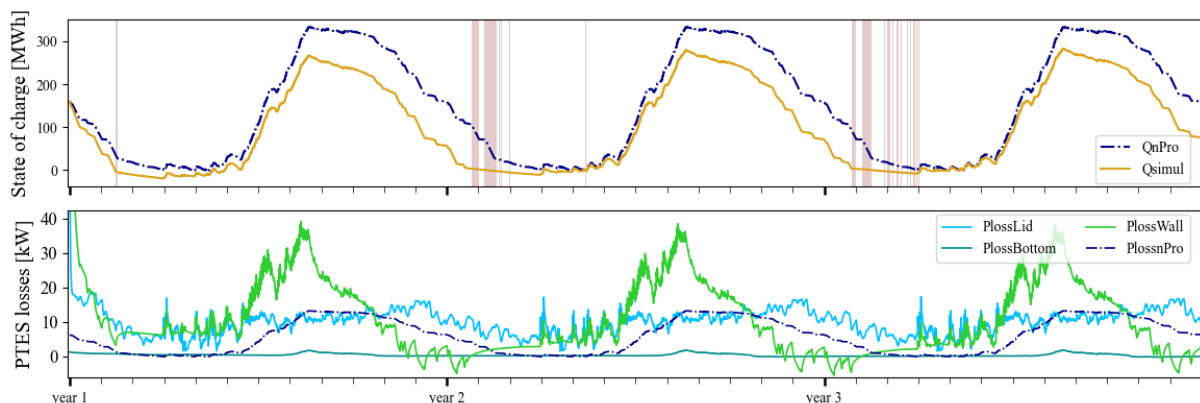


Figure 3.26 PTES state of charge and losses for scenario Ref_F5 operation. The red shaded areas indicate when the load cannot be met by the PTES system.

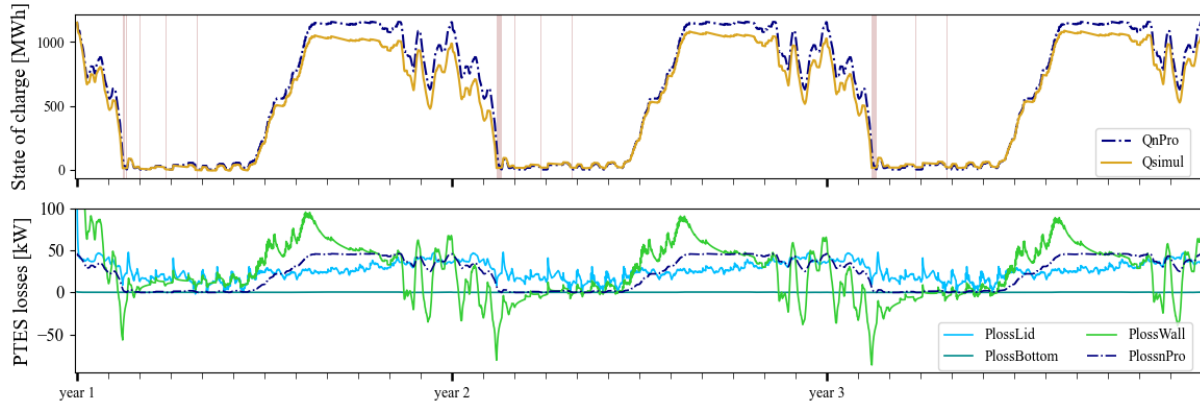


Figure 3.27 PTES state of charge and losses for scenario **Ref_M1** operation. The red shaded areas indicate when the load cannot be met by the PTES system.

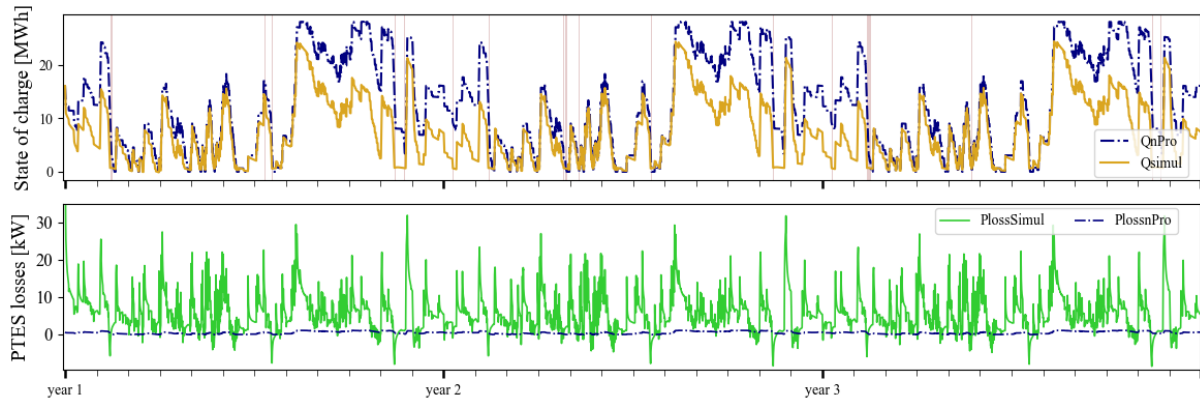


Figure 3.28 PTES state of charge and losses for scenario **Ref_F1** operation. The red shaded areas indicate when the load cannot be met by the PTES system.

Comparison with existing systems

Having examined the transient behavior, loss composition, and the accuracy of nPro linear parameters, it is now valuable to contrast these findings with real measured data from operational PTES systems. Table 3.10 presents this comparison.

	Ref_F5[3]	Ref_M1[3]	Ref_F1[3]	DronningLund 2016	Marstal 2016
Efficiency [%]	62.2	86.2	83.3	91	66
Relative losses [%]	37.2	13.7	16.7	8.8	34.1
Number of cycles [-]	0.84	2.17	8.4	1.9	1.0
Storage ΔT [K]	20	20	20	75	62
Surface-to-volume ratio [1/m]	0.48	0.28	0.97	0.29	0.23

Table 3.10 Comparison of simulated results for the third year of the Athena-Lauzelle PTES system across scenarios Ref_F5 and Ref_M1, Ref_F1, alongside measured data from Dronninglund and Marstal in 2016.[19]

Ref_F5 and the Marstal PTES system operate at the same cyclic frequency, indicating seasonal operation, and can therefore be compared with caution. Marstal demonstrates slightly higher efficiency due to a lower loss ratio. Despite having different sizes and operating temperatures, the performance of each system seems to balance out, resulting in comparable overall performance.

Ref_M1 and Dronninglund can also be compared, since their storage cycles are similar and they share the same surface-to-volume ratio. Dronninglund exhibits significantly higher performance compared to Ref_M1 although the opposite would be expected given the storage temperature difference between the two.

3.3.3 Stratification performance

To further understand the operation strategy's impact on the system performance, the stratification inside the PTES is studied. Table 3.11 summarizes the the two indicators average value for the simulated scenarios. The storage temperatures, stratification indicators, diffuser energy supply, for the simulated PTES system are shown in Figures 3.29, 3.30 and 3.31. The storage temperature and diffuser energy supply are included in the plot to demonstrate the storage operation and assist in understanding the stratification indicators.

Note that the MIX number isn't representative when the storage temperature falls below the reference temperature. Therefore, the MIX number has been bounded between 0 and 1. Extra caution must be paid to the MIX values analysis.

	Ref_F5			Ref_M1			Ref_F1		
	year 1	year 2	year 3	year 1	year 2	year 3	year 1	year 2	year 3
Average MIX number [-]	0.47	0.53	0.5	0.33	0.42	0.43	0.36	0.39	0.4
Average stratification coeff [K²]	18.76	12.87	12.82	15.05	13.95	14	21.69	19.42	19.41

Table 3.11 Review of three years PTES simulated stratification results for scenarios Ref_F5 and Ref_M1, Ref_F1.

Similarly to the load error ratio discussed in the previous section, the first year stratification indicators are biased by the ideal initial boundary condition, which assumes a perfectly stratified temperature gradient.

When comparing the MIX number to the stratification coefficient, a clear negative correlation emerges: as one metric increases, the other decreases. For example, towards the end of each charging and discharging cycle, the stratification coefficient tends to approach its lower limit, nearing zero, indicating a more uniform temperature distribution within the PTES. However, the stratification coefficient exhibits more variability, providing finer insights into the mixing dynamics within the storage. Its maximum value occurs when the temperature contrast between the top and bottom of the storage is most pronounced.

The maximum stratification coefficient typically occurs around the middle of each charging/discharging period. Small spikes in the coefficient during charge and discharge phases indicate mixing, as a more uniform temperature reduces the coefficient

value. For scenarios Ref_F5 and Ref_M1, the stratification coefficient suggests better stratification during charging periods than during discharging periods. However, these values are influenced by higher temperatures at the top of the PTES system rather than by improved stratification.

Heat losses can disrupt the stratification within the storage system by cooling the top water layer just below the lid, causing thermal inversion and inducing mixing. This behaviour is evident in scenario Ref_F5. Apart from mixing due to heat losses, heat conduction and diffusion within the storage system also contribute to mixing. These phenomena occur when the temperature profile within the storage system is non-uniform.

Overall, all stratification indicators suggest that Ref_F1 has a higher degree of stratification compared to Ref_M1, which in turn has a higher degree of stratification than Ref_F5. This ranking is contrary to what would be expected based on the operation time scales. This discrepancy can be explained by the fact that both the MIX number and the stratification coefficient are influenced by heat losses, which tend to favor systems with lower heat loss. As a result, no definitive conclusions can be drawn from this analysis.

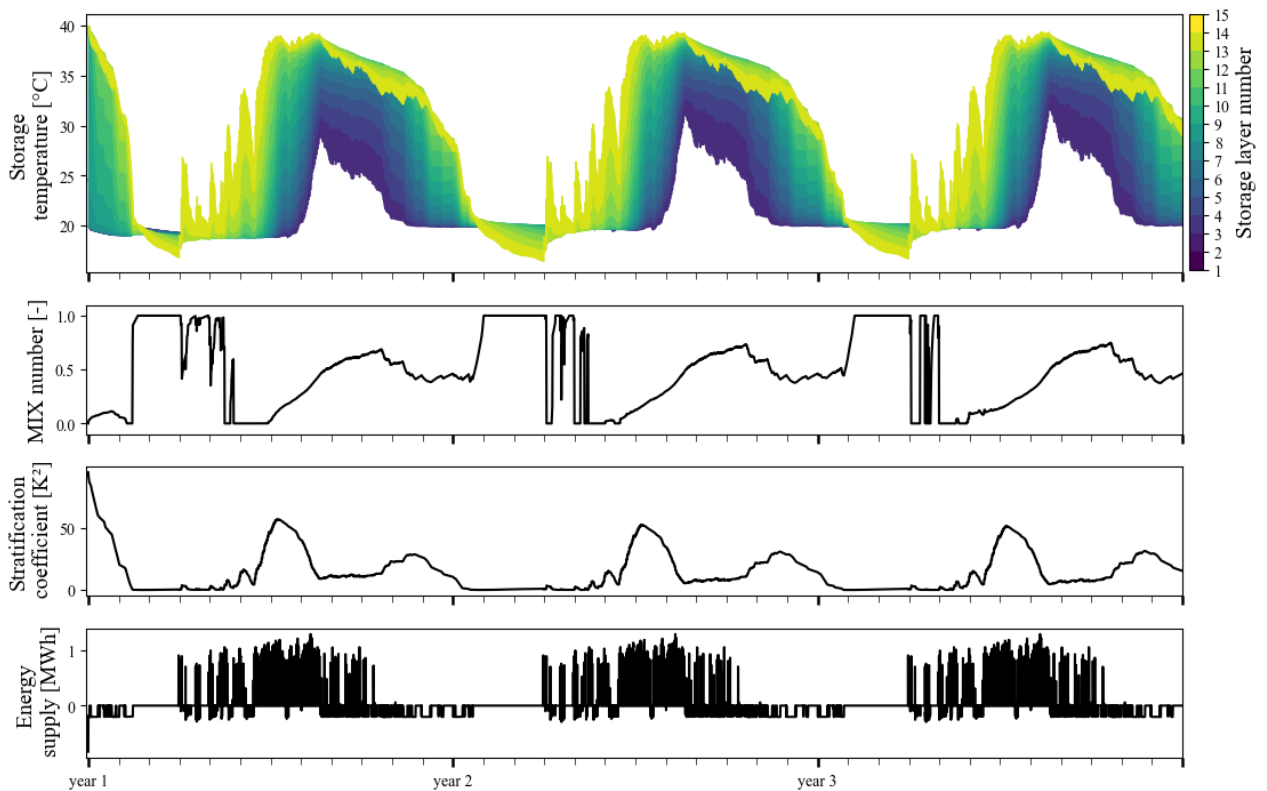


Figure 3.29 PTES temperature and stratification indicators for scenario Ref_F5.

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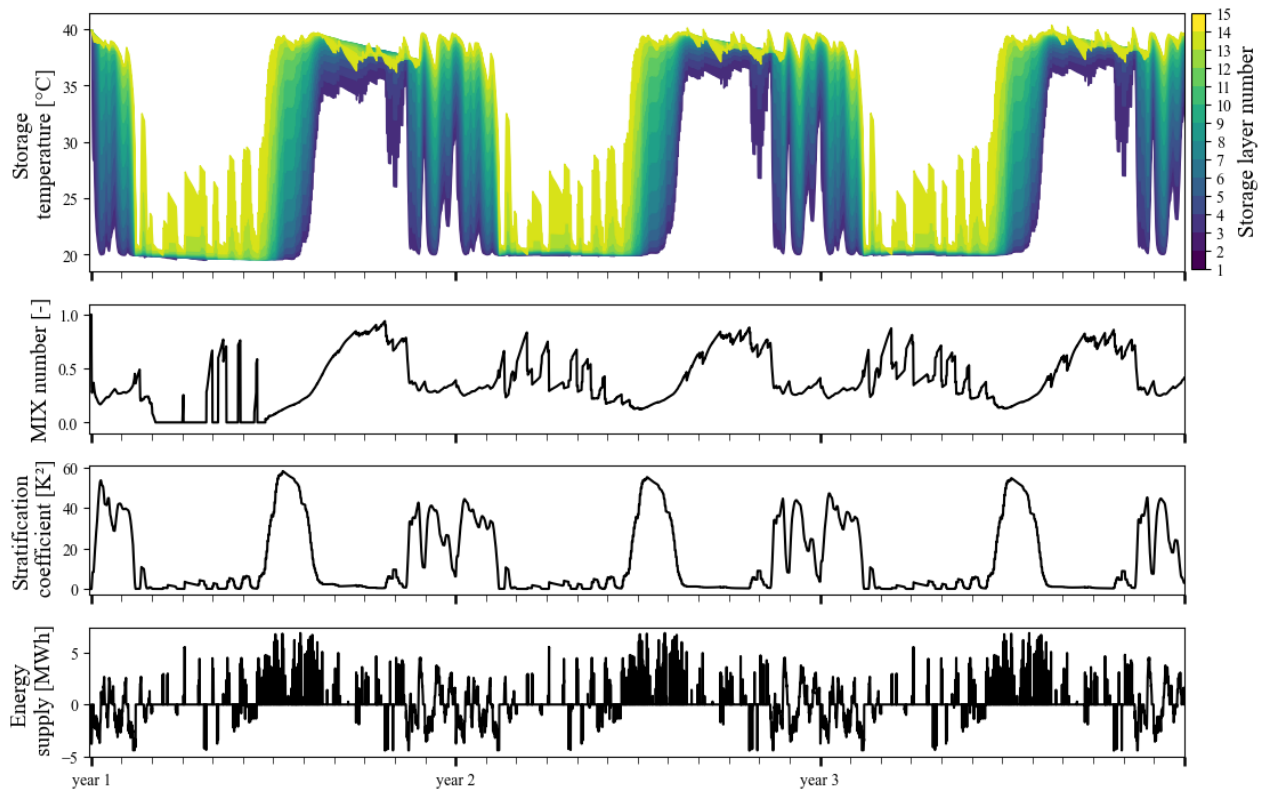


Figure 3.30 PTES temperature and stratification indicators for scenario **Ref_M1**.

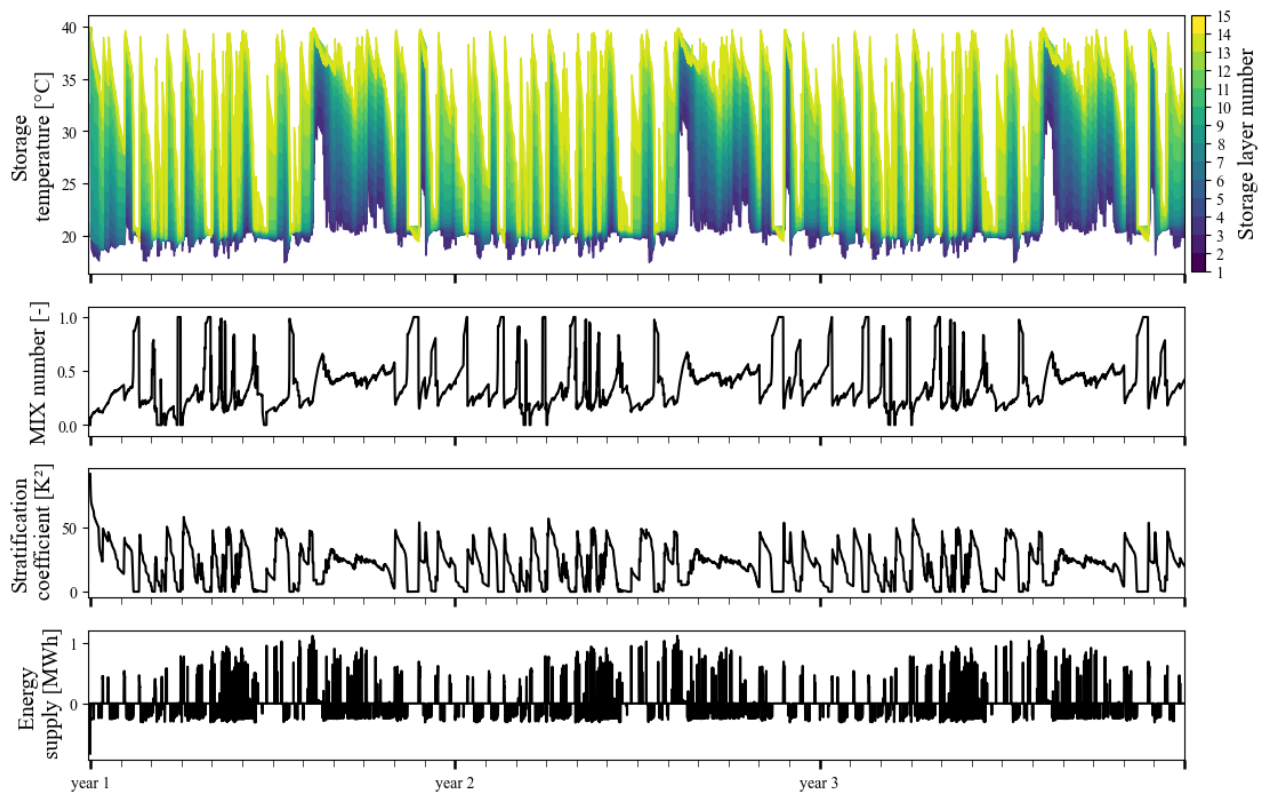


Figure 3.31 PTES temperature and stratification indicators for scenario **Ref_F1**.

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Key Learnings & Recommendations

4.1 Key learnings

The sensitivity analysis of the heating system design as well as the operation analysis carried out in this study explored a wide range of parameters and different scenarios. This section summarises the key learnings.

Internal energy supply: PV vs Solar thermal

The economically driven optimization of the system design scenarios revealed that PV panels demonstrate an excellent contribution to the system, even in the absence of PTES integration. With an investment and operation annuity cost making each electric kWh produced by PV panels cost 10c€, the model consistently favours PV over solar thermal energy which produce thermal kWh costs 7c€. This is because PV benefits of a conversion factor through the ASHP lowering the cost for a thermal kWh approximately by a factor 4.

External energy supply: impact of grid prices

The sensitivity analysis of grid prices revealed significant impacts on PTES design and operation. Consequently, a thorough understanding of the electricity market and a good intuition of its future trends are instrumental to anticipate an optimal design. From costs detailed in previous section, the system also favours PV over grid purchases.

Internal energy storage: PTES vs short-term buffer

The summary of cost benefits (Table 4.1) shows the annual cost savings gained from PTES integration. For the initial new district heat demand, the gain ranges from 0.7% to 1.9%. In comparison, after a short additional inspection, adding a buffer to the system yields a gain of 6% for Ref_F1. This clearly highlights the low impact of PTES

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and the crucial role of the buffer in providing intra-day balance, working in synergy with PV and taking advantage of the typically higher performance of ASHP during solar hours. This observation is supported by the significant differences in the amount of energy passing through the storage facilities (i.e. HSUR), which varies by at least a factor of 5.

	Ref_F1	Ref_F2	Ref_F3	Ref_F4	Ref_F5	Ref_G1	Ref_J1	Ref_J2	Ref_L1	Ref_L2	Ref_L3	Ref_M1
LCOH gain [c€/kWh _{th}]	0.26	0.32	0.22	0.22	0.23	0.45	0.29	0.24	0.44	0.61	0.63	1.91
Annual savings [k€/a]	15	18	13	13	13	26	17	14	25	35	36	517
Annual savings [%]	0.84	1.02	0.69	0.67	0.68	1.34	0.94	0.77	1.41	1.89	1.91	8.01

Table 4.1 Summary of the cost savings of the different scenarios compared to those without PTES integration.

For the exiting district scenario, the economic gain of PTES integration increases significantly to reach 8% with a higher HSUR reaching 13%. These positive results are not so much related to the absolute increase in demand, but more importantly to its highly seasonal distribution throughout the year. The installation of a PTES proves to be more advantageous when the demand profile exhibits greater seasonality. This highlights the importance of accurately estimating load patterns.

PTES model: simplified (linear) vs physical (non-linear)

Moreover, non-linear simulations examining different operations and sizes of PTES have demonstrated their inherent importance in studying the system dynamics. These simulations played a crucial role in understanding the transient behaviour at startup and the distribution and fluctuations of temperatures due to stratification in the PTES over time as well as the associated losses and thermal exchanges with the environment acting as a thermal capacity. This latter highlights a huge difference between the linear model (explicit losses) and the physical one (implicit losses).

This analysis has also revealed that, beyond operation strategies, the surface-to-volume ratio emerges as the most critical factor in estimating losses, particularly for low- insulated PTES. Therefore, according to the simulated load and state-of-charge error, it is essential to reconsider the relative loss factor of the optimized PTES depending on the sizing results. Note that the simulation over three years can be considered sufficient to reach a steady state regime.

4.2 Recommendations

Based on the technical, economic and environmental assumptions taken and the system parameters, we conclude that installing PTES in the new Athena-Lauzelle district heating network is not recommended. Despite PTES's capability to shift solar energy to compensate for load fluctuations on a daily, monthly, or seasonal level, its poor utilization rate and low economic gains indicate that it fails to deliver the significant

impact expected from such a large-scale installation. Furthermore, implementing PTES requires substantial space, planning, and resource allocation.

With the current setup, the recommendation is to implement a short-term buffer solution instead, such as a tank storage which allows for high synergy with PV.

4.3 Limitations

In addition to the limitations already discussed in section 3.1.2, which are specific to the operation configurations that the optimization model can handle, this study also has limitations related to the method, the tools, and the data used. Therefore, a review of these limitations is necessary to contextualize the study's learnings and recommendations.

Simplified loss model

The main simplification in the PTES consideration is the linearization of the loss model. These losses are expressed as a relative percentage loss (based on the state of charge) for a given period (here one year). Given that PTES performance is highly non-linear with its design and operation strategies, nPro is not the appropriate tool to study PTES operation as it lacks the necessary features. In addition, the given method doesn't compensate for load shortages when the PTES is empty. To increase the fit of the linear model on the physical model, a minimal state of charge in the linear model could be tested.

Simulation possibilities limited by tool performance

Another limitation is the significant computational power required for Modelica's simulations, which restricts the potential for extensive parametric analysis of operations.

Available existing operation measurements

Additionally, comparison with existing low-temperature DH networks is challenging because the available measurement data predominantly pertains to high-temperature networks.

Optimisation results robustness

One of the critical limitations of this study is its reliance on the theoretical annual operating model provided by nPro. The data used are based on a single year of weather patterns and do not accurately represent the operation of a real system under diverse conditions. To ensure more robust sizing, nPro's optimization should be conducted over multiple years using variable weather time series. Furthermore, the operation of each technology within the system should be thoroughly examined.

Final words & Perspectives

This study has shed light on various facets of PTES and its incorporation into DH networks. The specific focus on the Athena-Lauzelle project as a practical case study has been especially interesting. Not only because it is a potential real-life use case, but also because it was a perfect playground to challenge the backgrounds and the developed 2-step method with the aim to economically optimize the system and answer the question about the interest or not to insert a PTES.

Valuable insights have been derived from the various simulations and analyses. Key performance levers have been identified, key influencing factors have been highlighted and recommendations have been issued based on the chosen assumptions and methodology. Some limitations have also been reported which are certainly worth to be further investigated to improve the model and therefore increase the accuracy of the results and reliability of the conclusions.

As this work comes to a conclusion, it is also the time to raise some additional perspectives in connection to our subject which might be of interest to be studied.

Explore PTES stratification and understand its impacts/opportunities

The stratification performance analysis did not offer conclusive results, underscoring the necessity for more sophisticated evaluation metrics. Introducing an exergy destruction indicator could offer a valuable means of quantifying the extent of mixing within a storage system. This metric would provide a more precise and effective basis for comparing storage systems with varying levels of heat losses. In addition, studying the stratification within PTES by investigating the addition of a third diffuser could add flexibility to the system, further enhancing its performance and adaptability.

Consider alternative energy sources

The assumed energy hub model currently makes the system dependent on grid and solar energy sources. However, further exploration of additional renewable sources is recommendable. While geothermal energy could be suitable for low-temperature applications, it may be less compatible with PTES. Conversely, integrating biomass

and wind power could enhance the system's efficiency and reliability. Investigating the synergy between PTES and these other renewable sources, as discussed in section 1.1.2, could provide valuable insights and improvements.

Consider external dynamics (grid prices)

Introducing fluctuating grid supply prices to reflect the logical abundance of green energy in the grid when the sun shines or the wind blows is another important consideration. This variable pricing should enhance storage integration, especially given that the shares of solar and wind energy reached 9.5% and 18.5%, respectively, in Belgium in 2023 [37], and these shares continue to grow.

Consider the social and political factor

Furthermore, analyzing a scenario involving a carbon emission tax could yield valuable insights. This approach is relevant considering Athena-Lauzelle's ambition to become an exemplary neighborhood. Implementing a carbon tax has the potential to incentivize PTES integration by encouraging the maximization of self-consumption of locally produced renewable energy. Such a measure would align with broader sustainability objectives while reducing dependence on external energy sources.

Extend the system (beyond the district)

The emergence of new PTES applications, exemplified by the highly interconnected short-term Danish PTES system in Høje-Taastrup, presents a promising avenue for further exploration. These innovative systems have the potential to transform PTES into a versatile cross-sector battery, optimizing economic benefits and primary energy utilization. Contrary to the assumptions made in this study, future sourcing systems should be designed with consideration for both heat and electricity loads. Incorporating district electricity demand into simulation models is crucial for accurately assessing overall cost-efficiency within the available area.

Consider interconnected networks

While the energy flows within the Athena-Lauzelle district currently do not support large-scale storage, the study highlights potential integration pathways. For example, the Athena-Lauzelle heat network could establish connections with the existing district heating system in Louvain-La-Neuve or contribute to the broader electricity grid. Such integration efforts could play a pivotal role in supporting regional and national grid balancing efforts.

In conclusion, in the context of the necessity for thermal renovation of buildings to decrease primary energy consumption and carbon emissions, district heating systems in temperate climates will increasingly function at lower temperatures. The load patterns are anticipated to evolve similarly to those observed in Athena-Lauzelle. Consequently, large-scale energy storage will shift their focus from seasonal to shorter-term operations. The fundamental principle remains the same: adopting a large-scale perspective is essential when evaluating large-scale storage solutions.

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Annex: optimisation data

Tables A.1 and A.3 summarise the relevant data output from the optimised scenarios. Tables A.2 and A.4 show the same data for the corresponding scenario without PTES integration allowed.

Scenarios	PTES		System parameters		Available area [m ²]	PV [m ²]	STC [m ²]	Booster HP [kWth]	System design				
	ΔT [K]	losses [%/year]	Grid feed-in tariff [€/kWh]	Grid supply cost [€/kWh]					ASHP [kWth]	buffer [m ³]	PTES [m ³]	buffer nb cycles [-]	PTES nb cycles [-]
Ref_F1	20	35	0.04	0.35	10000	8824	0	144	1076	502	1206	298	11
Ref_F2	20	35	0	0.35	10000	6714	0	168	1012	474	4715	284	4
Ref_F3	20	35	0.04	0.39	10000	9,557	0	132	1112	515	7371	311	1.75
Ref_F4	20	35	0.04	0.44	10000	10,000	0	120	1,152	536	12,398	316	1.27
Ref_F5	20	35	0.04	0.49	10000	10,000	0	116	1,192	552	14,351	319	1.19
Ref_G1	20	35	0.04	0.35	10000	0	3346	164	836	484	3,092	239	3
Ref_J1	10	35	0.04	0.35	10000	8,786	0	112	1084	494	1384	303	19
Ref_J2	30	35	0.04	0.35	10000	9043	0	188	1084	531	6,067	293	1.38
Ref_L1	20	35	0.04	0.35	5000	5,000	0	176	980	451	1,360	271	9
Ref_L2	20	35	0.04	0.35	2500	2500	0	200	912	306	2,004	296	4
Ref_L3	20	35	0.04	0.35	1250	1,252	0	200	912	288	2,004	308	4
Ref_M1	20	35	0.04	0.35	10000	10,000	0	2528	5156	1268	49,860	244	3

Table A.1 nPro scenarios with PTES parameters and sizing results

Scenarios	PTES		System parameters		Available area [m ²]	PV [m ²]	STC [m ²]	Booster HP [kWth]	System design				
	ΔT [K]	losses [%/year]	Grid feed-in tariff [€/kWh]	Grid supply cost [€/kWh]					ASHP [kWth]	buffer [m ³]	PTES [m ³]	buffer nb cycles [-]	PTES nb cycles [-]
np_F1	20	35	0.04	0.35	10000	9,638	0	0	1,500	623	0	352	0
np_F2	20	35	0	0.35	10000	7,595	0	0	1,500	630	0	330	0
np_F3	20	35	0.04	0.39	10000	10,000	0	0	1,500	623	0	352	0
np_F4	20	35	0.04	0.44	10000	10,000	0	0	1,500	625	0	351	0
np_F5	20	35	0.04	0.49	10000	10,000	0	0	1,500	635	0	347	0
np_G1	20	35	0.04	0.35	10000	0	2253	0	1,276	492	0	372	0
np_J1	10	35	0.04	0.35	10000	9,638	0	0	1,500	623	0	352	0
np_J2	30	35	0.04	0.35	10000	9,638	0	0	1500	623	0	352	0
np_L1	20	35	0.04	0.35	5000	5,000	0	0	1,500	593	0	362	0
np_L2	20	35	0.04	0.35	2500	2,500	0	0	1,500	509	0	394	0
np_L3	20	35	0.04	0.35	1250	1,250	0	0	1,500	505	0	402	0
np_M1	20	35	0.04	0.35	10000	10,000	0	0	12,680	3124	0	328	0

Table A.2 nPro scenarios without PTES integration parameters and sizing results

Scenarios	System operation results						System KPIs		
	Total annual cost [€/a]	CAPEX [€/a]	OPEX [€/a]	Elec imports [MWh _e]	Heat demand [MWh]	LCOH [c€/kWh _{th}]	SLU [m ²]	GDF [kWhe/kWh _{th}]	HSUR [%]
Ref_F1	1,769,579	1,102,584	666,995	1,204	5,710	30.99	9101	0.211	5.4
Ref_F2	1,784,121	1,073,972	710,149	1,280	5,710	31.25	7401	0.224	7.6
Ref_F3	1,816,512	1,123,367	693,145	1142	5,710	31.81	10482	0.200	6.0
Ref_F4	1,872,118	1,138,870	733,248	1,096	5,710	32.79	11309	0.192	5.0
Ref_F5	1,926,987	1,144,371	782,616	1,080	5,710	33.75	11443	0.189	5.8
Ref_G1	1,916,353	1,045,775	870,578	1,747	5,710	33.56	3865	0.306	3.8
Ref_J1	1,768,056	1,101,051	667,005	1203	5,710	30.96	9089	0.211	5.3
Ref_J2	1,770,699	1,115,521	655,178	1159	5,710	31.01	9856	0.203	7.4
Ref_L1	1,785,950	1,043,144	742,806	1,406	5,710	31.28	5300	0.246	5.0
Ref_L2	1,839,363	1,003,805	835,558	1,677	5,710	32.21	2888	0.294	3.2
Ref_L3	1,886,265	986,048	900,217	1,871	5,710	33.03	1640	0.328	3.2
Ref_M1	6,461,779	2,381,910	4,079,869	9,705	27,082	23.86	13310	0.358	12.8

Table A.3 nPro scenarios with PTES operation results and KPIs

Scenarios	System operation results						System KPIs		
	Total annual cost [€/a]	CAPEX [€/a]	OPEX [€/a]	Elec imports [MWh _e]	Heat demand [MWh]	LCOH [c€/kWh _{th}]	SLU [m ²]	GDF [kWhe/kWh _{th}]	HSUR [%]
np_F1	1,784,364	1,136,677	647,687	1,124	5,710	31.25	9638	0.197	0.0
np_F2	1,802,573	1,107,932	694,641	1,207	5,710	31.57	7595	0.211	0.0
np_F3	1,829,135	1,141,781	687,354	1,116	5,710	32.03	10000	0.195	0.0
np_F4	1,884,807	1,141,799	743,008	1,113	5,710	33.01	10000	0.195	0.0
np_F5	1,940,069	1,141,883	798,186	1,116	5,710	33.98	10000	0.195	0.0
np_G1	1,941,966	1,038,197	903,769	1,830	5,710	34.01	2253	0.320	0.0
np_J1	1,784,364	1,136,677	647,687	1,124	5,710	31.25	9638	0.197	0.0
np_J2	1,784,364	1,136,677	647,687	1,124	5,710	31.25	9638	0.197	0.0
np_L1	1,811,376	1,071,012	740,364	1,366	5,710	31.72	5000	0.239	0.0
np_L2	1,873,995	1,035,006	838,989	1,649	5,710	32.82	2500	0.289	0.0
np_L3	1,921,811	1,017,372	904,439	1,842	5,710	33.66	1250	0.323	0.0
np_M1	6,980,176	2,743,412	4,236,764	9,767	27,082	25.77	10000	0.361	0.0

Table A.4 nPro scenarios without PTES integration operation results and KPIs

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