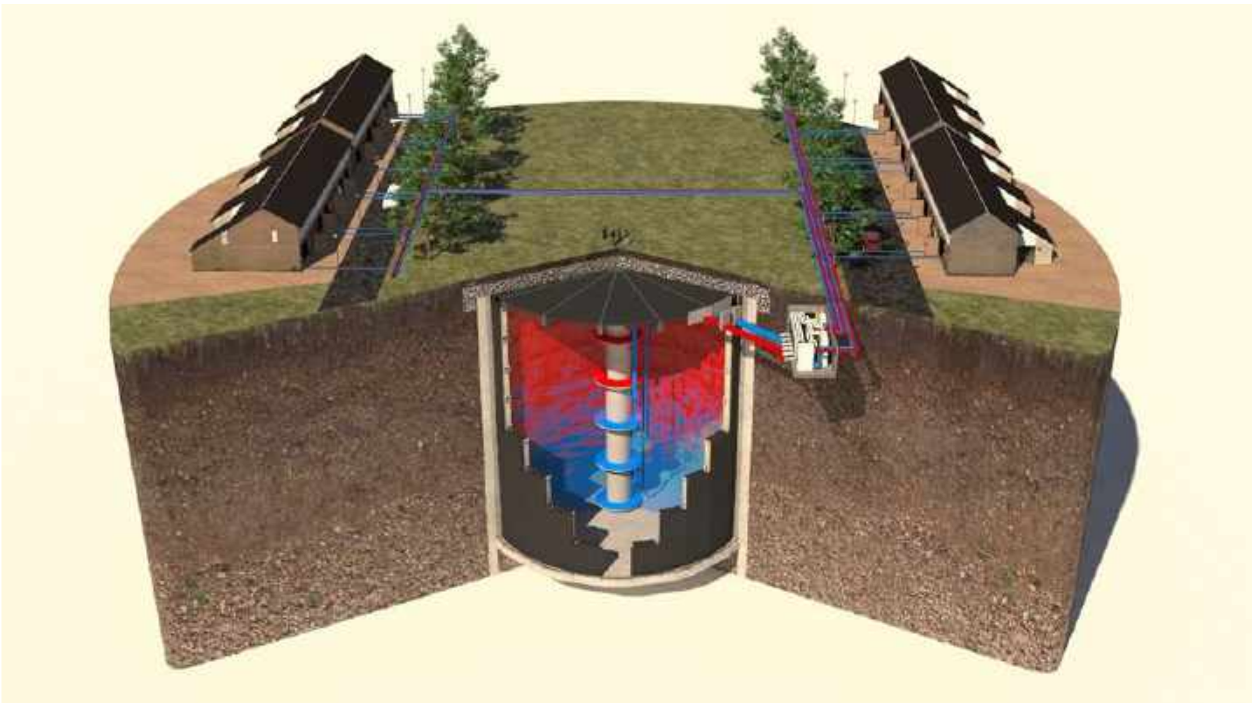
Research project:

Economic and thermal performance of Ecovat and comparable thermal energy storage technologies



Comparison of Ecovat to large, seasonal, sensible, thermal energy storage technologies for district heating networks

S.R.M. De Groot

Final Version V.2.0 – 9 June 2020

General

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Version overview

To verify and validate the statements made in the report Ecovat has asked external parties to review and provide feedback on the report. this process consists of two review rounds. The first reviewers (round 1) are experts who have checked the accuracy and objectivity of the numbers used for the calculations. The second reviewers primarily (round 2) looked at the assumptions and research set-up.

The document status is indicated by a version number as displayed in the table below.

The table below shows the function, company and area of expertise for the reviewers. Most of them have not reviewed the report in total and it is not intended to hold the reviewers accountable for the contents of the report. The goal is to show that experts have been consulted during the writing of this report and that serious efforts have been made to nullify any biases in the comparison.

Version number 0.1		Date 01.05.2020	First Draft
Reviewer(s)	Institution/company	Function & area of expertise:	Main comments
Dr. Niels Hartog	KWR	Scientist geohydrology: high-temperature heat storage (open systems), WKO, heat transport processes	Aquifer systems
Dr. Joris Koorneef	TNO	Sustainable geo-energy consultant: Carbon capture storage & energy storage systems.	Aquifer systems
Dipl.-Ing. Dirk Mangold	Solites	Director & university teacher, large scale solar heating systems, long term heat storage	Pit and tank systems
MSc. Peter Oerlemans	IF Technology	Geohydrologist, specialist in underground energy and geothermal energy	Aquifer and borehole systems
Maria Moser	Solid	Solar energy systems	Pit and tank systems

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Ed Smulders	InterProAdvies	Managing director, civil engineer	Research scope and assumptions
Fjo de Ridder	Thomas Moore	Research employee, energy forecasting, energy markets	Research scope and assumptions
Aart Kooiman	Invest NL	Impact engineer, energy transition consultant	Research scope and assumptions

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In no particular order I would like to thank:

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Stan de Groot, Uden

Abbreviations

Abbreviation	Meaning
LSSTES	Large sensible seasonal thermal energy storage
TES	Thermal Energy Storage
DH(C)(N)	District Heating (Cooling)(Network)
CHP	Combined Heat and Power
WGTES	Water-Gravel Thermal Energy Storage
PTES	Pit Thermal Energy Storage
TTES	Tank Thermal Energy Storage
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
WACC	Weighted Average Cost of Capital
CAPEX	Capital Expenses
OPEX	Operational Expenses
LCOE(S)	Levelized Cost Of Energy (Storage)
HT	High-temperature
LT	Low-temperature
GHG	Greenhouse gas

Preface

This document is written for anyone who has decided that large scale seasonal thermal energy storage is a necessary component of future energy systems and is wondering which systems are available and what their strengths, weaknesses, barriers to implementation and technical and economic performance are. The report is written for decision-makers like investors, municipalities, researchers, and companies that question which storage system best fits the needs of their specific situation. This document is a techno-economic analysis and comparison of the main Large sensible seasonal Thermal Energy Storage (LSSTES) technologies and Ecovat for applications in district heating networks. After reading, the reader knows:

- Why energy storage is a necessity to improve our energy systems
- Which forms of energy exist, how they can be stored, and which technologies are available to do so.
- The main benefits, drawbacks, possibilities, barriers to implementation and the technical and economic performance of the LSSTES systems and Ecovat
- Which LSSTES system is likely to perform best given a heat demand case.

The report contains four different cases, representing the heat demand of 700 to 7000 households (or a heat demand of 1500 and 14400 MWh resp.). 700 households may be accommodated using one small Ecovat. 7000 households may be accommodated by two of the largest Ecovat vessels.

Within these cases, the best LSSTES system to integrate into a (4th generation) low-temperature District Heating Network (DHN) is sought. Low-temperature is chosen because a trend in lowering the temperature of DHNs to reduce the thermal losses in the network is observed. The analysis focuses on the storage module and disregards the energy sources and DHN. The analysis focuses on heat demand, rather than cooling demand, although some technologies can also cool.

The following two graphs indicate the operation of the storage module within the DHN in summer- and wintertime. The blue encapsulated part is where the focus of the research is aimed.

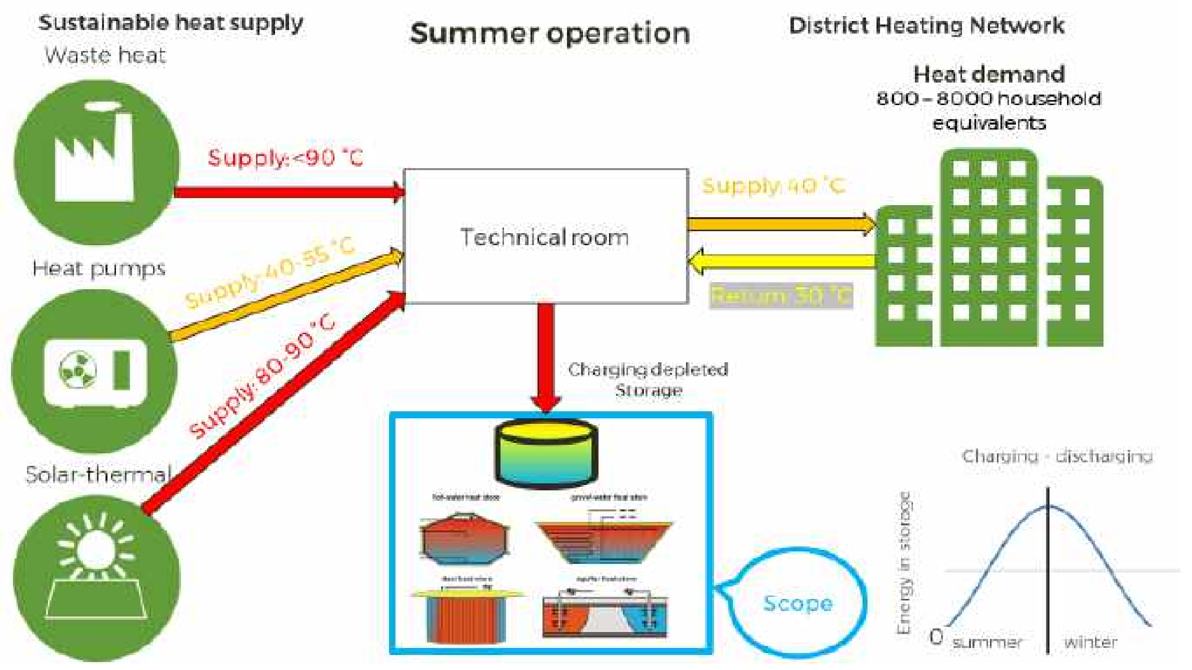


Figure 0-1: Summer operation and state of charge of the LSSTES within the DHN

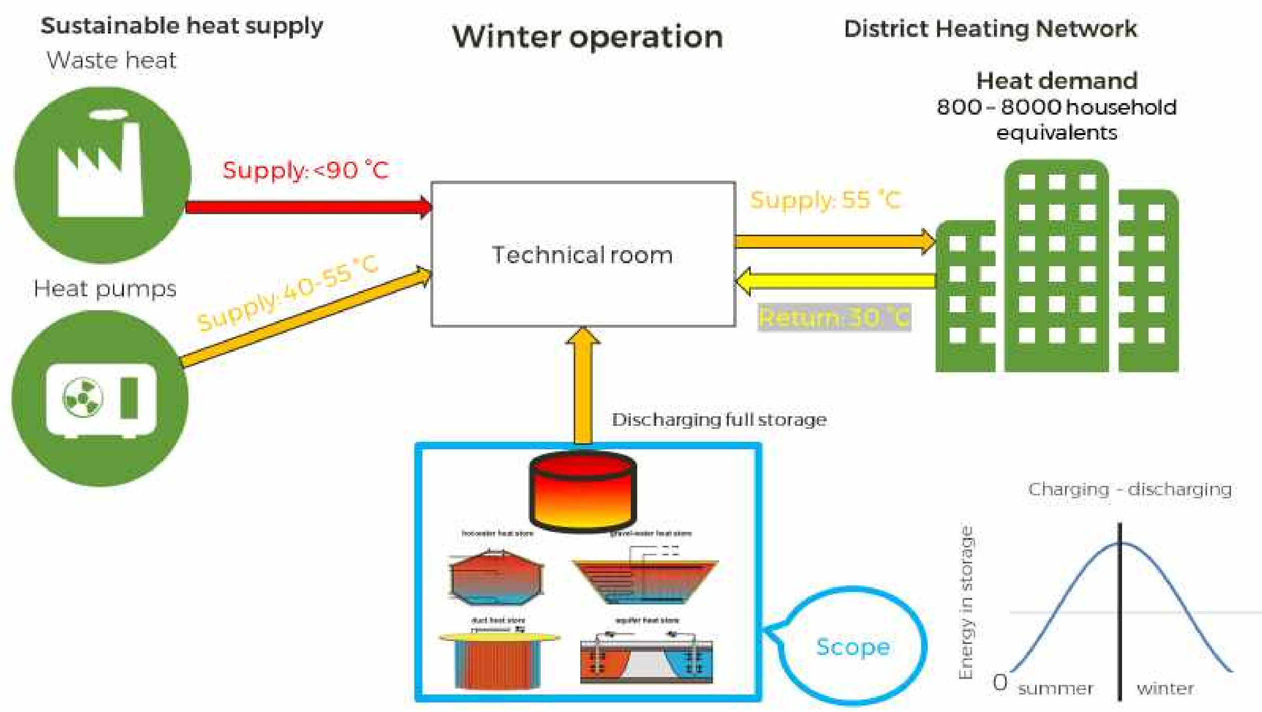


Figure 0-2: Winter operation and state of charge of the LSSTES within the DHN

To further highlight what is part of the research and what is not, the table below explicitly mentions what falls 'inside' and 'outside' of the scope.

Storage characteristic	Scope	Out of scope
Application	Low temperature District heating (55 °C supply – 30 °C return)	Peak buffer, High-Temperature-District Heating, Cooling
Scale	Large, Collective systems	Household scale, individual solutions (heat pumps etc.)
Project size in house equivalents	700 – 7000 households	Streets, single buildings or city-scale DH networks.
Energy storage form	Thermal, sensible (water)	Hydrogen, Green fuels, all-electric solutions
Storage duration	Seasonal	Hourly, Diurnal, weekly
Storage size (volume) [m^3]	10 000 - 500 000 m^3	< 10 000 m^3 & > 500 000 m^3
Storage capacity [MWh]	1500 – 16 000 MWh	< 1500 & > 16 000 MWh
Storage Temperature	60 – 90 °C	WKO, low-temperature storage, PCM, TCM

Table 0-1: Scope of the research

Five LSSTES systems are considered in this research, Pits, Tanks, Aquifers, Ecovat and Boreholes. These systems all have their own optimal range of application in terms of size and storage temperature.

The figure below displays in what sizes the systems are economically feasible in high-temperature storage mode and how many houses can be connected to the storage module (25% of heat demand from storage). The colours indicate that, for some storages, higher storage volume allows for a higher storage temperature.

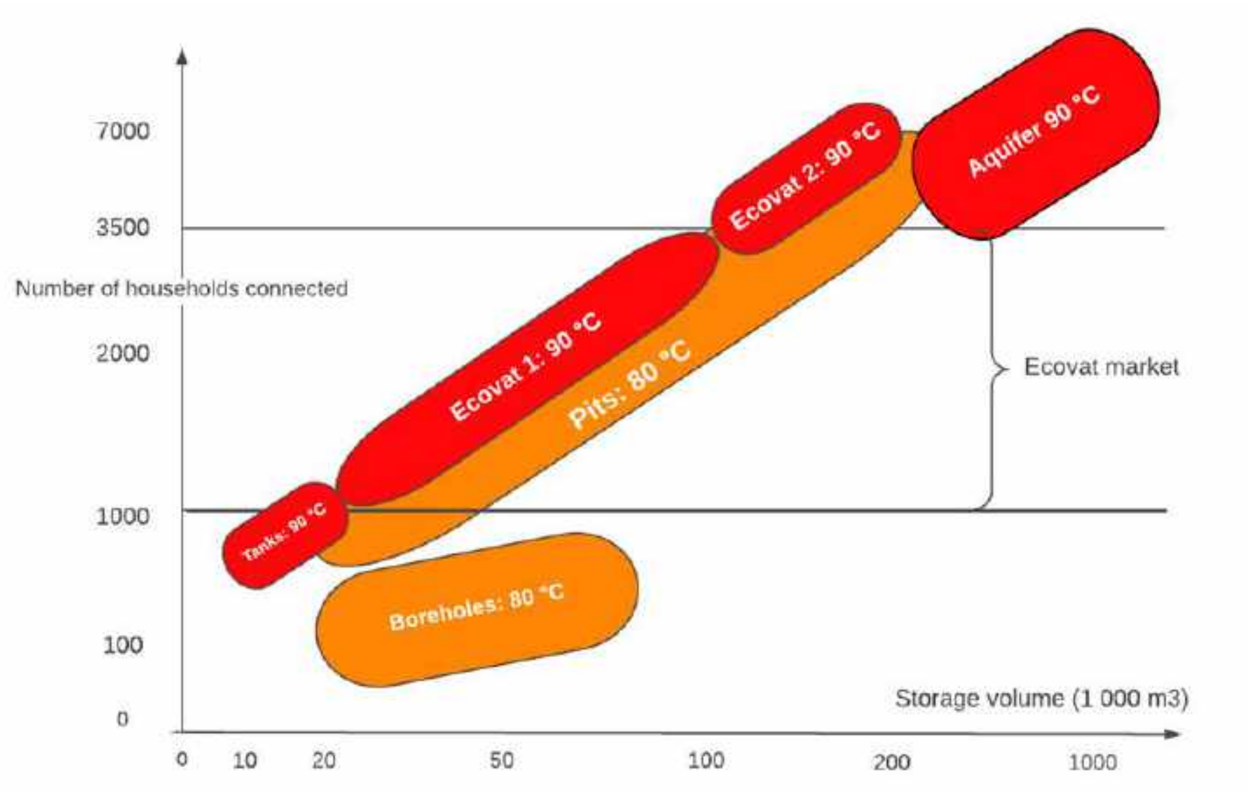


Figure 0-3: Suitable project sizes for high-temperature seasonal ATES, BTES, PTES, TTES and Ecovat.

Executive Summary

Energy storage takes an indispensable role in our future energy systems. A healthy and sustainable energy system with a high share of renewables will have to rely on storage on different time scales, both hourly, weekly and seasonally. Production, transportation, demand and storage of energy have to be aligned perfectly to yield an optimal system and it is not directly evident which of the multiple options we have is best suited for this. It is commonly agreed upon that district heating networks (DHN) will have a major role in our future energy systems and those networks require large scale seasonal thermal energy storage (LSSTES) when supplied with sustainable heat.

The author understands that it is by no means self-evident that LSSTES coupled to a DHN will be always the best option to pursue. It is, however, outside the scope of this report to provide extensive argumentation for the case that LSSTES will be the best option for some cases. So, it is expected from the reader to accept the premise that LSSTES will take an indispensable role in our future energy systems and that it can be the best solution in some cases.

This report focuses on medium- to high temperature (>50), large-scale, seasonal, collective thermal energy storage systems that can be coupled to district heating networks and aim to aid in the decision-making process of choosing an LSSTES in such a situation. The report provides a technical and economic analysis of five systems: Aquifers, Boreholes, Pits, Tanks and Ecovat. The benefits, drawbacks, market niche and barriers to implementation are discussed and a comparison based on four quantitative and three qualitative indicators is made for four hypothetical cases. In the main case, 3500 households are connected to a low temperature-DHN with an average supply temperature of 50 ˚C and return of 30 ˚C.

The report starts with outlining the forms of energy storage (electrical and thermal), the main market mature technologies available and their applications. It becomes clear that to store large quantities of heat seasonally for acceptable costs, large systems with cheap storage media are necessary. Such systems are (most often) underground systems using soil or water. The point is made that sensible heat storage in the underground is currently the only technically and economically feasible way to seasonally store large quantities of energy in the Netherlands. Four main technologies (and Ecovat) are identified in this field: Aquifers, Boreholes, Pits and Tanks.

Subsequently, the most important requirements for these systems are characterised and defined as performance indicators, which are subsequently used to compare the systems. The following performance indicators are used (the grey-marked are qualitatively rated):

- Levelized Costs of Energy Storage (LCOES) (€/GJ): Average cost for storing one GJ of energy over the lifetime of the storage, all costs included.
- Storage efficiency (%): the fraction of input heat that is recoverable after 6 months of storage
- Maximum storage temperature (˚C): Highest temperature stored in the storage module
- Land use (m^2): the amount of space rendered useless or notably reducing the utility of the land which the storage module occupies.
- Geological requirements: How stringent is the demand on the underground for the construction of the technology?

- Suitability for peak-buffer application: How adept is the technology at fast (dis)charging
- Construction-related greenhouse gas emissions

The report proceeds by discussing each of the technologies in detail, which is followed up by a comparison based on the defined case(s). The main assumptions are listen in section 4.2. Ultimately, the comparison lays out the pros and cons of each technology and the market niche of each technology becomes clear.

The general findings of the comparison per indicator (valid for the main case: 3500 households):

Levelized costs of energy storage (LCOES) and expected costs development

The LCOES values of Aquifer thermal energy storage & Pit thermal energy storage are lowest at a shared ~20 EUR/GJ. Ecovat and TTES cover middle ground at 25 EUR/GJ and 27.5 EUR/GJ respectively and BTES is more expensive at 34 EUR/GJ (see section 4.3). Systems with lower efficiency and especially systems with high uncertainty in efficiency have a large spread in costs at a high price of heat. This is significantly less at lower heat prices. So, the more efficient systems with a lower uncertainty (in efficiency) are more robust and show less LCOES variation as the heat price changes. In this regard, Ecovat has the lowest uncertainty and the lowest cost spread.

The build-up of the LCOES for Ecovat mainly consists of CAPEX and interest with low OPEX, heat loss compensation and heat pump costs. This also holds for TTES although the heat loss compensation is a bit higher. ATES systems are characterised by low CAPEX, high OPEX and – depending on the efficiency – high costs for heat compensation. PTES systems are quite moderate on all costs. BTES systems are least efficient and have high heat compensation costs. The other costs are all moderate but sum up to high costs, even when the investments for back-up power or peak buffers are not yet accounted for.

Eventually, PTES and ATES systems are cheapest for the base-case scenario (see section 4.2) (although the extra back-up power for ATES is not included in the calculations).

Cost reduction with upscaling is most apparent for Ecovat and PTES systems. This effect is mainly because of increased efficiency and lowered investment costs per unit storage volume related to upscaling. BTES and ATES systems enjoy this effect to a lesser degree since adding storage volume is not costly. It is predominantly the peak power that determines the investment and since that grows linearly with project size, the cost reduction effect seems somewhat less significant for BTES. ATES projects do become cheaper at larger projects but this is mainly because of the increased storage efficiency and higher full load hours. However, this effect is not yet strongly observed at the project sizes discussed in this research, implying that the ideal ATES market is at larger project sizes than considered in this research. TTES systems cannot scale up indefinitely and the lowest investment costs per unit of storage volume seem to be reached at systems of about 20 000 - 30 000 m^3.

In terms of expected price development, the least market mature technologies will have larger cost reduction potential for the future. The more mature technologies will see the majority of costs reduction coming from the ‘economy of scale’ effect as the storages become larger, due to improved efficiency, storage density and lower investment costs per unit of storage volume. Most LSSTES technologies are already quite mature and will have to rely on upscaling for the majority of their cost-reduction potential. Ecovat, having realised no commercial systems yet, is an exception to this rule. This flip side of this disadvantage is that there is ample room for cost reduction potential and so Ecovat can expect significant cost reduction through upscaling, technical maturation and improving the efficiency of the construction process.

Storage efficiency and temperature

Ecovat has the highest storage efficiency of all systems (~90 %) by a fair margin (~15 %). This is mainly beneficial in situations where the price of heat is high. In terms of storage temperature, the systems show little variation (80-90 °C). This is because the storage temperature is limited by 1. The boiling point of water and 2. The available temperature of (sustainable) heat sources. The high efficiency of Ecovat and ability to discharge the vessel to 20 °C by using stratification and heat pumps causes Ecovat to have the highest energy density and therefore store most energy in an equal volume.

Land use

In terms of land use, PTES systems use by far the largest amount of space. Above-ground TTES systems integrated into the landscape also use a fair amount of land but already much less. Ecovat, BTES and ATES systems are completely underground and can be said to have no land use, although some would object by stating that in the case of Ecovat the constructional possibilities with the above-lying land are limited. They would be right. In the case of ATES this is no problem.

Lifetime and suitability for peak demand

In terms of durability Ecovat, TTES and BTES systems are the most durable system with an estimated lifetime of 50 years (possibly longer), compared to about 25 years for ATES and 20 for PTES.

PTES, TTES and Ecovat systems are suitable to supply almost if not all the peak demand, whereas ATES is not suitable to supply peak power and generally supplies about 50% of the peak. This means an extra buffer or additional heat sources must be installed in the DHN, costs which are not included in this comparison. For BTES, this problem is even much worse.

Requirements of geology

Restrictions imposed by the underlying ground are most severe for BTES, ATES and PTES. In principle, BTES systems can be deployed almost everywhere but the geology strongly determines the thermal performance of the system. For BTES to function well, the groundwater flow must be nihil at the right depth, the soil must be drillable, possess moderate thermal conductivity and preferably be surrounded with low conductive soil. Clearly, these conditions are not found everywhere.

PTES must be constructed above the groundwater level to avoid excessive convective heat losses (bottom not insulated). This is not so much a problem in countries with low groundwater levels, but in the Netherlands, this renders the construction of PTES impossible or at least very troublesome in almost all areas of the country.

ATES systems also have strict requirements for the underground, although most of the underground in the Netherlands seems to be particularly suitable for LT-ATES exploitation. Whether this is also the case for HT-ATES is currently being investigated.

The only geological requirement for Ecovat is the possibility to drill, which is possible almost everywhere. Above-ground TTES systems have the advantage of not being dependant on the underground at all.

Building-related GHG emissions

In terms of building-related GHG emissions, BTES and ATES have the lowest greenhouse gas emissions associated with construction. PTES covers middle-ground and uses more energy for excavation and material. Tanks use more material than PTES per storage volume. Ecovat has much thicker walls than general TTES because of underground construction and has the highest building emissions associated with construction.

Market niches

The comparison at different project scales enabled the formulation of the market niches of each of the technologies. The graph below indicates (roughly) the range of project sizes in which each technology performs best (given the high-temperature scope)

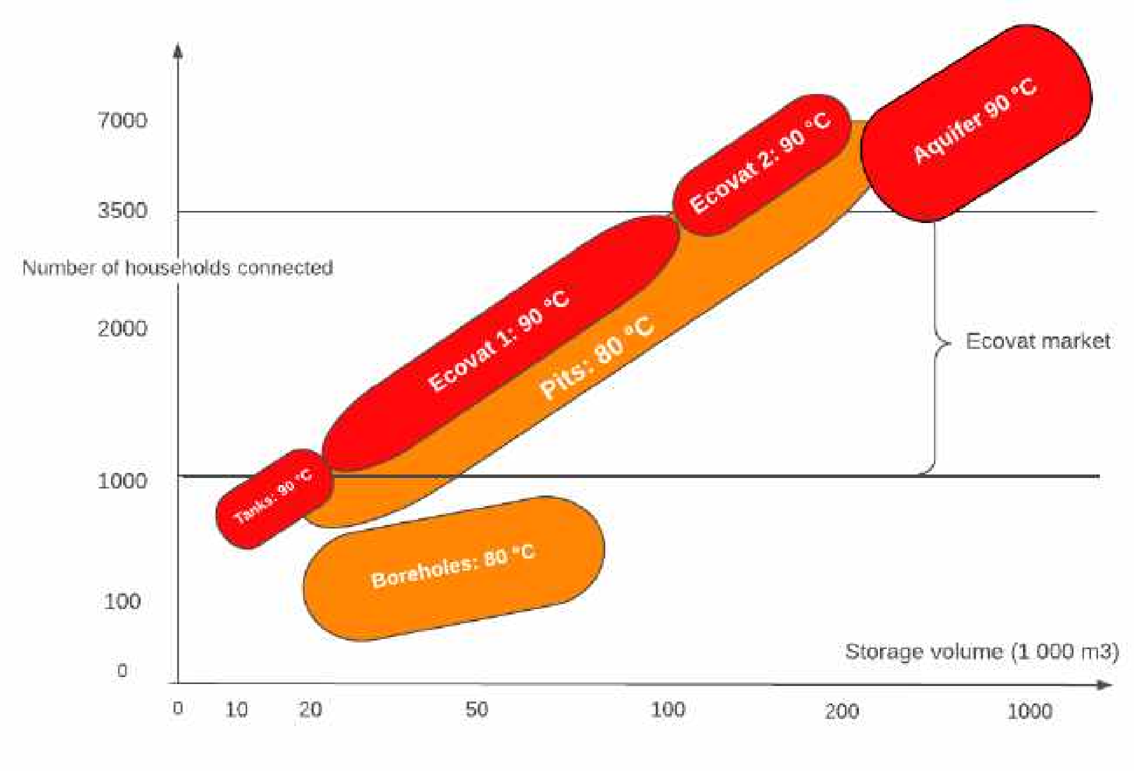


Figure 0-3: Suitable project sizes for high-temperature seasonal ATES, BTES, PTES, TTES and Ecovat.

Depending on the fraction of delivered heat that has to be stored, one storage capacity can accommodate a range of households, which is why the shapes are oval and not straight lines. From this graph it becomes apparent that the Ecovat market is inhabited fully by PTES and partially by TTES and ATES. The next two pages discuss the situations for which either of the technologies is more suitable than the other.

Pit thermal energy storage

PTES systems are the most similar system to Ecovat in terms of the range of possible project sizes. The differences in the systems are mainly in costs, lifetime, efficiency, uncertainty and geological requirements.

PTES systems outperform Ecovat in terms of levelized costs of storage, being cheaper at all system sizes. This is the prime advantage PTES has over Ecovat. Ecovats prime advantage is that is does not use land, whereas PTES uses a lot. Moreover, PTES systems can only be realised if the groundwater level is low enough, which is not the case in the majority of the Netherlands. Moreover, Ecovat systems are much more durable (50 years versus 20 years) than a PTES. The higher efficiency of Ecovat and lower uncertainty regarding OPEX, CAPEX and efficiency decreases the uncertainty in costs which is also advantageous. Overall, PTES systems are not considered to be direct competitors in the Dutch market since it is unlikely that a PTES system will be successfully constructed in the Netherlands and even if that would be possible the land use will often prove an insurmountable barrier in densely populated Netherlands. For other areas in which excessive land use is no obstruction and the geology allows for it, PTES systems are the better choice.

High-Temperature Aquifer Thermal energy Storage

The majority of possible HT-ATES projects are too large for Ecovat but there is small overlap at the lower end of the HT-ATES range, corresponding to the upper range of Ecovat. The main differences between the systems are in peak demand coverage, lifetime, efficiency, uncertainty in performance and geological requirements.

HT-ATES has the potential to store heat more cheaply than Ecovat but some conditions have to be met. First, the geological environment has to be suitable. If this is not the case, the system underperforms and it will still be more expensive than Ecovat. This dependence on the underground is a disadvantage for HT-ATES that Ecovat does not have. Secondly, the price of heat must be low since the efficiency of HT-ATES is less than Ecovat. More heat has to be charged into the aquifer to compensate for these losses. If this heat is expensive the costs rise significantly. If these two conditions are met and the HT-ATES system performs as expected, it can be a superior system to Ecovat. Next to the potentially lower costs, the second benefit of HT-ATES is that the space above the aquifer can be used to construct anything on. In the case of Ecovat, there are some constructions possible but not all. Ecovat is advantageous over HT-ATES because the uncertainty regarding system performance and eventual costs is much lower. Ecovat is also twice as durable and most importantly it is suitable for delivering high-power. HT-ATES systems are not dimensioned to accommodate peak power and therefore require additional back-up power sources in the DHN or a buffer installation. Whether ATES will still be cheaper when these costs are accounted for will depend on the specific project at hand.

Tank Thermal Energy Storage

Among the LSSTES technologies, TTES systems are most similar to Ecovat. An important distinction is that TTES systems are much smaller than Ecovat vessels although there is no constructional reason TTES systems could not be made of similar size to a small Ecovat. Currently, the largest TTES known is notably smaller than the smallest Ecovat (12 000 vs. 20 000 m^3). Should above-ground or partially dug-in TTES systems of this size be constructed, they are likely to be cheaper than Ecovat to construct, which would also be the prime advantage of TTES over Ecovat. It is, however, very doubtful if such a large tank will be placed above-ground in the Netherlands, given it would be about 30 metres high and wide. With that, the underground character of Ecovat is the prime advantages Ecovat has over TTES. Moreover, Ecovat is more efficient than a standard TTES, cutting costs for heat loss compensation. Still, TTES systems of 20 000 m^3 would be lower in the final LCOES.

Borehole Thermal Energy Storage

The low number of HT-BTES systems realised in the Netherlands (1), the small amount of research into HT-BTES and model calculations show that HT-BTES systems are not economically competitive at the large scales upon which Ecovat operates, especially considering the extra peak buffer investments that are required. HT-BTES might be an option for small volumes in which HT-ATES or an Ecovat is no possibility but at least in the Netherlands, HT-BTES is disregarded as a serious alternative to Ecovat.

Figure 0-4 visualises the biggest barriers to implementation for each technology. At the top, the range of possible connected households per technology is depicted. For Ecovat and TTES multiple systems can be built and connected, which indicated by numbering the systems (1-2 for Ecovat and 1-6 for TTES). Below the horizontal arrow, the main deal breakers of the four technologies that fall within the scope of the research are shown. The diamond at the bottom indicates the spread in costs for each technology for a system size equivalent to 3500 households. Ecovat has the least restrictions and the lowest spread in costs but is not the cheapest option for storage if the conditions for the other technologies are favourable.

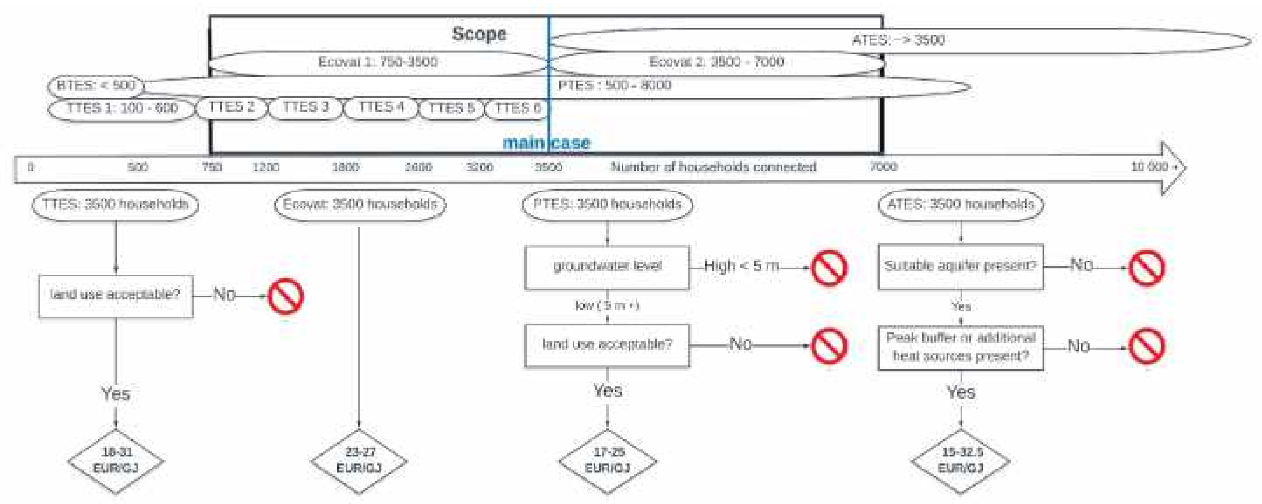


Figure 0-4: Barriers to implementation, project sizes and LCOES for the LSSTES technologies

1 Introduction

The complex world of energy entails production, transportation, consumption, and storage. The transition to clean energy systems necessitates the transformation of these, for which multiple combinations are possible. It proves very challenging to find out which options are the best. This is partly because of uncertainty regarding future technological breakthroughs, price developments, societal acceptance and political support. This combination often paralyses decision-makers as it remains unclear which path is best taken. As understandable as this may be, such vital decisions cannot be postponed indefinitely, and we mustn't let uncertainty render us idle in such critical situations.

The energy transition will inevitably be formed by a multitude of solutions, as each sector and individual situation calls for a tailored approach best accommodated by using a variety of technologies. In areas where heat demand from the built environment is clustered, it is widely agreed that district heating networks (DHNs) are a promising and viable option to transport energy. Such networks require large scale seasonal thermal energy storage (LSSTES) when supplied with sustainable heat to account for the irregular production and mismatch between demand and supply of renewable heat. This report aims to help the decision-maker with deciding which LSSTES will be most suitable to integrate into the DHN for a variety of situations.

The author understands that it is by no means self-evident that LSSTES coupled to a DHN will be always the best option to pursue, as mentioned in the previous paragraphs. It is, however, outside the scope of this report to provide extensive argumentation for the case that LSSTES will be the best option for some cases. So, it is expected from the reader to accept the premise that LSSTES will take an indispensable role in our future energy systems and that it can be the best solution in some cases.

Of course, reasonable explanation of the prime benefits of LSSTES is in place, especially for the readers less acquainted with energy systems. The reasoning for storing energy seasonally, on large scale and in thermal form will be given and alternative energy storage technologies will be discussed.

1.1 Goal and contents of the report

If it is wise to use integrate LSSTES in our future energy infrastructure systems, we must be able to differentiate the available technologies and assess their worth, so we can choose which system is optimal for a given situation X. The core aim of this report is to provide a method for this differentiation by formulating the requirements each LSSTES should satisfy. Identifying and rating the LSSTES systems given a particular case then becomes possible, which will outline the strengths, weaknesses, barriers to implementation and technical and economic performance. Consequently, the market niche for each technology emerges and Ecovat can be positioned within the LSSTES market. To aid the less acquainted reader in this process, the report begins with a general introductory chapter into energy storage. This leaves the following main goals:

1. Explain why energy storage is a necessity to improve our energy systems
2. Discuss which forms of energy exist, how they can be stored, and which technologies are available to do so.

3. Discuss the main benefits, drawbacks, possibilities, barriers to implementation and the technical and economic performance of LSSTES systems and Ecovat
4. Explore the role of Ecovat and the other LSSTES technologies within the LSSTES market by using a case comparison with the other LSSTES technologies.

After reading, the reader should be informed which forms of LSSTES systems are available, what their strengths and weaknesses are, and which system is best, given a particular set of conditions.

The report starts with a general introduction into energy storage and classifications of energy storage systems. Then, it proceeds to discuss comparable systems to Ecovat and their field of application. Performance indicators are defined to enable quantitative comparison, after which the results are presented. To close off, a summary of all the important characteristics and differences between Ecovat and the other system is given in textual and visual form. Details regarding the calculations and assumptions for LSSTES characteristics are included in the appendix.

1.2 Scope

The report focuses on medium-high temperature (>50), large-scale, seasonal, collective thermal energy storage systems that can be coupled to district heating networks.

The report is concerned with the storage module and not with the energy sources or the district heating network itself. To visualise the scope of the research a figure is shown below, with a blue scope outline surrounding what is included in this research.

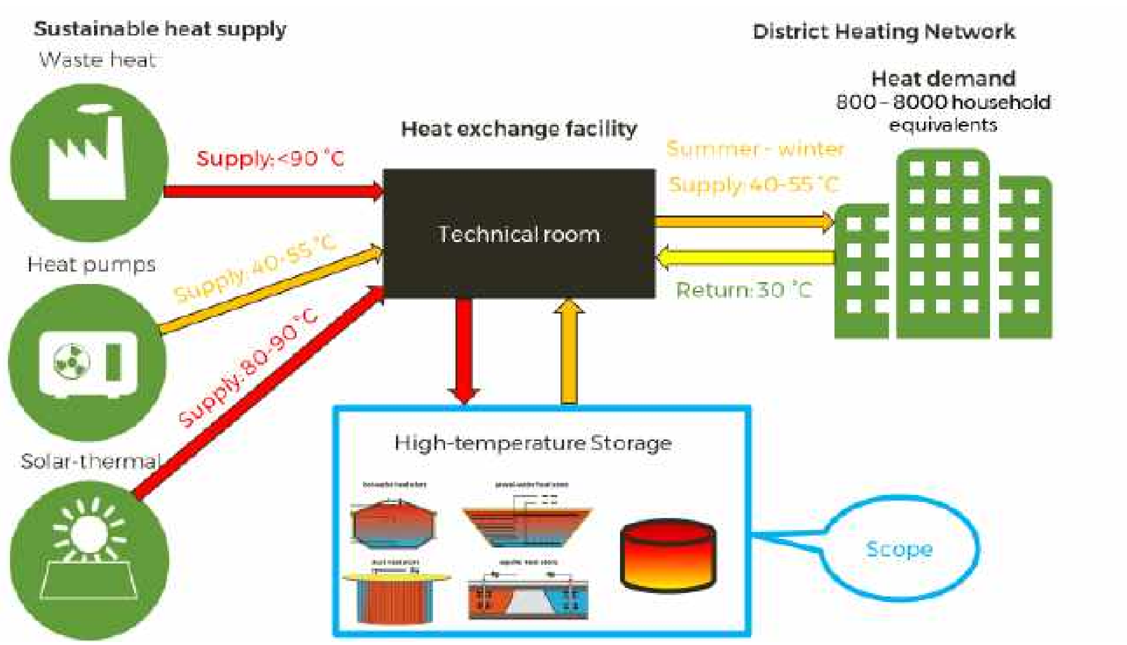


Figure 1-1: Scope of the research (encircled in blue).

Table 1 further specifies which aspects are considered within the research and which are not (out of scope).

Storage characteristic	Scope	Out of scope
Application	Low temperature District heating (55 ˚C supply – 30 ˚C return)	Peak buffer, High-Temperature-District Heating, Cooling
Scale	Large, Collective systems	Household scale, individual solutions (heat pumps etc.)
Project size in house equivalents	700 – 7000 households	Streets, single buildings or city-scale DH networks.
Energy storage form	Thermal, sensible (water)	Hydrogen, Green fuels, all-electric solutions
Storage duration	Seasonal	Hourly, Diurnal, weekly
Storage size (volume) [m^3]	10 000 - 500 000 m^3	< 10 000 m^3 & > 500 000 m^3
Storage capacity [MWh]	1500 – 16 000 MWh	< 1500 & > 1 6 000 MWh
Storage Temperature	60 – 90 ˚C	WKO, low-temperature storage, PCM, TCM

Table 1-1: Scope of research

This report will provide a comparison between the most prevalent LSSTES technologies from an economic and technical perspective. Legal requirements and social acceptance are not or only briefly discussed. In the comparison, minor issues of each technology are left out, as they are not considered deal breakers. Main characteristics and true barriers are discussed.

The technical and economic performance of a system is mainly dependent on the storage capacity, storage temperature and efficiency, which are interrelated. To allow a fair comparison, a base-case with boundary conditions is defined.

This report contains four cases corresponding to an annual heat demand of 700 to 7000 households. 700 to 3500 households may be served with a single Ecovat (assuming 25 % of heat demand requires storage), so to serve 7000 households two Ecovats are coupled.

Since Ecovat is currently only operating in the Dutch market, some of the statements – mostly about underground characteristics and value of land – will be biased towards the situation in the Netherlands. It is, however, always explicitly mentioned when conclusions or statements are based on the Dutch situation, to keep the results as general as possible.

Future DHNs will most likely also provide cooling (District Heating-Cooling Networks (DHCN). This research disregards the cooling aspect of future DHCNs.

2 Energy storage

A sustainable energy system can only be achieved by using a delicate balance between investments in renewable production, energy storage, energy infrastructure and load- and demand management. Studies regarding the optimization between these variables have shown that energy storage is an indispensable part of a cost-effective energy transition, both on long- and short term. Until now, the role of energy storage in energy systems has been marginal. This chapter introduces energy storage and explains what the causes for the lacking integration of storage into energy systems are.

This chapter starts by outlining which forms of energy exist, in what form energy can be stored and what technologies may be used for that. After that, a more in-depth analysis is made for electrical and thermal energy storage.

Energy is defined as the capacity of a physical system to perform work [1]. Energy may be stored in different forms by different technologies. It manifests itself in different kinds, which can all be exploited to store energy. These are:

- Potential energy: Potential energy is the energy of position [1]. Upon transitioning back from the high to the low state, this energy is released. Potential energy can be subdivided into:
  - Gravitational:
  - Electromagnetic:
  - Chemical:
  - Elastic:
  - Pressure:
- Thermal energy: energy of heat
- Kinetic energy: energy of movement
- Light
- Nuclear energy

Energy is generally consumed as either electricity, heat or motion, although some prefer to add molecules as a form of energy (chemical energy in essence). In the built environment, the majority of energy is consumed in the form of heat (i.e. ~70%). Generally, the form in which energy is stored is not per se the form in which it is consumed. On the contrary, energy is often converted from one form to another to facilitate storage, only to be converted back when it has to be used. For example, thermal energy may be stored in a chemical bond that releases heat when broken. This we call thermal energy storage while the thermal energy is stored as chemical energy. This storing of energy in a different form than in which it is consumed is typical for electricity. It is very hard to store electricity directly. Nevertheless, storing energy in chemical compounds to be used as heat is also very common (fossil fuels).

The ability to efficiently and cheaply store energy (either electricity or thermal energy) would be a major step forward in facilitating the energy transition. This is so mainly because solar and wind energy are intermittent, and the peak of their production does not coincide with the peak of energy demand. This means the energy must be stored or discarded when there the production of energy exceeds the demand. It also implies that creating a sustainable energy system that completely rests on solar and wind energy, will, in most areas, require some form of energy storage.

Unfortunately, there seems to be no golden technology yet that can combine all the requirements in one system, hence the lacking integration of energy storage systems.

As mentioned, the product of energy is either heat or electricity. Therefore, we proceed with the discussion of those.

2.1 Electrical energy storage

As mentioned, storing electrical energy directly is troublesome. Fortunately, there are some possibilities to store electrical energy in other forms:

- Chemical energy: electricity can be stored in chemical bonds, which can be again broken to free the energy again. This is the working principle of batteries
- Kinetic energy: electricity can be converted into movement of an almost frictionless object. Flywheels exploit this and can convert kinetic energy back into electricity using a turbine.
- Gravitational energy: electrical energy can be used to pump mass (often water) to a higher altitude (gaining gravitational energy). Upon falling back to ground-level, this gravitational energy is converted into kinetic energy, which drives a turbine and returns electricity. This is used in pumped hydro storage.
- Compression energy: electricity can be used to compress a medium (often air), pressurizing its container walls. When the medium is allowed to expand, the energy is released again, some of which can be regained as electricity. Compressed air energy systems (CAES) exploit this principle.
- Electromagnetic energy: electricity can be stored in magnetic fields using a superconducting magnetic energy storage (SMES) system.

Capacitors can directly store electric energy.

Electricity storage is characterised by short time-spans of minutes, hours to oftentimes maximally days. This is not because this is a suitable storage duration but because most storage options are not well-suited to store for longer durations, except for pumped hydro storage. This is a problem since the mismatch between energy supply for renewable sources is not only on hourly scale but also on weekly, monthly and yearly scale.

Figure 2-1 shows commercialized electrical energy storage systems with their capacity and storage duration range. Note that the only technologies able store for longer than a day are pumped hydro, compressed air and hydrogen.

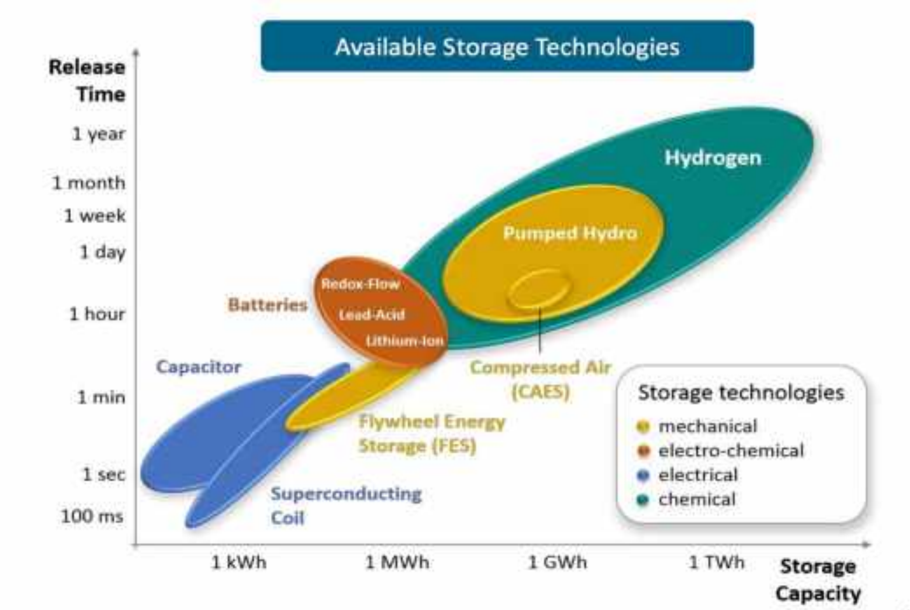


Figure 2-1: Electrical energy storage technologies and their range of applications

Of all the electrical storage power capacity currently installed, pumped hydro amounts to the vast majority (figure 2.2). Only a tiny amount is covered by CAES, batteries of different kinds, flywheels or conductors.

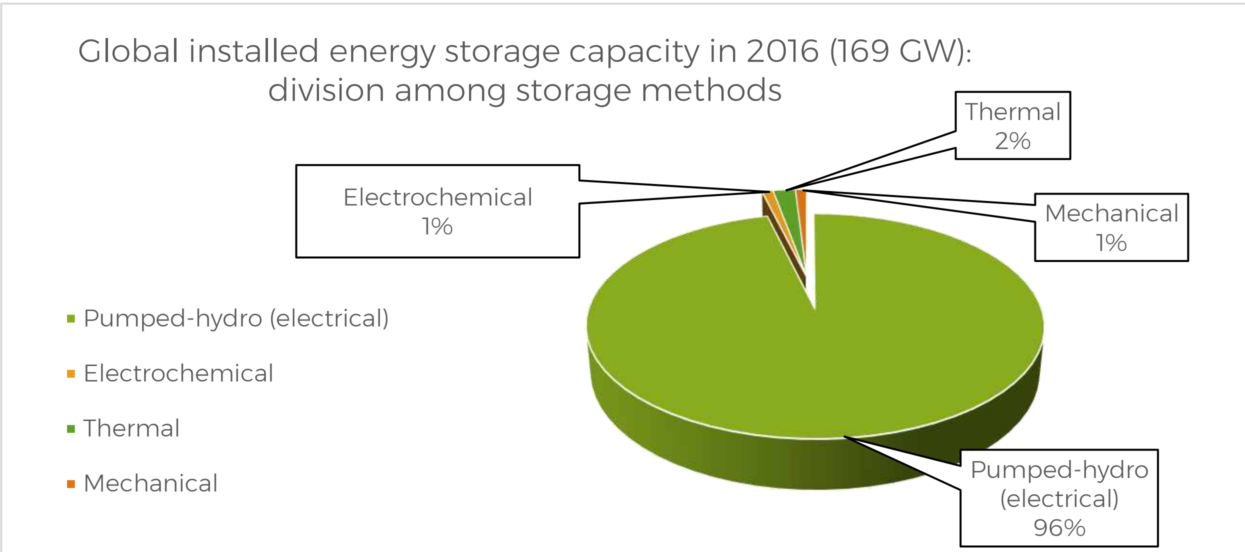


Figure 2-2: Global installed energy storage power in 2016 [29]

Pumped hydro storage requires large basins of water that are located at different heights. Unfortunately, these are not present in the Netherlands which is why pumped hydro has no application in the Netherlands. The second-largest contribution is made by CAES, which is not because of the many systems deployed but because of the large scale of CAES. CAES is currently still in the research phase even though the concept was already worked out some 50 years ago. The limited research efforts into CAES make widespread market availability unlikely. After pumped hydro and CAES, batteries make up for the largest part of the installed capacity. Batteries are suitable for hourly storage. Besides, batteries are quite an expensive method to store electrical energy. This means that batteries are suitable for short term and small scale storage but less so for the long term and large scale storage. Then, finally, there is hydrogen (and methane). In these applications, electricity is used to produce fuels (Power to fuel P2F) that can be converted back to electricity using fuel cells (in the case of H_2). This method is beneficial for several reasons among which the ability to store the electricity indefinitely with low losses. However, there are also some significant downsides among which the low roundtrip efficiency of the storage and the transportation of the fuels. It is currently heavily debated what the role of hydrogen can/should be in future energy systems. The current expert outlook is that hydrogen will certainly play a role in the future energy system but will not serve as a main energy storage depot.

As we've concluded earlier, a balanced energy system requires both short & long term storage as well as small and large scale storage. As of yet, the electrical storage technologies are not able to provide with the full spectrum needed for a complete energy system, leaving a gap in the energy storage market (large scale & long term) that must be filled.

2.2 Thermal energy storage

Thermal energy can be stored in three different ways (see figure 2-3):

- Sensible heat:
  Sensible heat storage is storing energy in the temperature of a certain liquid or solid. Since temperature is a measure for energy, maintaining the high temperature of any medium is a way of 'storing' energy. Upon cooling of the medium, this energy is dissipated/released to the environment.
- Latent heat:
  latent heat is the heat associated with the phase transition of a substance. Phase transitions always require or release heat. Therefore, keeping a medium in a high-energy phase (i.e. gas) is essentially 'storing' the heat of the condensation (phase transition (gas → liquid)). The materials used for this kind of storage are called Phase Change Materials (PCMs)
- Thermochemical heat:

Thermochemical heat, like the name suggests, is the heat that is required for or released in a chemical reaction (not a phase transition). Thermochemical heat storage exploits reversible endothermic/exothermic reactions, in which excess heat can be used to form reaction products that when brought back together, produce heat again. These products are stored separately, where they can be indefinitely stored with negligible heat losses. Such reactions are typically sorption reactions (A + B ←→ AB + heat).

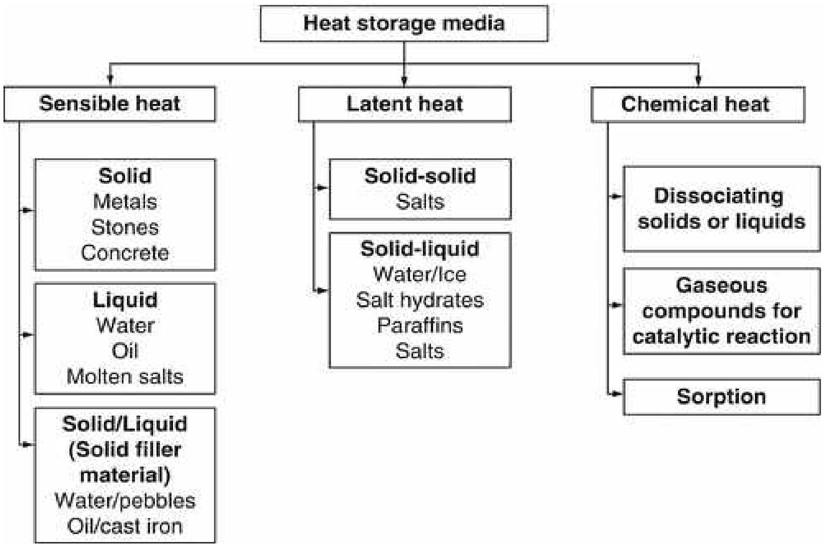


Figure 2-3: thermal energy storage classification [30]

2.2.1 Sensible heat storage in solids and liquids

As mentioned, sensible heat manifests through the elevated temperature of a medium. This medium can be in any phase, solid, liquid or gaseous. Since the differences between liquid and solid energy storage are large, techniques are often classified by their storage medium. For applications of sensible heat, only solids, liquids or combinations are used. The choice for a storage medium depends on a lot of factors among which, volumetric storage capacity, price, heat transfer characteristics, temperature range and toxicity. Liquids are often preferred over solids, because they have beneficial heat transfer and transportation characteristics compared to solids, keeping the design of their systems simpler. For low to moderate temperature, water is the go-to storage medium, while molten salts and steam are used for higher temperature applications. Sensible heat in solids is often used when the solid is integrated into a building, but not to store energy at large scale for a long time (at least not for the temperatures suitable for domestic heating). Soil is an exception to this.

2.2.2 Latent heat storage

The heat associated with phase transitions is significant, allowing PCMs to store a lot of energy on small temperature intervals (in phase transitions the temperature does not change). This is the prime advantage of PCMs. Furthermore, the energy storage density is high, allowing small storage systems compared to sensible liquid storage volumes. Almost all PCMs use the solid-liquid phase transition to store heat, as the gaseous phase is much more voluminous and storage systems would need to be very large. The main materials used are salts, salt hydrates, water/ice and paraffins. Currently, a lot of research is ongoing into PCMs and the results are promising. Disadvantages of PCMs are generally troublesome heat transfer because of their solid nature combined with low thermal conductivity. Furthermore, some PCMs are flammable, toxic, corrosive and or, are subjected to supercooling and separation which are obstacles for practical applications.

Unfortunately, as of yet, the applications of PCMs are mainly small scale (building integration, mobile cooling, electronics cooling) and their market is not fully commercialized, rendering them unsuitable for large scale, long term thermal storage. Water/Ice systems are an exception to this case, but because of the freezing point of water, it is inconvenient to extract heat from the freezing phase transition (a medium can only be warmed by the melting heat if the water can lose heat to a different medium which should be colder than 0 °C).

Since PCMs are currently not used for large scale seasonal storage, they will not be considered as an alternative to Ecovat.

2.2.3 Thermochemical storage

Thermochemical heat is the heat need for or released by chemical reactions. One can store the reactants (A & B) separately and bring them together whenever heat is needed. Upon doing so A & B form AB, which is a lower energy compound. The difference in energy is repelled as heat, which can be used as wished. Such a reaction is reversible, enabling the creation of A & B out of AB when excess energy is available.

Such reactions can be of any kind, but the most used is the sorption reaction, in which water is absorbed into a salt (or another compound) to form a salt hydrate. Thermochemical storage enables the compact and indefinite storage of heat with virtually no losses. Main benefits include high storage density, low losses, a large temperature range of application and little to no deterioration of the system upon use.

Currently, there is a lot of research ongoing into finding the right materials to optimize and exploit these beneficial characteristics. As of now, the applications for thermochemical heat are in sorption systems, gas cleaning and separation processes. Thermochemical heat is not something that is applied on large scale as of yet and remains in the research phase. Therefore, such systems are not considered realistic solutions to the problems Ecovat tackles today.

2.3 Large scale, seasonal sensible heat storage

We have seen that both latent and thermochemical heat storage do not offer commercialized, large scale seasonal storage systems. That leaves us with sensible heat storage in solids, liquids, or a combination. Large scale sensible heat in solids (rocks) is mainly used for concentrated solar power storage, where solar heat is stored at high temperature to produce electricity at night. Solids are useful here because of the high temperature they can store.

For lower temperature storage, almost all large scale heat storage systems use sensible heat. The long term (seasonal) and large scale character of storage implies a need for high storage capacity. Coupled with the low storage density of sensible heat compared to latent or thermochemical, this mandates the use of large systems. Because of this, such systems are mainly built underground. This group of energy storage systems is referred to as Underground Thermal Energy Storage (UTES) and consists of the most prevalent large scale seasonal thermal energy storage systems. Since some Large scale, Sensible Seasonal Thermal Energy Storages are also built above ground, the term LSSTES is used to be more inclusive.

2.3.1 Applications

Large sensible seasonal thermal energy storage in DHC systems can serve for various purposes: short-term heat storage or peak shifting, long-term or seasonal storage of e.g. solar thermal or surplus heat, energy management of multiple heat producers or cold storage of e.g. ambient cold or evaporator cold from heat pumps. In realized projects, the typical applications include [2]:

- Seasonal thermal energy storage for solar district heating
- CHP optimization
- Integration of power-to-heat applications
- Storage of industrial waste heat
- Combined heating and cooling applications

2.3.2 Classifications of seasonal sensible thermal energy storage systems

This chapter categorizes the most prevalent LSSTES technologies along with their characteristics. The commercialized LSSTES systems can be roughly categorized into four main groups:

a) ATES: Aquifer Thermal Energy Storage
b) BTES: Borehole Thermal Energy Storage
c) TTES: Tank Thermal Energy Storage
d) PTES: Pit Thermal Energy Storage

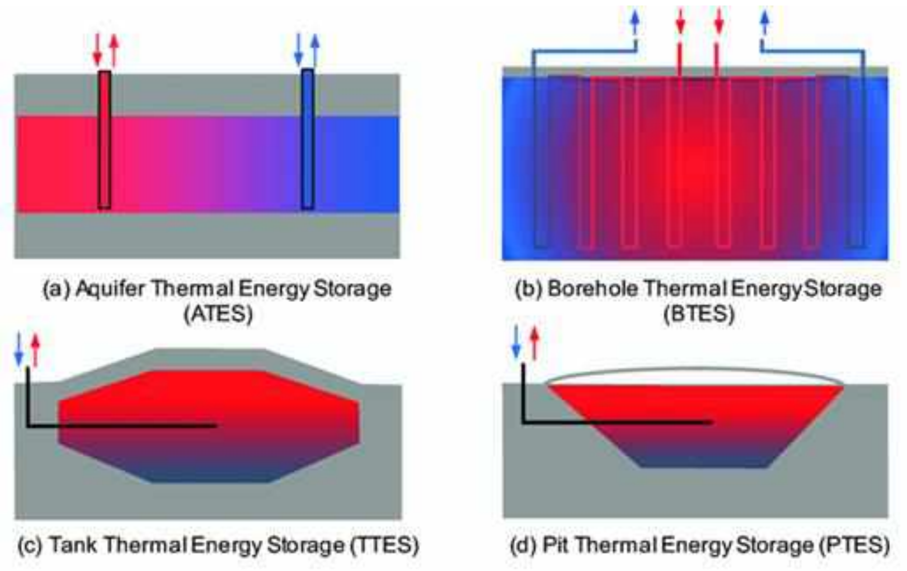


Figure 2-4: Classification Overview [3].

LSSTES systems can be further classified regarding the heat exchange (direct or indirect), storage medium and whether the storage medium is separated from the surroundings or not. These hold some generic implications that are discussed to prevent having to repeat them when discussing each storage system.

Open-loop / Closed loop: Open-loop systems use one medium for both storage and transport. This medium is almost always water. Closed systems store energy in one medium and extract/inject it using another medium, which is not in direct contact with the storage medium. This is often the case when the storage medium is solid and cannot be freely pumped.

Storage medium: LSSTES systems store energy in water, soil, rock or a water-gravel combination. The storage medium determines the energy storage density, as well as the energy transport medium and with that the design of the heat exchange and the size of the system.

If the storage medium is a solid, heat exchange takes place through conduction. This is a relatively slow process, implying that solid storage media are in general less suitable for high-power applications. If the storage medium is a liquid, heat exchange predominantly occurs via convection which enables faster heat transfer and extraction of higher power relatively easily. This makes high-power application much easier for storage systems using liquid storage media.

The storage medium also determines how much heat can be stored in a unit of space (volume). Water has the highest volumetric storage capacity (of common sensible heat storage materials), meaning that systems using water are smaller than systems using other storage media, for the same storage capacity.

Insulation: Some LSSTES systems have their storage medium completely out of contact with the surrounding soil or water. These systems are called insulated. Other systems have their storage medium in direct contact with the surroundings, these systems are 'not (or non) insulated'. This distinction between insulation/no insulation is not to be confused with open/closed loop.

Non-insulated systems face much more stringent legislative demands because the storage medium can directly (negatively) affect the surrounding environment. Changing the temperature of the soil or adding chemicals to the water in which the heat is stored are examples of practices that are bound to legislative restrictions. This means that non-insulated systems are much harder to get a permit for, which is something to be considered from the investor's perspective.

Technology	Open/closed loop	Storage medium	Insulation
Ecovat	Open	Water	Yes
TTES	Open	Water	Yes
PTES / WGTES	Open Closed	Water Water-Gravel	Yes Yes
ATES	Open	Sand-water or rock-water	No
BTES	Closed	Soil or rock	Yes

Table 2-1: Classification of LSSTES systems

2.3.3 Requirements of Large scale, seasonal sensible heat storage performance

The requirements of an LSSTES storage unit differ depending on the application. Nevertheless, there are main properties that are vital for each system. The performance of a storage system can be rated based on those properties. The most important ones are discussed in the following paragraphs.

Storage capacity (MWh)

One of the most important indicators for a storage module is the amount of energy it can maximally store (per cycle). The storage capacity of each technology can be varied to some degree but there is always an optimal range. This is because the storage capacity directly influences many other characteristics of the storage such as maximum storage temperature, efficiency and costs. The interaction of these factors determines a range in which the technology can be economically and technically feasible. This makes the storage capacity one of the most important defining variables for an LSSTES system.

Storage efficiency (%)

Since the goal of a LSSTES system is retaining heat, it is no surprise that the efficiency of a storage system is one of its most important characteristics. High efficiency means low thermal losses, implying that less energy has to be produced in the first place, which has a cost-cutting effect. Efficiency from a thermodynamic perspective is the part of the energy input, that is useful for the intended goal. For the application of storage, the goal is to preserve and thus the efficiency can be viewed as 'how much of the energy I add to the system is still there when I want to retrieve it'. In other words, the storage efficiency (η) is defined as the ratio between energy added to the system (heat) and the energy retrievable after a storage cycle.

Efficiency is interrelated closely to the storage volume and storage temperature. The storage efficiency depends on the thermal losses of the system, which are governed by the degree of insulation, stratification, storage temperature, storage volume and surrounding medium mostly. In general, increasing the size of a storage will make it more efficient, because the storage will have a more favourable volume to surface ratio. Better insulation improves the efficiency and lower storage temperatures lower the thermal losses. For non-insulated systems, the surrounding medium is a critical determinant of the system efficiency.

Storage temperature (˚C)

The maximum storage temperature is closely related to the storage efficiency since temperature difference is the driving force for heat transport and thus heat losses. This means that a higher storage temperature means higher losses. Still, it is beneficial to be able to store heat at as high as possible temperatures since high-temperature heat has more possible applications than low-temperature heat. Foremost, >60 ˚C water can be fed directly into DH networks, without requiring further temperature upgrading (which is often accompanied by unwanted carbon emissions and additional investment and operational costs). Secondly, a higher storage temperature means that more heat can be stored per unit volume of water, increasing the energy storage density. This, in turn, decreases the necessary system size for the same storage capacity, lowering the costs of the system.

Thus, storing higher temperature heat has its benefits as well as drawbacks. For each storage technology and situation, a careful consideration is necessary to gauge where the optimum balance between these lies so that an optimal system can be designed. For each technology, this optimum will vary across projects and so it is often the case the optimal storage temperature is not the same as the physical limit of the storage. When the storage temperature is viewed as a single characteristic, which is the aim of the performance indicator, one could state that a higher storage temperature is always better, given the higher energy storage density it provides. Moreover, there are simply more applications for high-temperature heat.

Levelized Costs of Energy Storage (LCOES) (€/GJ)

What good would a comparison between technologies be if costs were not involved? Many kinds of costs could be compared but the most meaningful in the world of energy storage is the levelized costs of energy storage (LCOES). The LCOES is an all-in-one indicator denoting the average cost for storing a unit of energy over the lifetime of the system. It is a very straightforward way to compare the economic viability of a system and it is computed by taking all the expenses of the system during its lifetime and divide that by the total energy that is supplied by the system during that time. The LCOES takes into account the capital expenses, operational expenses, lifetime, interest rate, heat-loss compensation and heat pump costs. It does not take into account the costs for decommissioning of the system after it is no longer in operation.

$$LCOES = \frac{\sum Investment\ costs + operational\ costs + interest + heat\ loss\ compensation + heat\ pump\ costs}{\sum Delivered\ energy\ from\ storage}$$

The LCOES is not to be confused with the LCOE. The aim here is to quantify the costs of STORING the energy, not to quantify the total costs of the energy, which is what the LCOE denotes. *Note that the LCOES is affected by the system efficiency (heat loss compensation) and is therefore not a 100 % independent indicator.*

Land use (m^2)

Nowadays, the heat infrastructure is fully underground and out of sight. In future energy systems, which require storage, some space will have to be sacrificed to integrate storage systems into the heat infrastructure. To minimize energy losses, such a storage system is best placed near the heart of the heat demand (since heat transportation through pipes brings about losses). For urban areas, this means valuable land will have to be used for this purpose. An ideal storage module would not take up any space, which is why the amount of land occupied to a storage module is an important criterium for a LSSTES system.

Suitability for peak-buffer application

The maximum thermal power of an LSSTES is also an important characteristic, which is not mentioned as one of the main indicators. Maximum thermal power is integrated into the ‘Suitability for peak-buffer application’ indicator.

LSSTES systems are almost always connected to a DHN, which roughly follows the heat demand profile of a typical household, meaning the peak demand will occur in winter. Especially during these times, solar heat production may be lower than demand or almost nothing at some times. At those times the entire peak demand has to be supplied from the LSSTES. As the LSSTES discharges during the winter, the temperature inside the storage drops, making it harder for the storage to supply the full peak demand as winter progresses. Designing the LSSTES to deliver more power is a possibility but this is often costly or troublesome from a technical point of view. It is therefore desirable, if possible, to have a LSSTES that can accommodate at least a fair share of the peak demand so that excessive investments into back-up power of peak buffer installations are not necessary.

Building-related GHG emissions

While it is true that LSSTES systems have significant potential to save on greenhouse gas emissions of the energy system they are integrated into, (when the heat is produced sustainably), it is also true that the greenhouse gas emissions associated with the construction of LSSTES systems can be significant.

There is large variability in the amount of material need for insulated versus non-insulated storage systems. The production processes of these materials can, depending on the material, be energy-intensive and involve high CO_2 emissions. These can be so high that a few years of (sustainable) energy storage are necessary to just negate the CO_2 emissions produced during the construction. This is often referred to as the CO_2 payback period. Since the calculation of CO_2 'savings' of a thermal energy storage system compared to conventional heating requires numerous assumptions and the compared storage systems are expected to score very much alike on the CO_2 savings, building emissions are chosen as a sustainability indicator.

Geological requirements

Each LSSTES system has different requirements regarding the underlying soil. Depending on the severity of these geological needs, some areas are not suitable to place a certain LSSTES system. Next to geological requirements, restrictions of legal and technical nature can also be deal-breakers, although the latter are generally less severe restrictions. Because of this, the demand for appropriate geology is chosen as the main indicator.

When looking at a specific case, the geology is fixed and the geological requirements are better viewed as preconditions than as performance indicators. From a more general point of view, a technology can be said to perform better if it can be deployed anywhere, regardless of the underground. Since this comparison aims to give a general view of the strengths and weaknesses of the LSSTES systems, the second option is chosen.

These are the performance indicators used to rate the performance of the LSSTES systems. Two other interlinked characteristics that do not rate performance but are nevertheless interesting to include in the discussion are the future **cost reduction potential** and **technological maturity**. The latter can be viewed as a potential for cost reduction potential through technological advances but also for performance improvement over time.

3 Large seasonal sensible thermal energy storage systems & Ecovat

This chapter discusses the LSSTES systems in greater detail by elaborating on characteristics, advantages, disadvantages and barriers to implementation. To enable a comparison of these systems to Ecovat, several requirements for LSSTES systems have been defined in paragraph 2.3.2 These will be discussed for each technology and a summarizing table for each system is included as a recap of the paragraph.

The four main LSSTES technologies are displayed in Figure 3-1.

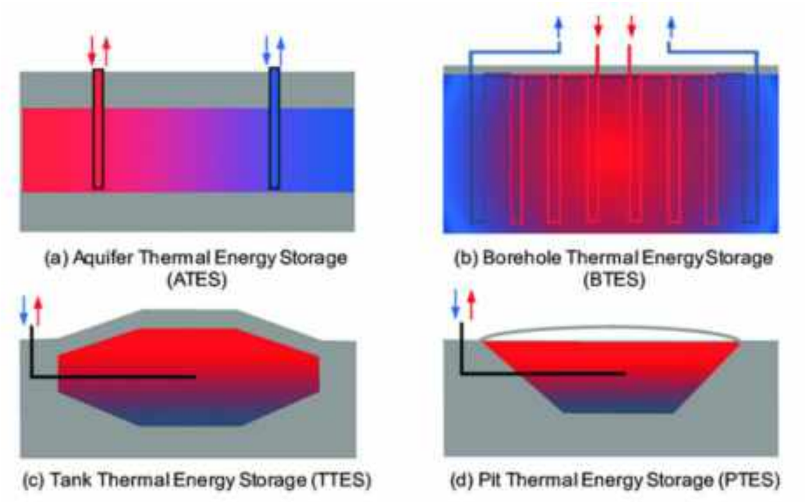


Figure 3-1: Four main LSSTES systems: [3]

3.1 ATES: Aquifer thermal energy storage (a)

An aquifer is a water-carrying layer in the underground. If such a layer is surrounded by soil layers possessing suitable characteristics, an aquifer can store heat (or cold) for long periods, which is the case in the majority of the areas in the Netherlands [3].

Water is directly injected and extracted from the aquifer, which is not insulated by any artificial materials. Because of this, ATES systems are prone to heat losses, more so than insulated systems (although the soil can be considered a fine insulating material as well). This is also one of the prime reasons ATES main area of application is low-temperature heating and cooling.

Typically, an ATES system is composed of two wells of which the filter screens are placed in the same aquifer (a doublet system). Warm water is extracted from one well for heating purposes. The warm water cools down by delivering heat to a building and is reinjected into the cold well. When there is cooling demand, the flow reverses (see Figure 3-2).

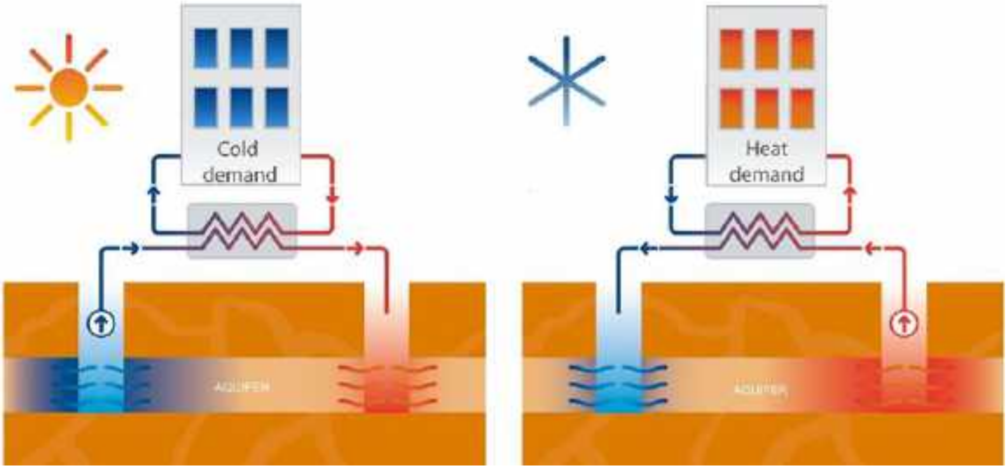


Figure 3-2 Workings of ATES two well system (IF technology) https://www.iftechnology.nl/aquifer-thermal-energy-storage-wko-in-dutch-is-catching-on-in-japan

Applications

The mode of operation shown in Figure 3-2 is by far the most common for ATES systems and is also called low-temperature ATES or in Dutch: warmte-koude opslag. ATES technology is mainly developed in the Netherlands, because of the many aquifers present in this delta area. Since 1985, more than 3 000 (licensed) systems have been realised, 99% of which serve as seasonal storage systems[4]. ATES systems are almost always used to provide heating and cooling of facilities with a large heat and cooling demand (as shown above). When ATES systems are used in this manner, the temperature levels of the cold and hot well are generally in between 5-20 degrees ˚C, shifting slightly as the seasons change. This application of ATES does not store excess heat, but merely stores the heat rejected during cooling of buildings. Because the supply temperature is only 15-20 ˚C, the heat must be upgraded via the use of a heat pump to allow for space heating and tap water preparation is generally not possible. In this regard, low-temperature ATES is very different than a high-temperature storage system, which seeks to store heat (renewably produced) heat from solar collectors etc.

Figure 3-3 shows where ATES systems are mostly applied.

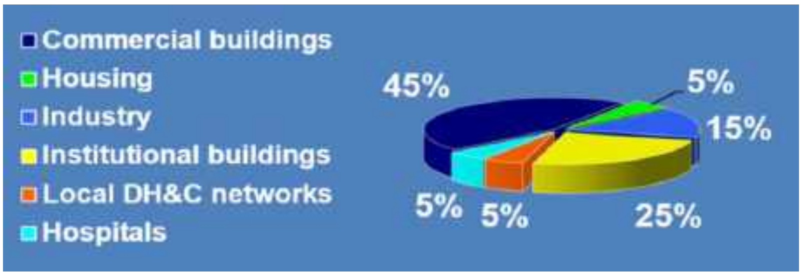


Figure 3-3: Subdivision of ATES projects in Europe by market sector (IFTech) [1]

Next to providing heating and cooling for large buildings, ATES systems can also be used to store high-temperature heat enabling direct heating of buildings and providing tap water without heat upgrading. In such a case, we speak of HT-ATES or HTO in Dutch (Hoge Temperatuur Opslag). This application is far less common and has remained in the research phase until now.

State of technology

In the Netherlands, ATES with storage temperatures > 30 ˚C has only been implemented in six projects [5]. So, there is a lot of experience with LT-ATES but a lot less with HT-ATES. Since the technologies overlap quite a lot, the experience gained with LT-ATES can certainly assist with HT-ATES deployment but there are also distinct differences that can cause serious trouble (as turned out in the research projects started in the '90s)[5]. After the disappointing results of these projects, the attention for HT-ATES subsided for some time. Currently, the technical problems that afflicted HT-ATES have been solved (mostly), spiking renewed interest in HT-ATES. Large scale successful reintroduction of HT-ATES is yet to be shown but the predominant opinion is that the technology is ready for it.

Technical and economic characterisation

When geological conditions required for successful ATES are present, ATES systems can store huge amounts of heat seasonally for low investment costs (CAPEX). Since aquifers are not insulated, they require a very large scale > 250 000 m^3 to attain a decent efficiency (50-75 %) for high-temperature storage. This means ATES systems are suitable to store very large amounts of heat, which is also the main area of application for Aquifer systems. The final efficiency of ATES is only reached after 5 years or more and is typically 50-75 %, depending mainly on the geology of the aquifer and hydraulic design. The efficiency is significantly less during the first years of operation because much of the injected heat is used to warm the aquifer-surrounding soil. After about 5 years the soil is warmed up and the recovery efficiency stabilizes. These so-called start-up losses imply that the heat extraction during the first years of operation is less and additional back-up heat sources must be present to compensate for this. Among the LSSTES systems, ATES systems are generally relatively cheap to make (low CAPEX) but do have higher operational costs (OPEX) than insulated systems. This makes ATES particularly useful when heat is available for a (very) low price. ATES does not take up much space above ground and the ground above the Aquifer can be used for almost all purposes, which is a strong benefit of the technology. For ATES systems, the main determinant for investment costs is the thermal power of the system. Typically, ATES systems are base-load systems since it is not cost-effective to dimension the system to supply peak demand or change the thermal output fast. Therefore, they are not well suited to serve as buffer systems and are always connected to systems that have multiple heat sources that can accommodate extra thermal power during peak demand (or a buffer system). ATES systems require very little building materials and have minimal building-related CO_2 emissions. In terms of costs, the LCOES of HT-ATES is among the lowest of the LSSTES systems. HT-ATES systems are expected to have a lifetime of about 25-30 years.

Barriers to implementation

- Complicated policy situation (difficulty acquiring permits)
- Geological requirements on the underground
- Limited experience with HT-ATES
- Risk for underperformance of the system, large uncertainty

Still, ATES faces some barriers to implementation. Next to a multitude of geological requirements, which are not met everywhere in the Netherlands, legal issues pertaining to permits and legislation can obstruct the deployment of HT-ATES systems as detailed policy guidelines are often missing. Furthermore, there is still limited experience with HT-ATES systems although pilot and demonstration projects have been commissioned in the past. Lastly, the risk of an underperforming system is larger for non-insulated systems (ATES & BTES) compared to insulated systems.

Summary

Advantages	Disadvantages
Investment costs are mainly determined by (peak) power, not by storage capacity	Not possible everywhere due to geological requirements
Very little to no land use and no visual obstruction above-ground. The above-laying ground can be used for a variety of applications.	Lack of detailed policy guidelines
Low specific investment costs (CAPEX) and LCOES	High operational costs
Low building-related CO_2 emissions	Minimal system size for HT-ATES can be very large (depending on geology)
Huge amounts of heat can be stored in aquifers	Not suitable for peak demand applications
Huge amounts of heat can be stored in aquifers Many LT-ATES systems have already been realised in the Netherlands	Heat supply from storage is lower during the first years of operation
	Efficiency is lower during the first years of operation
	Little experience with High-Temperature ATES

Table 3-1: Main (dis)advantages of HT-ATES in relation to other LSSTES systems.

3.2 BTES: Borehole thermal energy storage (b)

BTES systems are closed, not insulated systems in which excess heat is stored into a formation of rock or sediment. Thus, BTES uses the underground as a storage medium. BTES systems consist of multiple pipes (heat exchangers) drilled into the ground through which water flows. Heat is extracted from the soil by flowing cold water through the pipes. The water (or other media inside the pipe) takes up heat from the underground (by conduction). Conversely, heat is added to the soil by letting warm water flow through the pipes, heating the surrounding soil in which the heat is stored.

BTES systems consist of grouped boreholes filled with an often U-shaped hollow pipe through which the heat exchange medium (most often water) flows. These pipes can be placed in the ground either horizontally or vertically, as displayed in Figure 3-4. Grouping of such pipes yields the BTES system, for which many configurations are available.

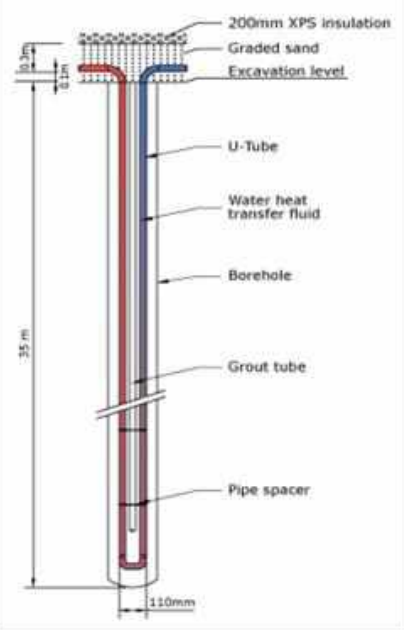


Figure 3-4: Left, horizontal U-tubes. Right, a cross-section of vertical borehole heat exchanger [4]

For high-temperature storage, vertical boreholes are used in which the boreholes are placed in a cylindrical shape, with a high-temperature zone in the middle and a low-temperature zone at the side edges of the cylinder. Figure 3-5 shows a top view of this configuration. This configuration is chosen to prevent mixing and heat losses. The boreholes are typically 30-100 metres deep with approximately 3-4 metres separation [6].

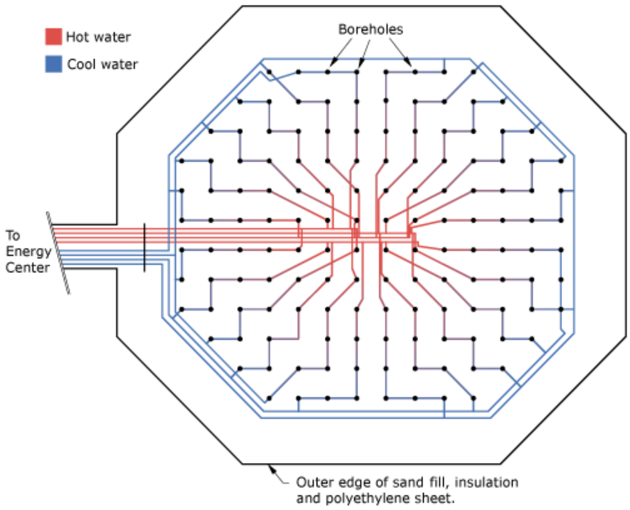


Figure 3-5: Top view of BTES heat exchanger pipes [4]

Applications

In terms of applications, BTES systems are utilized for the same purposes as ATES systems, which is mainly seasonal storage of heat and cold, thereby services large buildings with low-temperature heat and coolth. The working principle is the same as in ATES but the storage medium and heat transfer are different.

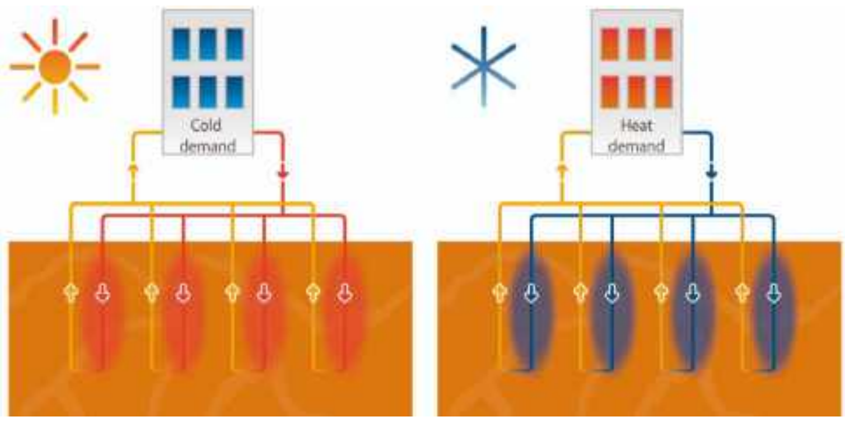


Figure 3-6 Working principle of seasonal BTES storage

https://www.iftechnology.com/borehole-thermal-energy-storage/

All BTES systems in the Netherlands are employed as low-temperature systems (WKO (warmte-koude opslag (heat-cold storage))), where the goal is not to store excess heat in the ground but to use the heat already present in the ground for heating and cooling of buildings. Similar to ATES, BTES systems can also be used to store excess heat, in which case the storage temperature is higher and the system is called High-Temperature BTES (HT-BTES). This mode of operation has received far less attention, although there have been some (foreign) HT-BTES projects and some HT-BTES systems are currently in commission.

State of technology

Research efforts in the Netherlands focus much more on HT-ATES than HT-BTES. Similar to ATES, virtually all BTES systems are low temperature and only a hand full are HT. In fact, the Netherlands has only seen one HT-

BTES system being commissioned (in Groningen). Therefore, much of the knowledge in HT-BTES is acquired in foreign projects, which are also scarce. Low-temperature BTES systems, on the other hand, are much more common in the Netherlands, similar to LT-ATES. From a technological viewpoint, HT-BTES is still in its infancy with a very limited amount of systems realised.

Future costs reduction potential

The main cost driver for BTES is drilling of the boreholes and installation of the geothermal probes, which is also where the most pressing need for cost reduction lies. A second cost-saving opportunity is to improve on the efficiency of HT-BTES systems by improving thermal performance modelling. Lastly, increasing the scale of BTES will yield large cost reduction potential. Together these factors might yield a significant reduction in costs. However, given the absence of research attention (in the Netherlands), I think it is very unlikely that this potential will be met.

Technical and economic characterisation

BTES, together with ATES form the non-insulated LSSTES systems. BTES systems are generally much smaller (in terms of storage capacity) than ATES systems and are often employed where there is no natural aquifer (or other geological conditions do not permit ATES) present or when the heat demand is lower than the minimal ATES system would be ideal for. BTES systems typically lose more than half of the heat that is injected (efficiency <~50%), which makes it a quite poor LSSTES system in terms of thermal performance. The maximum temperature of HT-BTES systems is often kept lower than the other LSSTES systems to prevent larger losses (i.e. max 80 °C). One of the most problematic features of HT-BTES is the slow heat transfer, implying low peak power. HT-BTES systems typically go up to only 0.5-1 MW (in and around the Netherlands) and are therefore not suitable to supply the entire peak demand [7]. To account for this, extra buffer vessels are often installed, which increase the total costs of the system. The BTES market seems to focus on smaller systems than the cases in this research represent. In terms of land use, BTES is comparable to ATES, as no visual obstruction or severe land-use limitation remains after commissioning. Whether all constructions can be put onto a BTES system will most likely depend on the depth of the system. In terms of building emissions, BTES, like ATES, requires little building materials and so the related carbon emissions are minor. BTES systems are expected to last for 50 years.

BTES systems are characterised by high investment costs per unit of produced peak power, which is why the systems are always designed to store rather than to (dis)charge fast. Since the losses are high, the heat compensation costs are also high. The OPEX is relatively low (compared to other non-insulated systems) but is moderate in comparison to insulated LSSTES systems. The LCOES of HT-BTES is, at least for tested cases, the highest of the LSSTES technologies.

Barriers to implementation

- Complicated policy situation
- Substantial requirements on underground
- Limited experience
- The risk for underperformance of the system
- Additional investments for buffer tanks are necessary

Similar to HT-ATES, HT-BTES faces some legal restrictions related to the energy balance, temperature of the underground and lacking detailed guidelines. Furthermore, the requirements of BTES on the underground are quite demanding (low groundwater flow, suitable soil characteristics and drillable soil) and it by no means self-evident that construction of BTES is a possibility on all sites. In terms of experience with previous systems, only one HT-BTES system is known in the Netherlands and a few more in foreign countries. Thus, the experience is very limited. Similar to HT-ATES, the heavy dependence on geology brings extra uncertainty and the risk of an underperforming system.

Summary

Advantages	Disadvantages
Very little to no land use and no visual obstruction above-ground.	Stringent geological demands
Fairly low investment costs for small systems	Legislative framework lacks, although the restrictions are less stringent than for HT-ATES.
Smaller systems are possible	Not suitable for peak demand applications due to slow conductive heat transfer
	Low storage efficiency / High thermal losses
Low building-related CO_2 emissions	Highest levelized costs
	Little experience with High-Temperature BTES

Table 3-2: Main (dis)advantages of HT-BTES in relation to other LSSTES systems.

3.3 TTES: Tank thermal energy storage (c)

Tanks are well-insulated systems that generally use water as storage medium. They can both use and open or closed circuit for heat exchange. Seasonal storage tanks are generally made out of concrete.

Figure 3-7: partially dug-in water storage tank (Solites)

(http://www.saisonalspeicher.de/Projekte/ProjekteinDeutschland/M%c3%bcnchen/tabid/416/Default.aspx#)

Figure 3-8: Water storage tank at Nebraska University

(https://news.unl.edu/newsrooms/today/article/tank-projects-help-cut-campus-energy-costs/)

Buried, elevated or above-ground

TTES storage systems are commonly built above-ground but sometimes the tanks are built partially above and partially below ground level (dug-in tanks). TTES that are partially or fully buried in the ground rely on certain (hydro-)geological conditions such as ground stability and absence of groundwater. Applications above the ground are less site-dependent. For reasons of better storage performances and aesthetics, it is often recommended to integrate the above-ground storages into the visible environment to reduce the visual obstruction. Underground construction via the conventional building method is more expensive than building above-ground, which is why tanks are rarely built completely underground [8].

Applications

Tanks are generally smaller in terms of storage volume than installations of the other LSSTES technologies (largest known tank used for seasonal storage is 12 000 m^3, Friedrichshafen). They are most often used to store hot water for times of peak demand, but can also serve as seasonal storage. Using a tank as peak-buffer makes the business case easier to close as there are much more (dis)charge cycles per unit of time (compared to seasonal storage). This comes in handy for high CAPEX tank systems. Designing larger tanks for TTES is an option but there have not been reports of designs able to reduce the specific investment costs below 90-100 €/m^3 [9]. Yet, tanks have some distinct advantages over the other LSSTES systems that make them an interesting seasonal storage option nonetheless.

State of technology

TTES systems are a market mature technology with ample systems realised. Tanks are much easier to design and less risky to construct than HT-ATES or HTBTES systems. There are less technical problems and uncertainties, which has enabled TTES systems to develop to a mature state in which there are no big risks for successful operation. Future technological improvements will aim at optimization rather than eliminating serious problems for successful operation. This also implies that the expected improvements in TTES systems will be minor [10].

Future cost reduction potential

TTES systems require high upfront capital investments and it appears to be troublesome to greatly reduce the need for these high capital investments in TTES systems, even if upscaling is taken into account (although for larger tanks this effect is still significant)[9]. Add to that the technical maturity of TTES and there is little future cost reduction potential to be expected. With that, it seems that TTES does not have much potential to greatly reduce investment costs and will have to focus on increasing the storage density and exergy retainment to compensate for this. This might be achieved through the use of pressurized storages or storage media other than water.

Technical and economic characterisation

Tanks enjoy high thermal efficiency thanks to insulation. The well-insulated character of a tank and material choice enables it to store water at high temperature (95 °C) without excessive heat losses. Another prime advantage of tanks is their independence of geological conditions, especially when constructed above-ground. Yet another benefit of tanks is the fact that the storage medium (water) is closed-off from the external environment, which is why the legal restrictions for tanks are much less stringent compared to systems that have their storage medium in contact with the surroundings (ATES & BTES). The land used by tanks can be minimal if the tank is entirely built underground but because of the higher costs of building underground, tanks are very rarely if ever built completely underground. If TTES systems are partially or entirely built above-ground, the land use can be obtrusive and measures should be taken to integrate the tank in the landscape to minimize visual obstructiveness. Tanks are very suitable to be used for high power applications as their heat exchange system can easily be designed to deliver high-power and change the thermal power quickly. Due to the large amount of building material needed to construct tanks and the fact that tanks are made of the energy-intensive concrete and steel, the building emissions of tanks are much larger than that of non-insulated systems. The reward for the high construction-related GHG emissions is a durable structure with a long lifetime.

Looking at the average cost for storing a unit of energy, tanks make up for the high initial investment with their long lifetime, low OPEX and high thermal efficiency. In the end, the levelized costs are not much higher than that of other LSSTES systems.

Barriers to implementation

- High CAPEX
- Limited possibility for upscaling
- Land use

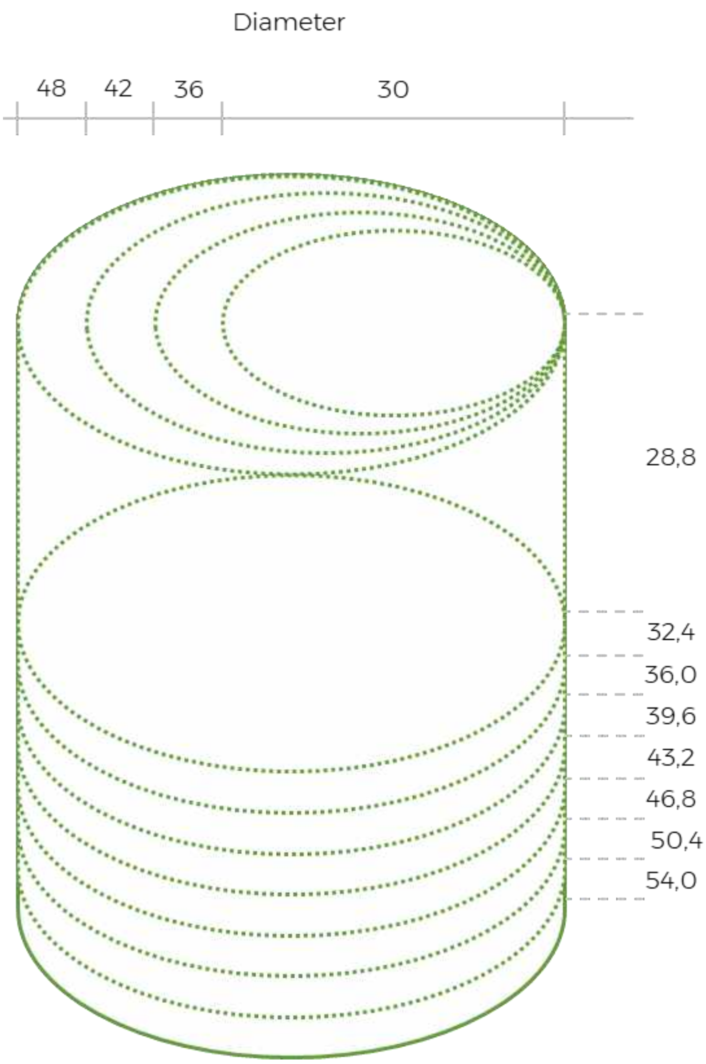
Summary

Advantages	Disadvantages
High storage efficiency	High initial investment costs
Above-ground: Can be built anywhere independent of geological conditions	
Very suitable for high-power applications	. Land use is considerably more in the case of (partially) above-ground application.
Able to store the highest temperature of LSSTES systems (95 ˚C)	
Much less legal restrictions than non-insulated systems	High building-related CO_2 emissions
Low operational expenses	
Plenty experience	

Table 3-3: Main (dis)advantages of TTES in relation to other LSSTES systems.

3.4 Ecovat

Ecovat is a tank, so (most of) the advantages and disadvantages named in the previous section also hold for Ecovat. Distinctions between Ecovat and regular TTES systems are summarized here.



Specifications:

- Tank volumes from 20,000 to 98,000 m3
- Storage capacity from 1.2 to 5.0 GWh-thermal (ΔT = 50 K)
- Charging and discharging capacities from 1.0 to 30.0 MW (thermal)
- Underground or partly above ground
- 750 to 8,000 homes per Ecovat

Ecovat portfolio

Ecovat systems are commercially available from 21 000 m^3 – 98 000 m^3 storage volume. In case of larger storage volume needs, multiple vessels can be built and connected. The largest Ecovat has as much larger storage volume than currently built TTES tanks (largest known is 12 000 m^3), which grants Ecovat the option to be utilized as seasonal storage much more effectively than smaller tanks while retaining the suitability to be used as a peak buffer. Ecovat has not yet built a commercial system but has realised a demo Ecovat to validate the working principles of the system. Ecovat spends much effort into innovation and technological improvement, hence significant improvements in technical performance and cost reduction are expected. Like TTES systems, the improvements are aimed at optimization, not so much alleviating true technical barriers to implementation. Larger tanks have a more favourable volume/surface ratio (improves efficiency), which, together with superior insulation material and insulative properties of the underground yield a very high storage efficiency (>85-95 %). The maximum storage temperature of Ecovat is 95 °C, similar to other tanks. Ecovat has higher investment costs than regular tank because of the unique building method of

Ecovat. This method allows the vessel to be constructed below the groundwater level and explains the large amounts of concrete needed to make the vessel strong enough to withstand external forces during construction. One major advantage of Ecovat compared to regular tanks is that the entire vessel is built underground, eliminating visual intrusiveness of the land above the tank. Furthermore, Ecovat makes use of variable inlet heights, making it possible to store both coolth and warmth in one tank. With that, it is a combined high-temperature and coolth storage. This is possible due to the principle of stratification, which is not utilized in all tank storages to the same degree as in Ecovat. As mentioned, Ecovat uses concrete, more than regular tanks. This leads to a fair amount of building-related CO_2 emissions. The CO_2 payback time is around 1.9-2.5 years for respectively the largest and smallest Ecovat (assuming all stored heat is sustainable).

Cost-wise, Ecovat vessels are CAPEX dominant. The OPEX, heat pump costs and energy losses amount to small costs because of the high thermal efficiency and structural integrity of the vessel. The levelized costs are somewhat higher at smaller project scales but become comparable for the larger projects.

Barriers to implementation

- Similar to TTES, high CAPEX is the main barrier to implementation. Luckily, land use is not a barrier to implementation for Ecovat.
- No commercial systems operational yet

Summary

<table>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td>Highest storage efficiency of LSSTES</td><td rowspan="4">High initial investment costs</td></tr>
<tr><td>Can be built almost anywhere, independent of geological conditions</td></tr>
<tr><td>Very suitable for high-power applications</td></tr>
<tr><td>Able to store the highest temperature of LSSTES systems (95 ˚C)</td></tr>
<tr><td>Much less legal restrictions than non-insulated systems</td><td rowspan="3">High building-related CO_2 emissions.</td></tr>
<tr><td>Entirely built underground. No visual obstruction above-ground. The above-laying ground can be used for a variety of applications.</td></tr>
<tr><td>Can provide heating and cooling from one tank due to stratification and variable inlets</td></tr>
</table>

Table 3-4: Main (dis)advantages of Ecovat in relation to other LSSTES systems.

3.5 PTES & WGTES: Pit thermal energy storage (d)

In pit storage systems, large, shallow dug, lined pits with insulated covers are used to hold a thermal storage medium that is either water or a water-gravel mixture. The pit, which is usually 5-15 metres deep, is usually dug with inclined walls. The excavated soil is then used to elevate the surroundings of the pit and create extra storage volume, simultaneously saving on costs for removing the left-over soil (Figure 3-9).

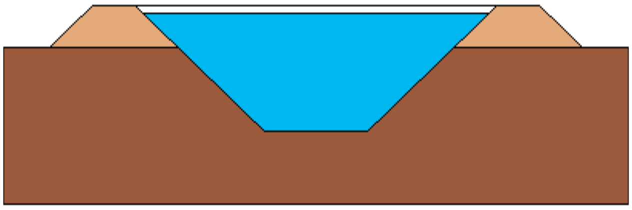


Figure 3-9: Schematic side-view of pit store [2]

Figure 3:10 Pit of PTES system without cap [11]

Pit stores are often classified according to their storage medium. When water is used, we speak of Pit Thermal Energy Storage (PTES), when water-gravel is used, we speak of Water-Gravel Thermal Energy Storage (WGTES) (Figure 3-11).

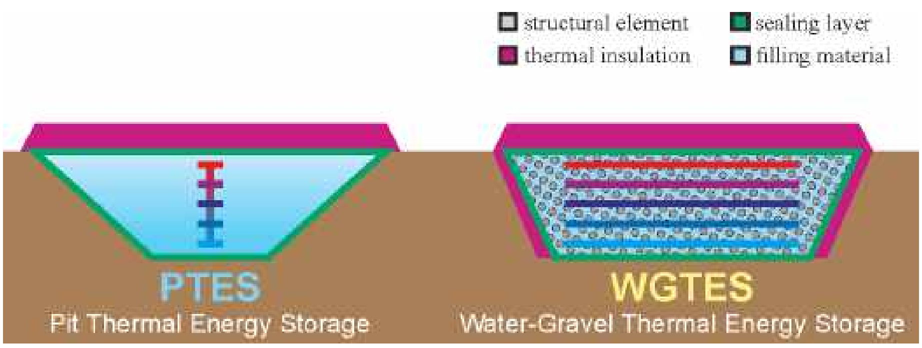


Figure 3-11: Subdivision of pit storage systems according to storage medium [28]

WGTES has a lower energy storage density than PTES (due to the water-gravel mixture having a lower volumetric heat capacity), which causes WGTES systems to be 1.3 to 2 times as large to achieve the same storage capacity compared to PTES [11]. Both variants use thermal insulation to cover up the lid of the pit. The sides of the pit are generally not insulated in PTES, in contrast to WGTES. PTES and WGTES both use liners to seal of the contents of the pit from the surrounding soil. In PTES, water is the storage medium, which allows the system to be open (although it can also function on a closed system). WGTES stores cannot pump the water-gravel mixture out of the pit and thus are forced to use a closed system with (coiled) heat exchangers in the pit. PTES oftentimes makes use of a floating lid in contrast to WGTES, which can be statically loaded due to the solid content. Therefore, the surface can be used for other purposes and no complex coverings are necessary [12].

The lower energy storage density of WGTES (and troublesome heat exchange) compared to PTES is probably one of the main reasons why WGTES systems have seen limited scaling-up in the previous decade. This is in sharp contrast to PTES systems, of which five very large storages have been commissioned in the last decade. For this reason, PTES systems are deemed most likely to dominate the future pit store market and hence the remainder of this paragraph will focus on PTES.

Applications

PTES systems are almost always used for large scale seasonal storage of solar heat in combination with a DHN connection.

State of technology

The development of pit stores has mainly taken place in Germany, Sweden and Denmark, as many pits have been built as part of research projects in those countries. At first, smaller PTES were built to prove the concept in the '90s (800 – 10 000 m^3). Around 2010, tremendous scaling up of PTES systems is observed and five large PTES systems have been realised (62 000 – 203 000 m^3)[13]. PTES is sufficiently developed to be deployed on a large scale and function properly at relatively low investment costs but there are still problems that PTES has to overcome. Limited lifetime of the liner material (i.e. ~15 years) at high-temperature exposure (i.e. >75 °C) and higher thermal losses than expected are such problems [2]. All in all, PTES can be said to be a mature technology with little significant further technological advances expected.

Potential for future cost reduction

The main cost-reducing factor for PTES is increasing the size of the storage to

1. Lower the investment costs per unit of storage volume and
2. Improve the efficiency of the system.

PTES systems can also save costs by using more durable liner materials to extend the lifetime of the pit store. The latter is currently being researched heavily and the former has already been achieved. With that, it is not expected that PTES will see a radical reduction in costs anymore [10].

Technical and economic characterisation

Even though PTES systems are insulated at the top, they can still lose a relatively large fraction of their heat. This is because the sides and bottom are not insulated and because the geometry of the store is far from optimal. For PTES systems, the maximum storage temperature and lifetime are related. Currently, there are no liner materials than can withstand high-temperature (95 °C) exposure for a long duration (i.e. 10+ years), although much research is ongoing and new liner materials with a 20+ year lifetime at 95 °C are under development as we speak. Until these materials have proven themselves, this means that either lifetime has to be sacrificed if high storage temperature is required, or the storage temperature should be reduced to increase the lifespan of the liner materials. The latter is often preferred, yielding a maximum storage temperature of ~80 °C with a lifetime of about 20 years. Land use is the main barrier to full market acceptance for PTES. Pit stores are generally no deeper than 15 metres (due to troublesome construction below groundwater level), implying that scaling-up should come from larger width and length of the store, increasing the land demands for the storage pit. Especially for WGTES systems, the lower volumetric storage capacity aggravates this problem and increases the demand for land to achieve similar storage capacity even more. This is most likely the primary reason why WGTES stores have not seen a scale-up to the degree that PTES has. Additionally, the pit is always elevated above ground-level, making the storage module quite obstructive and simultaneously rendering the entire surface area covered unusable (in case of a floating lid). Another major downside of pits is that they can only be constructed in areas that have low groundwater level. PTES systems are almost as suitable for high-power applications as tanks and Ecovat. Building emissions are moderate.

The specific capital expenses for pits can be very low (in the range of 20-40 (€/m^3)) if the system size is large (> 50 000 m^3) [10][2][5]. This is the major advantage of pit stores. If the system is designed properly pits performs well on LCOES.

Barriers to implementation

- The main barrier for PTES is the excessive demand for land needed to acquire large storage capacities. The shallowness of the Pit and the above-ground character make PTES systems very obtrusive and are a true deal-breaker for urban areas where such an amount of land cannot be sacrificed.
- Construction of pits in regions of high groundwater levels is troublesome if not impossible. Since the pits are not insulated at the bottom and sides, large heat losses are expected where the geological environment is not optimal.
- The last barrier is the currently limited lifetime of PTES systems (about 20 years). This is not a true deal breaker but this life is considered quite short compared to the other LSSTES systems.

Summary

Advantages	Disadvantages
Low specific investment 20-40 (€/m³) for > 50 000 m³ systems.	Very land-use intensive. The land is rendered unusable and the pit is often considered visually obtrusive
less legal restrictions than non-insulated systems	Can only be built in places that have low groundwater level
Low LCOES	Maximum storage temperature is limited by liner materials (to 80°C)
suitable for high-power applications	Lifetime is currently in the order of (only) 20 years
Multiple large scale systems operational	Current PTES systems operate at low efficiency, despite their insulation

Table 3-5: Main (dis)advantages of PTES in relation to other LSSTES systems.

4 Performance assessment

The previous chapter discussed the LSSTES systems and Ecovat mostly in a qualitative manner. This chapter continues the discussion by quantifying the performance of the technologies using the requirements of LSSTES systems defined in chapter 2 and showing how the systems compare.

4.1 Performance indicators of LSSTES

Some of the LSSTES requirements are rated qualitatively, some quantitively.

- The qualitative indicators are scored on a five-point scale, from very bad to excellent. The symbols used for this are --, -, +-, + and ++.
- The quantitative indicators are expressed in values with a certain unit as mentioned in the text.

The indicators used in the assessment are:

1. Levelized Costs of Energy Storage (LCOES) (€/GJ)
2. Storage efficiency (%)
3. Maximum temperature (˚C)
4. Land use (m^2)
5. Geological requirements
6. Suitability for peak-buffer application
7. Building emissions

For elaboration on these indicators please see section 2.3.2

4.2 Case definition and main assumptions

The comparison is based on the hypothetical yet common situation in which a number of households, corresponding to certain annual heat demand, are connected to a DHN and require LSSTES heat storage to be integrated into the heat infrastructure. All storages should be able to deliver that heat after storage losses have occurred. So the heat demand fixates the necessary storage capacity (together with efficiency), which in turn determines the remaining properties of the storage.

Since each technology has its niche in terms of ideal storage volume, temperature etc, the LSSTES system performance will vary across a variety of heat demand cases. To account for this, multiple heat demand cases (project sizes) are used. These cases are based on the portfolio of Ecovat vessels because this research aims to gauge the market niche of Ecovat in relation to other LSSTES systems. Four of such cases are used as displayed in the table below. Case 3 is the main case (also base-case) and most of the results displayed in this chapter are valid for that case. The method of the calculation is the same for all cases, only the heat demand and with that storage characteristics are different. More details on the calculation of the other cases and the outcomes can be found in appendix 8.

Case #	Ecovat Storage Volume (m^3)	Heat delivered from storage (MWh)	Project size (houses)	Fraction of heat demand from Storage
1	20 000	1500	700	25%
2	50 000	4000	2000	25%
3	100 000	7220	3500	25%
4	200 000 (2 tanks)	14420	7000	25%

Table 4-1: Project characteristics of the four cases

The cases are characterised by some assumptions. The main of which are:

- 25% of the total heat demand is supplied from the storage, 75% is directly delivered and bypasses the storage module.
- Valid for Case 3:
  The total heat demand is 32,500 MWh, corresponding to the heat demand of approximately 3,500 homes (30 GJ/household). Correspondingly, the annual heat supply from the storage is 7216 MWh_{th}
- The storages complete one (dis)charge cycle per year
- The Weighted Average Cost of Capital (WACC) is between 4% for all projects.
- Apart from standard losses, HT-ATES and HT-BTES suffer from start-up losses since the efficiency is lower in the first years of operation. The efficiency is assumed to increase linearly from 30% in the first year to the final efficiency in year 5. The extra heat losses are compensated for by purchasing extra heat.
- The difference between the initial groundwater temperature and the temperature level to which discharge is possible is also considered heat loss since it is none retrievable heat for all systems.
- The (yearly) OPEX is taken as a % estimate of the CAPEX if no specific data was available.
- The price of charging of the storage is not included in the LCOES since the aim is to quantify the costs of storage, not production & storage. The heat that is lost is paid for since that is the amount of heat that has to be produced extra. The costs of this extra produced heat are 10 €/GJ.
- For TTES the largest tank possible is assumed 20,000 m3. If more storage volume is necessary, multiple tanks are built to reach adequate storage volume.
- ATES and BTES systems are designed to provide 50 % of peak demand power. TTES, Ecovat and PTES deliver 100 % of the peak demand. Costs for additional peak power of peak buffer vessels are not included in the comparison.

Further discussion regarding the assumptions made, methods of calculations and the numbers used for the calculations are included in the appendices. There a table with all the input parameter has been included.

4.3 Results of the main case (3) indicator comparison

Technology	Storage Volume[1]	Efficiency	Temperature	LCOES	investment costs	Lifetime	Land use	Peak demand	Requirements on geology	Building emissions
Units →	*(m^3)*	*(%)*	*(°C)*	*(€/GJ)* [2]	*(€/MWh)* [3]	*(years)*	*(m^2)*	--, -, +-, +, ++ [5]		
Ecovat	98 000	90 %	90 °C	25 €/GJ	1850 *(€/MWh)*	50	0 or 2200 m^2 [4]	++	+	--
TTES	125 000 [1]	70 %	90 °C	29.5 €/GJ	1350 *(€/MWh)*	50	1700- 6500 m^2 [4]	++	++	-
ATES	250 000	70 %	90 °C	20.3 €/GJ	150-300 €/kW [3] 160 *(€/MWh)*	25	0 m^2	-	-	++
BTES	480 000	50 %	80 °C	31.2 €/GJ	715 *(€/MWh)*	50	0 m^2	--	--	++
PTES	155 000	75 %	80 °C	19.9 €/GJ	430 *(€/MWh)*	20	14 500 m^2	++	--	+-

Table 4-2: Summary of performance indicator values for case 3

1. If the storage volume of TTES needs to exceed, it is assumed that multiple tanks of size 20 000 m^3 are built to reach the necessary storage volume.
2. The levelized costs of energy storage denote the costs to store a GJ of thermal energy. Not all energy will have to be stored and thus the LCOES can be higher than the total costs of heat on project level.
3. The investment costs for HT-ATES are determined more so by required power than storage volume, hence a price range per kW is used as well as a price estimate of storage volume.
4. TTES is always partially or entirely above-ground, different tank shapes (long and thin or short and thick) are possible, causing different land use. Furthermore, some tanks are covered with sand to reduce the visual impact of the tank and integrate the tank into the environment (taking up more space than a freestanding tank would). This causes a large spread in land use. For Ecovat, the land above the vessel can be used but not all constructions are possible, so it is debatable whether the land is 'used' or not. The 2200 m^2 is the surface on which limitations hold for construction of buildings.
5. The last three columns display the criteria that cannot be dismissed but a hard to quantify with a single indicator. Therefore, the choice is made to rate the performance of each technology qualitatively, using a five-scale rating from --, to ++. The higher the score, the better the performance, so if a technology scores '++' on building emissions, this means that the technology has low building emissions. Similarly, '++' for requirements on geology means that there are very little to none requirements on geology and that the technology is widely implementable.

The radar plots below display the quantitative indicators of Table 4-2, each along a different axis. The black line depicts a fictional ideal storage unit and shows that the highest scores reach to the outer bounds of the radar. Accordingly, the lowest possible score is the origin of the plot. At the end of the axis, the variable and the axis range is displayed. For example, the ideal score for LCOES is 0 and the lowest score is the most expensive: 33.4 EUR/GJ. Each storage module can be characterised by the shape of the plot. The degree to which a perfect diamond is approached is a measure for the performance of the system. Figure 4-2 shows the LSSTES systems displayed in the format of the ideal storage unit (Figure 4-1). Further explanation on next page

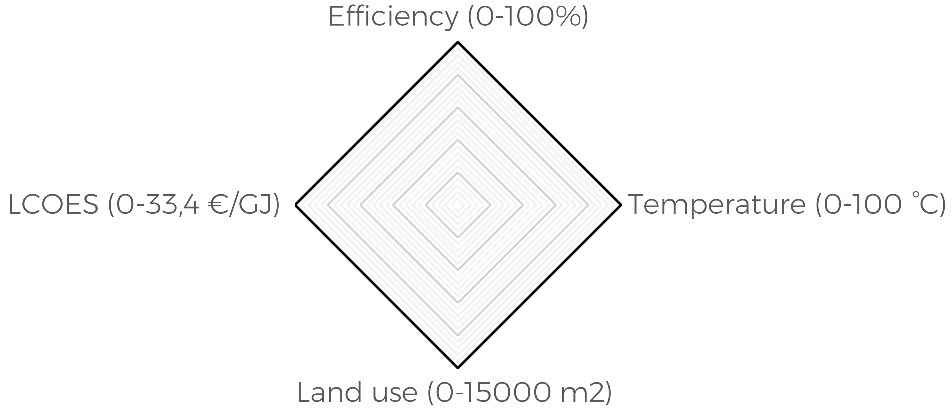


Figure 4-1: black line depicts the ideal storage unit

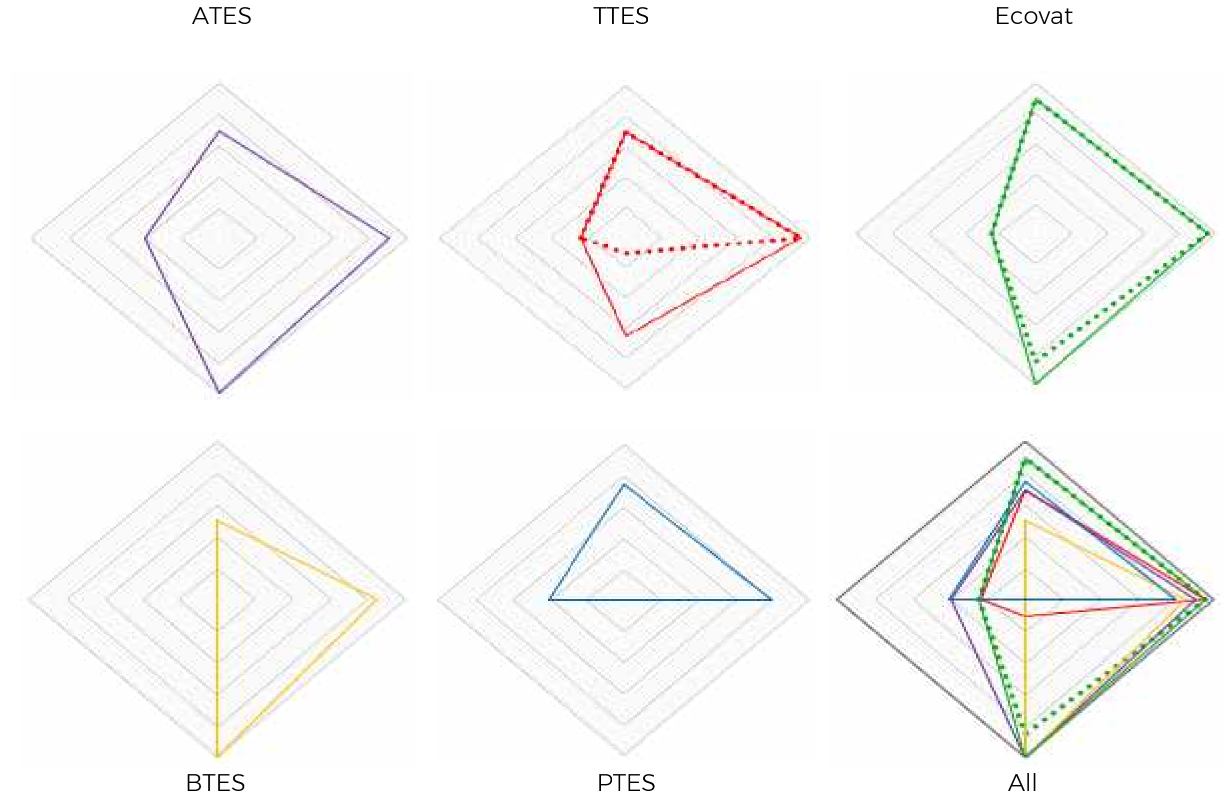


Figure 4-2: Radar plot of quantitative indicators for all LSSTES systems

The first 5 plots (left to right) are individual systems. The last plot displays all of them simultaneously in one plot for comparison with the ideal storage outlining the outer edges of the plot in grey. A larger version for improved visibility is included in (Figure 4-3). The dashed lines at TTES is the scenario in which the tank is covered with a layer of sand to integrate the tank into the landscape. This takes up more land, which is why the dashed line scores lower. For Ecovat, the dashed line is the scenario in which the land above the vessel is regarded as 'used'. The full line assumes Ecovat does not use land. To enable a more clear comparison between the technologies a bigger version of the last plot is depicted below.

From the radar plots the following can be derived:

- Ecovat is the most efficient storage system. PTES, ATES and TTES are very close together and BTES is significantly less efficient.
- PTES and ATES are the cheapest option. Ecovat is second. TTES and BTES systems are more expensive (under tested conditions)
- PTES and TTES use most land. Ecovat, ATES and BTES do not use land or only little
- Storage temperature shows only small differences

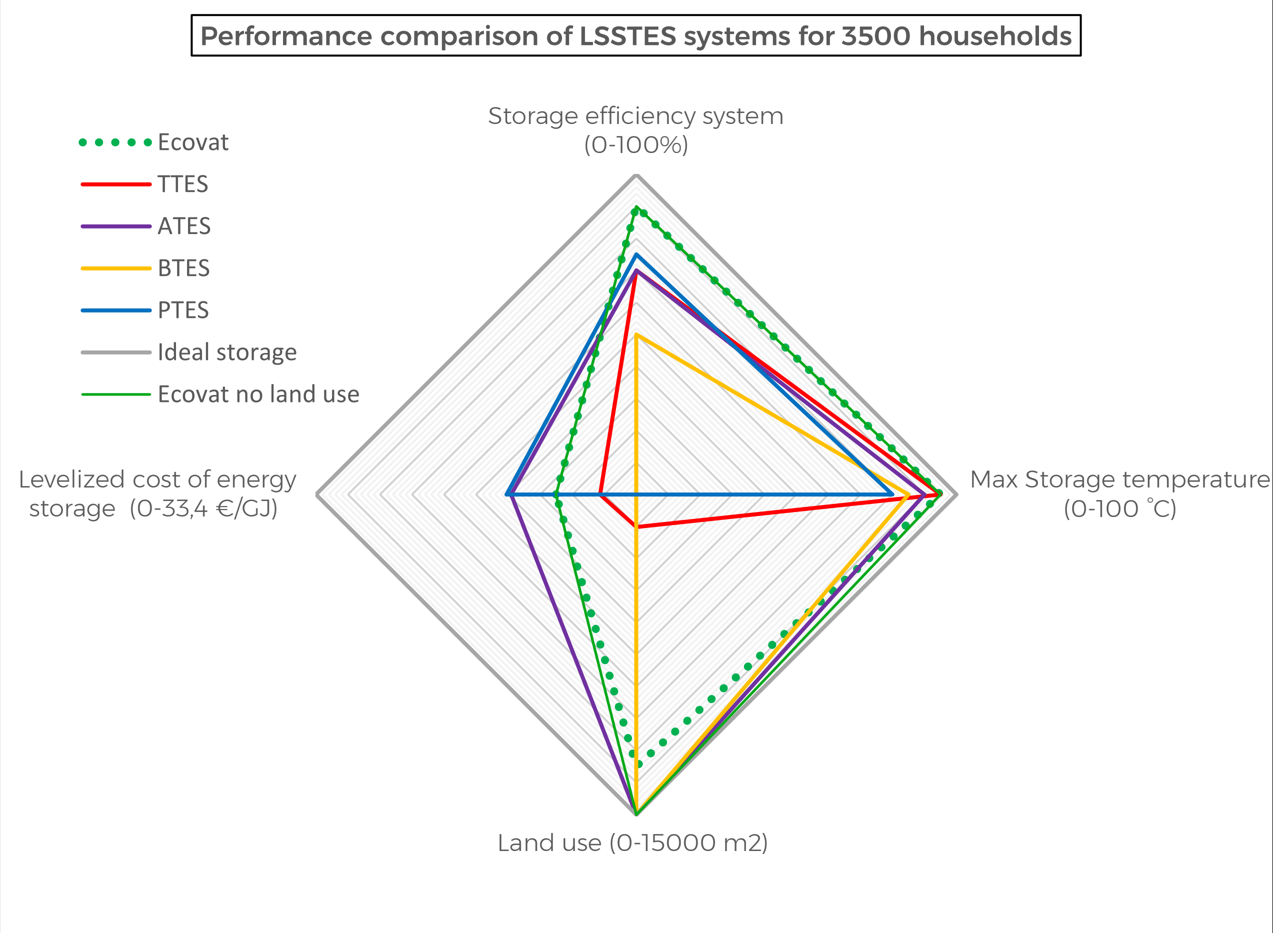


Figure 4-3: Enlarged radar plot of all LSSTES systems and the ideal storage unit

The different colours of in the columns below display the contribution of the CAPEX, OPEX, interest, cost of heat and the heat pump costs to the total LCOES. Each technology is represented for two scenarios, one in which the price of heat is 2.5 and 10 EUR/GJ. The black bars indicate the margin in LCOES due to uncertainty in system efficiency. The effects of other uncertainties are not display in this graph. Notably the systems that have a large range in efficiency have a large spread in costs, especially when the price of heat is high. This is clear in the ATES-10 and BTES-10 cases. This graph is valid for the 3500 households project scale (base case). All technologies are displayed for completeness although it is questionable whether BTES and TTES would be realised at this scale.

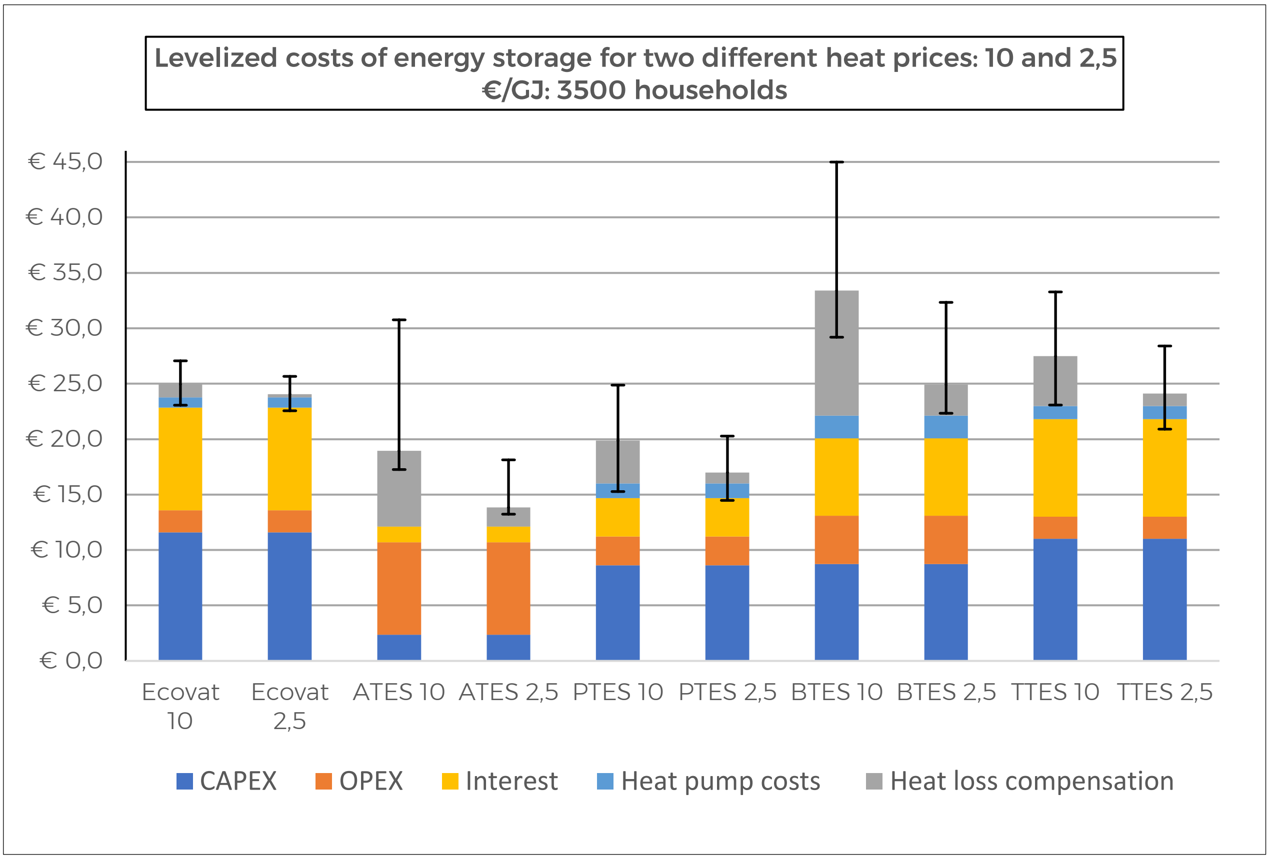


Figure 4-4: Levelized costs of energy storage for two different heat prices: 10 and 2,5 EUR/GJ, for 3500 households

The levelized cost of energy storage tends to decrease as the project size (households connected) increases. This familiar 'economy of scale' effect is true for most of the LSSTES technologies. Based on the four earlier-defined cases, the LCOES can be estimated for projects with an 'in between' size of the cases. This estimation is shown by the trendlines in the graph below. HT-BTES (blue) is typically a smaller-scale application and is thus only shown for 700 households. HT-ATES has a minimum of 3500 households and thus only the data for 3500 and 7000 households is shown. For TTES no cost reduction in sizes over 700 households is observed since the max size is already reached and the same tanks are replicated to reach the total storage capacity. This also goes for Ecovat from 3500 households and more. Trendlines for Ecovat and PTES are included.

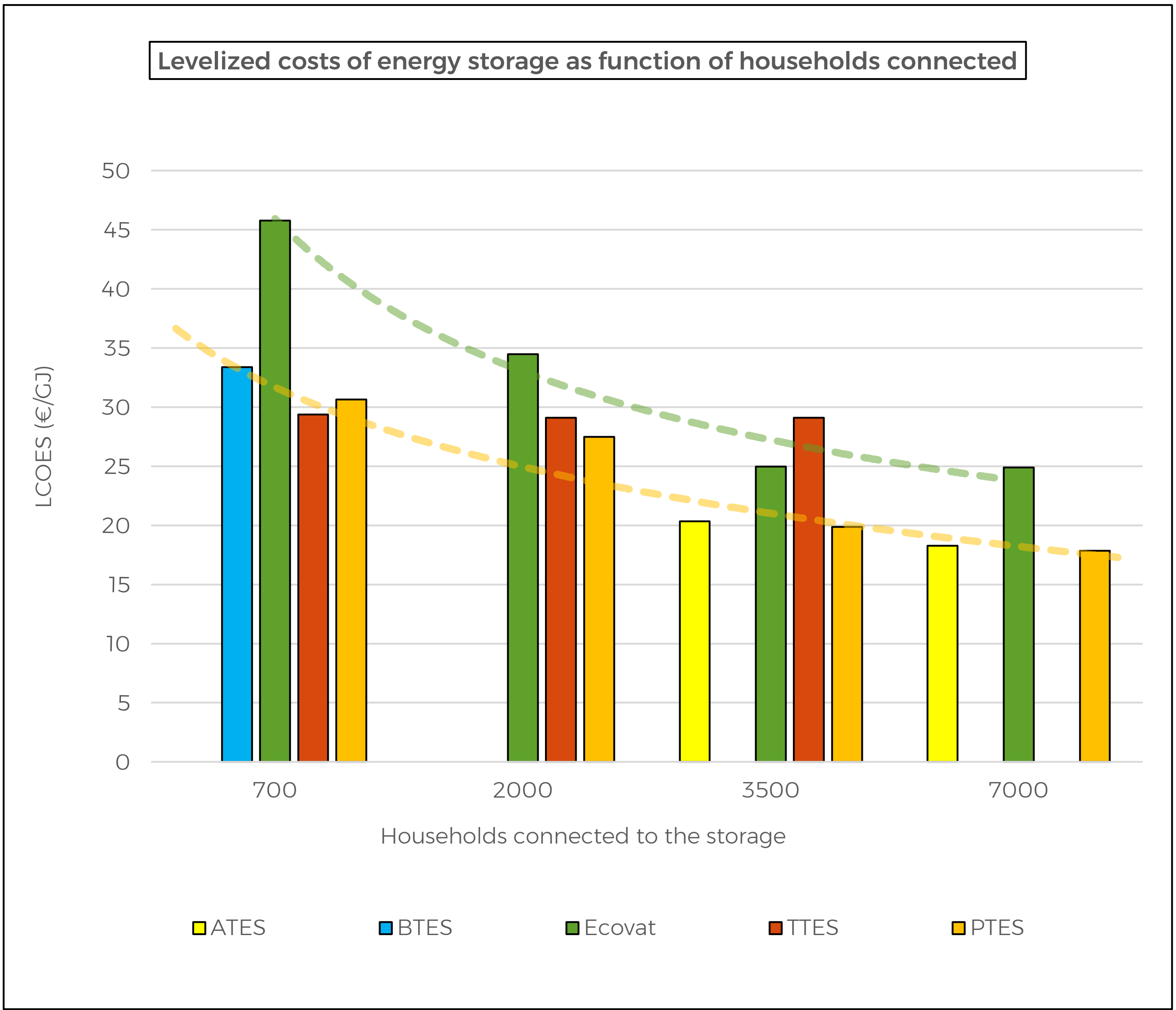


Figure 4-5: Levelized costs of energy storage as function of households connected

4.4 Sensitivity analysis

As you have noted in the LCOES graph from the previous section, uncertainties in the price of heat and efficiency can have a substantial effect on the total average costs of storing a unit of energy. Obviously, there are more parameters which are uncertain and they also bring about an error margin of the costs estimates of these graphs. To account for this effect and enable the formulation of rounded conclusions, a sensitivity analysis is performed. The main result s of the analysis are discussed. The full outcome of the analysis is included in the appendix.

in general, the results show that the LCOES is in the range of 20-35 EUR/GJ and that the errors margins by individual parameters are in the order of a few EUR/GJ. On average, efficiency causes the largest spread, followed by CAPEX and lifetime, although the latter two differ substantially per technology. Uncertainty in OPEX and WACC has a low impact on the LCOES. For all technologies, the maximal compounded error of the individual parameters is very large, approximately 10-40 EUR/GJ, although it is an extremely unlikely case that all these errors will compound simultaneously.

For Ecovat, the uncertainty of the system costs mainly originates from the uncertainty in lifetime. The uncertainty in CAPEX, WACC and efficiency is rather small because of the closed nature of the system. This means that Ecovat is much less dependent on external factors such as the price of heat for the LCOES outcome. All in all, the total spread for Ecovat is on the lower end of the spectrum compared to the other technologies.

4.5 Summary performance comparison

The performance assessment for the base case did not produce a clear 'winning' LSSTES system. There was no system that 'won' on all the indicator and so it is clear that each system has its strong points, weaknesses and niche within the energy storage market. The largest variation between the systems is in the requirements of underlying geology, suitability for peak demand coverage, land use and commissionable storage capacity . In terms of economic performance there was also variability but a significant part of this variation was within the margins produced by uncertainty as the sensitivity analysis showed. In terms of market competition, PTES and ATES systems are identified as the strongest competitors of Ecovat.

BTES and TTES are deemed inappropriate systems for the intended project size. In BTES this is because the largest systems known around the Netherlands are only 0.5-1 MW peak power[7], while the project requires a peak demand power of 12 MW, meaning virtually the entire peak should be supplied via another heat source which will require significant extra costs. In the case of TTES, about 6 tanks of 20 000 m^3 will be required to amount to enough storage volume to store enough heat. This is technically possible but as the analysis point out, it is not an optimal or convenient solution.

Levelized costs of energy storage and expected costs development

In terms of costs, the LCOES values of ATES and PTES are lowest at a shared ~20 EUR/GJ. Ecovat covers middle ground together with TTES at 25 and 27.5 EUR/GJ respectively and finally BTES is more expensive at 34

EUR/GJ. Systems with lower efficiency and especially systems with high uncertainty in efficiency have a large spread in costs at a high price of heat. This is significantly less at lower heat prices. So, the more efficient systems with a lower uncertainty (in efficiency) are more robust and show less LCOES variation as the heat price changes. In this regard, Ecovat has the lowest uncertainty and the lowest cost spread.

The build-up of the LCOES for Ecovat mainly consists of CAPEX and interest with low OPEX, heat loss compensation and heat pump costs. This also holds for TTES although the heat loss compensation and OPEX is a bit higher. ATES systems are characterised by low CAPEX, high OPEX and – depending on the efficiency – high costs for heat compensation. PTES systems are quite moderate on all costs. BTES systems are least efficient and have high heat compensation costs. The other costs are all moderate but sum up to high costs, especially when the investments for back-up power or peak buffers are accounted for.

Eventually, PTES and ATES systems are cheapest for the base-case scenario (although the extra back-up power for ATES is not included in the calculations).

The following findings were inferred from comparing the cases:

- Cost reduction with upscaling is most apparent for Ecovat and PTES systems. This effect is mainly because of increased efficiency and lowered investment costs per unit storage volume related to upscaling.
- BTES and ATES systems enjoy this effect to a lesser degree since adding storage volume is not costly. It is predominantly the peak power that determines the investment and since that grows linearly with project size, the cost reduction effect seems somewhat less significant for BTES.
- ATES projects do become cheaper at larger projects but this is mainly because of the increased storage efficiency. However, this effect is not yet strongly observed at the project sizes discussed in this research.
- TTES systems cannot scale up indefinitely and the lowest investment costs per unit storage volume seem to be reached at systems of about 20 000-30 000 m^3.

In terms of expected price development, the least market mature technologies will have larger cost reduction potential for the future. The more mature technologies will see the majority of costs reduction coming from the 'economy of scale' effect as the storages become larger, due to improved efficiency and lower investment costs per unit of storage volume. Most LSSTES technologies are already quite mature and will have to rely on upscaling for the majority of their cost-reduction potential. Ecovat, having realised no commercial systems yet, is an exception to this rule. This flip side of this disadvantage is that there is ample room for cost reduction potential and so Ecovat expects to reduce the investments costs by 20 % in the coming 5 years.

Storage efficiency and temperature

Ecovat has the highest storage efficiency of all systems (90%) by a fair margin (15%). This is mainly beneficial in situations where the price of heat is high. In terms of storage temperature, the systems show little variation (80-90 °C). This is because the storage temperature is limited by 1. The boiling point of water and 2. The available temperature of (sustainable) heat sources. The high efficiency of Ecovat and ability to discharge the vessel to 20 °C by using stratification and heat pumps causes Ecovat to have the highest energy density and therefore store most energy in an equal volume.

Land use

In terms of land use, PTES systems use by far the largest amount of space. Above-ground TTES systems integrated into the landscape also use a fair amount of land but already much less. Ecovat, BTES and ATES systems are completely underground and can be said to have no land use, although some would object by stating that in the case of Ecovat the constructional possibilities with the above-lying land are limited. They would be right. In the case of ATES this is no problem.

Lifetime and suitability for peak demand

In terms of durability Ecovat, TTES and BTES systems are the most durable system with an estimated lifetime of 50 years, compared to about 25 years for ATES, 20 for PTES.

PTES, TTES and Ecovat systems are suitable to supply almost if not all the peak demand, whereas ATES is not suitable to supply peak power and generally supplies about 50% of the peak. This means an extra buffer or additional heat sources must be installed in the DHN, costs which are not included in this comparison. For BTES, this problem is even much worse.

Requirements of geology

Restrictions imposed by the underlying ground are most severe for BTES, ATES and PTES. For BTES to be a possibility, the groundwater flow must be nihil at the right depth, the soil must be drillable, possess moderate thermal conductivity and preferably be surrounded with low conductive soil. This means it is certainly not a evident that BTES can be employed everywhere.

PTES must be constructed above the groundwater level to avoid excessive convective heat losses. This is not so much a problem in countries with low groundwater levels, but in the Netherlands, this renders the construction of PTES impossible or at least very troublesome in almost all areas of the Netherlands.

ATES systems also have strict requirements for the underground, although most of the underground in the Netherlands seems to be particularly suitable for LT-ATES exploitation. Whether this is also the case for HT-ATES is currently being investigated.

Ecovat has as only requirements the possibility for drilling, which is possible almost everywhere. Above-ground TTES systems have the advantage of not being dependant on the underground at all.

Building-related GHG emissions

In terms of building-related GHG emissions, BTES and ATES have the lowest greenhouse gas emissions associated with construction. PTES covers middle-ground and uses more energy for excavation and material. Tanks use more material than PTES per storage volume. Ecovat has much thicker walls than general TTES because of underground construction and has the highest building emissions associated with construction.

5

5 Conclusions

The main goal of this research was to see how Ecovat compares to other LSSTES technologies within the project sizes Ecovat can accommodate. To do this, seven performance indicators and four cases were used, of which one was analysed in detail. This case assumes a DHN supplying 3500 households with heat by using an HT-storage module integrated. The analysis indicated a large variety of scores across the performance indicators and project sizes. This implies that each technology inhabits its niche within the market. The following conclusions, if not stated otherwise, are valid for the main case.

Levelized costs of Energy storage

In terms of levelized costs of energy storage, ATES and PTES are cheapest at a shared ~20 EUR/GJ. Ecovat and TTES cover middle ground at 25 EUR/GJ and 27.5 EUR/GJ respectively and finally BTES is more expensive at 34 EUR/GJ. Typically, the majority of the costs for LSSTES systems are CAPEX and interest. OPEX and additional expenses are typically much lower. This makes the high CAPEX a shared barrier to implementation for the LSSTES technologies.

To account for the uncertainty in the accurateness of the input parameters, a sensitivity analysis was carried out to gauge the effect on the LCOES. The results show that the LCOES is in the range of 20-35 EUR/GJ and that the errors margins by individual parameters are in the order of a few EUR/GJ. If these errors are compounded, a significant part of the price variation falls within the uncertainty margins, indicating that the LCOES values should not be seen as hard facts but more as indicators. Especially when the case-specific variations are accounted for as well.

The analysis also pointed out clearly that systems with lower efficiency and especially systems with high uncertainty in efficiency have a large spread in costs at a high price of heat. This is significantly less at lower heat prices. So, the more efficient systems with a lower uncertainty (in efficiency) are more robust and show less LCOES variation as the heat price changes. In this regard, Ecovat has the lowest uncertainty and the lowest cost spread.

Future cost reduction potential

To assess the future cost reduction potential, the expected technological improvements and methods for costs reduction were discussed. Cost reduction with upscaling is most apparent for Ecovat and PTES systems. This effect is mainly because of increased efficiency and lowered investment costs per unit storage volume related to upscaling. BTES systems also enjoy this effect but to a lesser degree. This is because, but the investment costs are directly related to peak power, which grows linearly with the project size and specific investment costs do not fall with BTES as much as with the other techniques. ATES projects do become cheaper at larger projects, mainly because of the increased storage efficiency but this effect is not yet strongly observed at the project sizes discussed in this research. TTES systems cannot scale up indefinitely and the lowest investment costs seem to be reached at systems of about 20 000 m3. At larger projects, these systems are just replicated and there is no further cost reduction potential.

In terms of expected price development, the least market mature technologies will have larger cost reduction potential for the future. The more mature technologies will see the majority of costs reduction coming from the 'economy of scale' effect as the storages become larger, due to improved efficiency and lower investment costs per unit of storage volume.

Land use

In terms of land use, big differences are observed among the technologies. PTES systems use by far the most amount of land, which can be deal-breaker for urban areas. ATES, BTES and Ecovat do not use any space above-ground and negate this problem. TTES systems can be built above-ground but also partially or completely underground.

Peak Power

The not-insulated systems ATES and BTES are much less suitable to provide high-power from the storage than PTES, TTES and Ecovat. This means ATES and BTES systems are obligated to include back-up power sources or a buffer vessel in the system. These costs are not accounted for in this comparison.

Storage density, efficiency and temperature

The storage efficiency ranges from 50 – 90 %, with Ecovat scoring the highest by a fair margin (15%). This is mainly beneficial in situations where the price of heat is high. In terms of storage temperature, the systems show little variation (80-90 °C). The corresponding energy storage density per cubic metre is highest for Ecovat, enabling a smaller storage volume for the same energy content

Requirements on geology

The LSSTES technologies differ significantly in their demands imposed on the underground. The well-insulated systems (TTES and Ecovat) pose very little to no demands on the underground, whereas ATES, BTES and to a lesser extent PTES, have a significant list of requirements that have to be met to construct a workable system.

PTES must be constructed above the groundwater level to avoid excessive heat losses. This is not so much a problem in countries with low groundwater levels, but in the Netherlands, this renders the construction of PTES impossible in almost all areas of the Netherlands.

ATES systems require the presence of an aquifer of suitable size, geometry, soil characteristics and limited groundwater flow. It is currently being investigated whether this is the case for the majority of the locales in the Netherlands.

BTES systems can only be placed if the groundwater flow is negligible and the groundwater level is low. Moreover, the soil should be drillable, possess high heat capacity, low hydraulic conductivity and high thermal conductivity. Obviously, this is not the case at all sites.

Ecovat has as only requirements the possibility for drilling, which is possible almost everywhere. Above-ground TTES systems have the advantage of not being dependant on the underground at all.

All LSSTES systems have their advantages, disadvantages, technical impairments and requirements that shape the range in which each technology is suitable to deploy. The second major aim of this research was to uncover that range for each technology is using the comparison cases. That is roughly what is done in the graph below. Bear in mind the scope of this research (see introduction) that is valid for this graph. The black lines indicate the ranges for which the analysis is made, corresponding to the Ecovat market. In Case 4, two

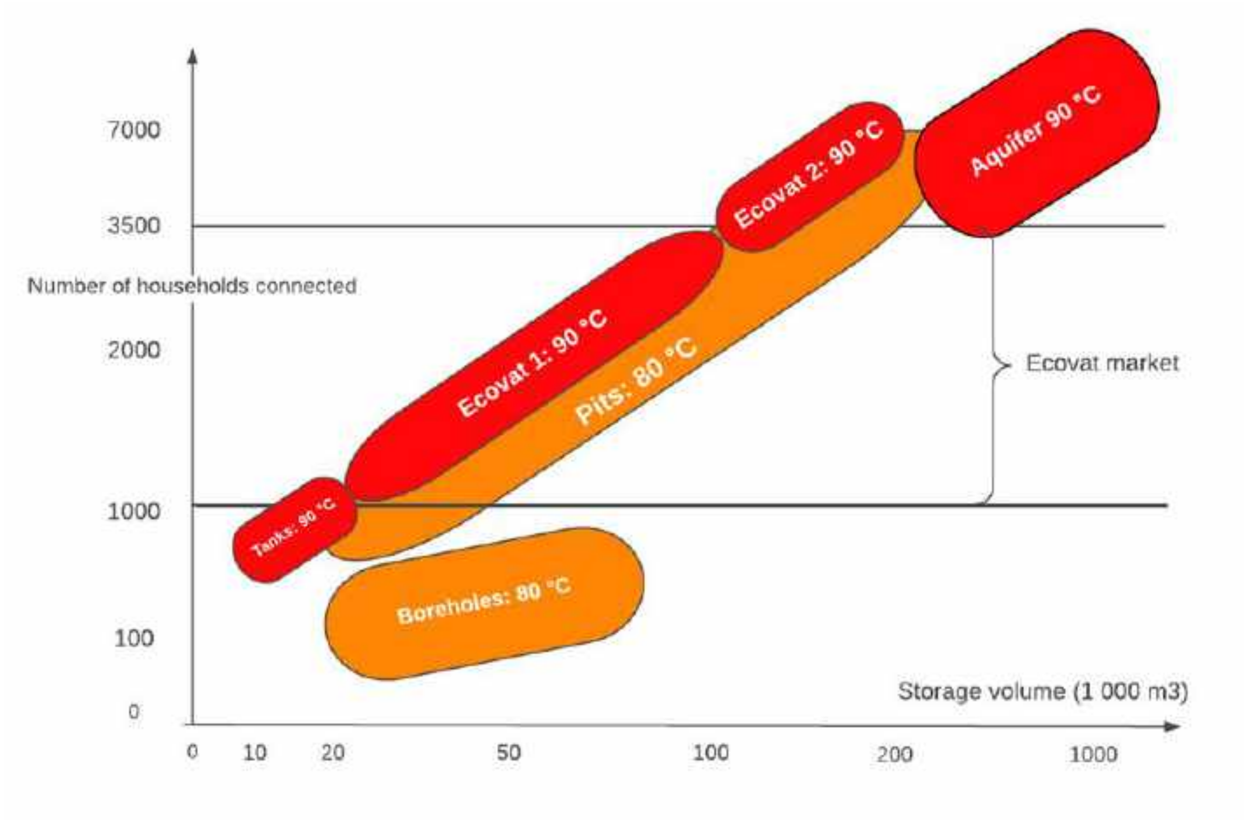


Figure 0-3: LSSTES technologies and their range of high-temperature storage application

Ecovats are combined, hence the naming Ecovat 1 and 2. The intensity of the colour marks the maximum storage temperature (graph assumes 25% of heat demand comes from storage). What stands out

immediately is that borehole systems can be quite large in terms of storage volume but fail to accommodate large energy storage capacity because of the low energy storage density. This places HT-BTES out of the Ecovat market and more suitable for smaller scale applications. The largest seasonal TTES is currently 12 000 m^3 and it does not seem likely that much larger tanks will be built soon, suggesting tanks will continue to fulfil their role as peak-buffers or seasonal storage for smaller project sizes. Should a larger TTES be constructed (i.e. 20 000 m^3), than this would probably be a cheaper variant than the smallest Ecovat. The PTES systems recently built are in the order 50 000 – 200 000 m^3 but smaller ones have also been constructed. This puts PTES systems in the same market as Ecovat. ATES systems are very large systems, the smallest of which are about equal to the largest Ecovat possible.

Pit thermal energy storage

PTES systems are the most similar system to Ecovat in terms of the range of possible project sizes. The differences in the systems are mainly in costs, lifetime, efficiency, uncertainty and geological requirements.

PTES systems outperform Ecovat in terms of levelized costs of storage, being cheaper at all system sizes. This is the prime advantage PTES has over Ecovat. Ecovat has the advantage of no land use whereas PTES uses a lot. Secondly, PTES systems can only be realised if the groundwater level is low enough, which is most likely not the case in the majority of the Netherlands. Moreover, Ecovat systems are much more durable 50 years versus 20 years of a pit. The higher efficiency of Ecovat and lower uncertainty regarding OPEX, CAPEX and efficiency also decreases the uncertainty in costs which is advantageous. All in all, PTES systems are not considered to be direct competitors in the Dutch market since it is unlikely that a PTES system will be successfully constructed in the Netherlands and even if that would be possible the land use will often prove a insurmountable barrier. .

High-Temperature Aquifer Thermal energy Storage

HT-ATES is outside of the Ecovat market but the smallest projects HT-ATES is able to accommodate correspond to the largest project Ecovat is able to accommodate. The two systems differ in peak demand coverage, lifetime, efficiency, uncertainty and geological requirements.

HT-ATES has the potential to store heat more cheaply than Ecovat but there are some conditions that have to be met. First, the geological environment has to be suitable. If this is not the case the system underperforms and it will still be more expensive than Ecovat. This dependence on the underground is a disadvantage for HT-ATES that Ecovat does not have. Secondly, it is important that the price of heat is low since the efficiency of HT-ATES is less than Ecovat, meaning more heat has to be charged into the aquifer. If these conditions are met and the HT-ATES systems performs as modelled it can be a superior system to Ecovat. The main benefit of HT-ATES over Ecovat is, again, the potentially lower costs. A second benefit of HT-ATES is that the space above the aquifer can be used to construct anything on. In the case of Ecovat there are some constructions possible but not all. Ecovat is advantageous over HT-ATES because the uncertainty regarding system performance and eventual costs is much lower. Ecovat is also twice as durable and most importantly it is suitable for delivering high-power. HT-ATES systems are not dimensioned to accommodate peak power and therefore require additional back-up power sources in the DHN or a buffer installation.

Tank Thermal Energy Storage

TTES is also possibly a competitor of the smallest Ecovat vessels, although the largest TTES known is currently is still notably smaller than the smallest Ecovat (12 000 vs. 20 000 m^3). TTES systems seem to be cheaper at the 20 000 m^3 in terms of levelized costs, but do have the drawback of land use. Still, on the economic balance Ecovat will remain more expensive. Ecovat might be able to tip this by offering cooling to the DHN which not all TTES systems are able to do.

High-temperature Borehole Thermal Energy Storage

The low number of HT-BTES systems realised in the Netherlands (1), the small amount of research into HT-BTES and model calculations show that HT-BTES systems are not economically competitive at the large scales upon which Ecovat operates, especially considering the extra peak buffer investments that are required. HT-BTES might be an option for small volumes in which HT-ATES or an Ecovat is no possibility but at least in the Netherlands, HT-BTES is disregarded as a serious alternative to Ecovat.

Summarizing, Ecovat is an LSSTES system operating in the 20 000 – 100 000 m^3 storage volume range. It is characterised by high CAPEX, low OPEX, moderate levelized costs, high efficiency, long lifetime, high building-related emissions, no land use, high storage density, low uncertainty in performance, high storage temperature, suitable for high-power applications with little to no geological requirements. Ecovat expects to reduce costs significantly over the coming years through economy of scale and technological advances.

6 Discussion

This analysis focused on the characteristics of LSSTES storage modules within a district heating system. This section is included to reflect on the implications of these findings on the bigger picture view, considering not just storage but also the network and the total costs of heat. One important questions left unanswered is what the costs of storage (per unit of energy) imply for the average total cost of a unit of energy. This is essentially asking what the difference between the levelized costs of energy and the levelized costs of energy storage is.

6.1 Difference between average costs of heat and costs of storage

This research focuses on the costs of storing energy, which is only one of the three factors that determines the final costs of heat:

1. Production
2. Storage
3. Transportation & delivery

Figure 6-1 is a schematic view of these three costs factors in a DHN. The Dutch ACM tariff sets the maximum price of delivering heat. There is a tariff for the price of delivered heat (EUR/GJ) and a tariff that always has to be paid, regardless of the amount of heat used. For a household with a heat demand of 30 GJ, this amounts to 35 EUR/GJ of total income, to be spent on production, storage, transportation and delivery as desired. This calculation is given in table 6-1.

The costs for storing one GJ vary from 10-30 EUR/GJ, but luckily not all produced heat has to be stored and so the addition of storage costs per delivered unit of heat is much lower than 10-30 EUR/GJ. To display the effect of different heat source prices and the fraction of heat demand requiring storage on the joint heat production and storage price, some examples are worked in tables 6-2, 6-3 and 6-4. Figure 6-1 shows the contribution of heat production ,storage and transportation on the total costs of heat per delivered GJ of heat. In total, these costs should sum up to maximally 35 EUR/GJ, but preferably less. This implies that project with expensive and highly intermittent heat sources must have low costs for transportation and, vice versa, that stable and cheap heat permits more expensive transportation infrastructure.

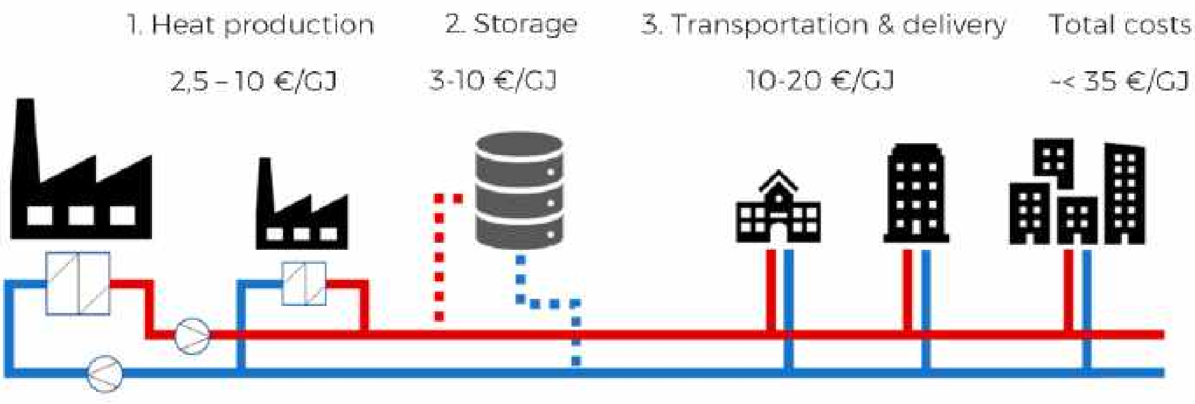


Figure 6-1: Schematic of the three major costs in a DH

ACM tariffs	Fixed costs	Price per GJ
Inc. VAT	€ 469	€ 26,1
Ex. VAT	€ 388	€ 21,5
Costs per GJ	€ 13	€ 21,5
Total (EUR/GJ ex (VAT)	34,5	

Table 6-1: Total costs for heat production, storage, delivery and transportation for 30 GJ/household heat demand

Costs of heat production	Unit	Value
Costs solar thermal	€/GJ	12
Costs heat from pumps	€/GJ	10
Costs waste heat	€/GJ	5
Costs of heat average	€/GJ	10
Costs of storage average	€/GJ	25

Table 6-2: Costs of heat production and storage

Share of demand requiring storage	0 %	10 %	20 %	30 %	40 %
Total costs of production and storage	€/GJ 10,00	€/GJ 12,50	€/GJ 15,00	€/GJ 17,50	€/GJ 20,00

Table 6-3: Effect of fraction of demand requiring storage on production & storage costs of heat

Heat source: Percentage of demand	Example 1	Example 2	Example 3	Example 4
Solar thermal collectors	50 %	0 %	100 %	0 %
Heat pumps (baseload winter)	50 %	50 %	0 %	0 %
Waste heat (baseload)	0 %	50 %	0 %	100 %
Share of demand requiring storage	25 %			
Total costs of production & storage	17,25 €/GJ	13,75 €/GJ	18,25 €/GJ	11,25 €/GJ

Table 6-4: Effect of heat source composition on production & storage costs of heat

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8 Appendices

Appendix 1: Ecovat

Ecovat is an underground tank thermal energy store. Since it resembles TTES so much, Ecovat shares many of the characteristics with other tank stores. The differences will be highlighted in this paragraph. For detailed information about Ecovat, there is a report available called *"Product information Ecovat"*. Please request the author to grant you access to this report.

Ecovat is a large, concrete, well-insulated, underground tank using (ground)water as storage- and transport medium. Currently, investigations are ongoing to clarify if the use of groundwater is possible, or if water treatment is necessary. The system utilizes a closed-loop for heat exchange, meaning that the water only leaves the vessel to exchange heat and is reinjected upon return (see *Figure*).

As you may have noticed in *Figure*, the water in the tank is warmer at the top than it is at the bottom. This separation of temperature in stagnant water bodies with different temperatures is called stratification and is brought about naturally, without interference. Stratification is the natural separation of water with different temperatures due to temperature-induced differences in the 'weight' of the water. Hotter water is lighter and will rise to the top of the vessel, while the cold water remains at the bottom of the vessel. This is advantageous since it allows Ecovat to store warmth and coolth simultaneously in one vessel. Ecovat can inject and extract water at different heights in the vessel (via ring-like structures in *Figure*), enabling it to (dis)charge different temperatures while retaining the stratification.

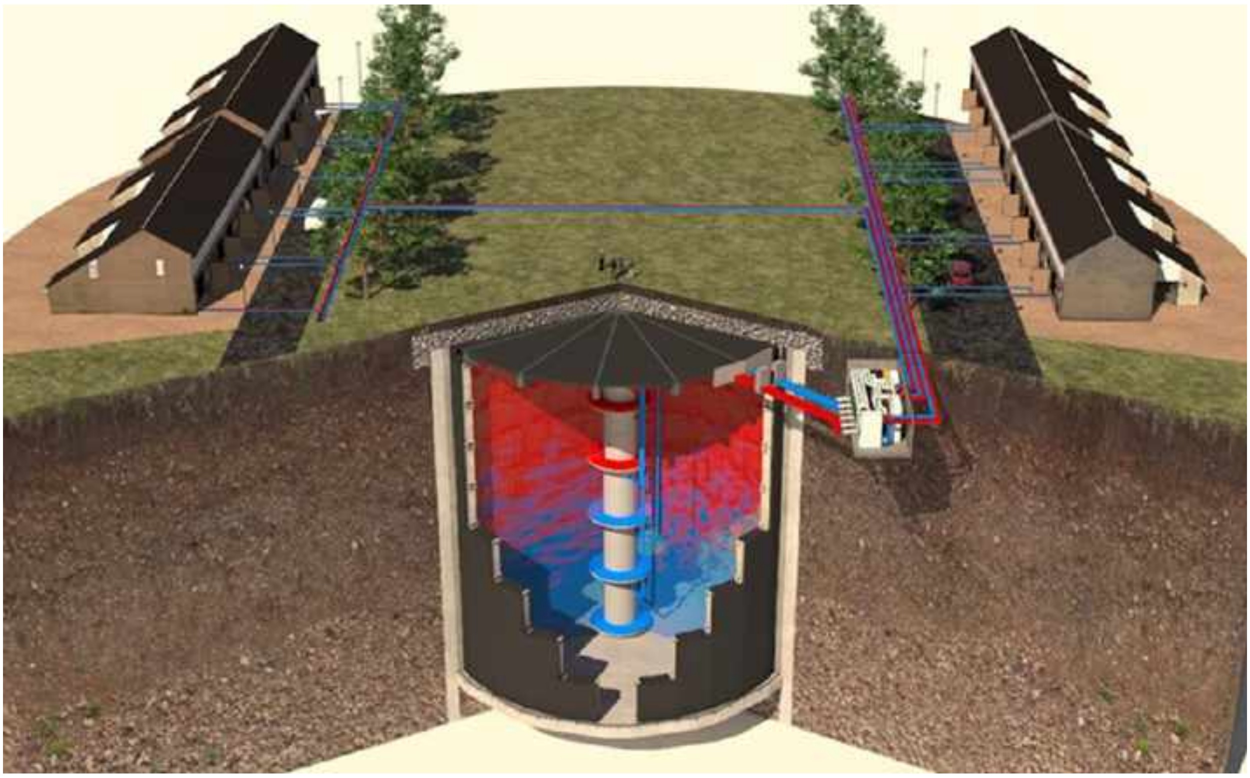


Figure Ecovat tank and connection to heating infrastructure schematic

1.1 Geological) Requirements and barriers to implementation

Since Ecovat is insulated and closed from the environment, legal restraints are milder compared to open and non-insulated systems. In terms of geological requirements, virtually the only requirement is that the soil should allow for excavating to place the outer wall. For Dutch soils, this is possible almost everywhere (except maybe for some hard rock in the southern parts of Limburg). Ecovat uses a unique construction method that allows construction underneath the groundwater level, allowing the vessel to be fully built underground. The link below will lead you to a video showing the construction method.

https://www.ecovat.eu/video/bouw-ecovat-beeld/

1.2 Storage capacity

The storage capacity of Ecovat is dependent on the size of the Ecovat. Ecovat vessels employ the ideal cylindrical configuration with an ideal diameter/height ratio of 1. Slight deviations of this ratio are possible (see *'product information Ecovat'*). The smallest vessel is 30 metres wide and high and stores approximately 21,000 m^3 water. This amounts to 1,856 MWh_{th}/cycle storage capacity per full charge/discharge cycle (no losses assumed). The largest vessel is 50 metres wide and high, amounting to 98,000 m^3 volume, corresponding to 8,590 MWh_{th}/cycle.

1.3 Storage efficiency

Ecovat has a very high storage efficiency due to the underground character and superior insulation material Foamglas. This enables limited heat losses while retaining the possibility for high-temperature storage. The storage efficiency of Ecovat is in between 85-95 % (depending on the size) over a period of 6 months (so for seasonal storage application). This is experimentally determined using the pilot Ecovat (in Uden) for a fully charged vessel (entire vessel at 90 °C). DNV-GL validated the methods, calculations and measurements that support this claim. The data for this is available in the report *'Validation of thermal efficiency Ecovat'*, which is also available on request. In reality, an Ecovat will not be fully charged to 90 °C, meaning the operational efficiency is expected to be even higher. The efficiency is defined as the ratio of (retrievable) energy content at day 1 of the vessel over the energy content after 6 months of the vessel.

1.4 Maximum temperature

The materials used in Ecovat can all withstand high-temperature water up till temperatures higher than the boiling point of water. This means the upper-temperature level is marked by the boiling point of water, so 100 °C. However, to prevent vapour formation, a slightly lower max temperature is preferred i.e. 95 °C. Just like in other LSSTES systems, the available energy sources might also mark the upper limit of storage temperatures.

1.5 Levelized cost of energy storage

Ecovat is characterised by high capital investment, low operational costs and long lifetime. The high upfront costs that have to be made to construct the vessel is one of the prime barriers to a successful project. The high investment cost repays itself with a long lifetime, high storage efficiency and low operational cost. This means that for the lifetime average storage cost, Ecovat is still an economically competitive system. The expected levelized cost of energy storage ranges from 21 to 43 €/GJ for respectively the biggest and smallest Ecovat.

Lifetime

The lifetime of Ecovat is estimated at to be at least 50 years. Currently, investigations are ongoing to prove this lifetime by the use of accelerated ageing tests.

Capital expenses

Capital expenses range from 5 900 000 € (Ecovat small) to 14 582 000 € (Ecovat large). This comes down to a specific investment of 150 €/m^3 (large) to 280 €/m^3 (small). Further information regarding costs in *"Product information Ecovat'.*

Operational expenses

The operational expenses for Ecovat are still somewhat unsure since there is no commercial system working as of yet. The expectation is that the largest operational expenses will be by a large margin due to the purchasing of heat. Since other LSSTES systems also have to purchase heat, which is likely to come from comparable sources, this is not considered in this comparison of operational costs. Maintenance is not expected to be necessary, however, periodic inspection of the status of the vessel will be necessary and pertain to costs. These are expected to be in the order of 15 000/year (small Ecovat). The largest Ecovat is estimated to have an OPEX of 50 000 €/year.

1.6 Land use

Ecovat is always built entirely underground. After commissioning, the space above Ecovat can be utilized as a parking lot, park or greenery. Therefore, the land use impact is minimal and there is no visual obstruction like is the case in above-ground tanks.

The land use is considered to equal the surface area of the lid of the Ecovat. For a small Ecovat (20 000 m^3) this is 850 m^2. For an XXL Ecovat (98 000 m^3), this is 2200 m^2.

1.7 Suitability for high-power application

Ecovat is suitable for high-power applications. The maximal power that Ecovat can deliver is dependent on the maximal flow rate of the diffusers, which is 215 m^3/hour in the current design. The state of the charge of the vessel will determine the highest temperature extractable from the vessel and, with that, the maximal power. When Ecovat reaches its lowest state of charge, the max power is still 3.8 MW. The power deliverable by Ecovat depends, as said, on the sizing of the diffusers and therefore is the same for all vessels, irrespective of the size of the vessel (small to XXL).

Ecovat can change its thermal power in about a minute. With these characteristics, Ecovat is suitable for high-power applications and scores ++ on this indicator.

1.8 Building emissions

Since Ecovat is so large and built underground, the vessel should be able to endure high forces and possess high structural strength. To achieve this, it is necessary to use thick concrete walls. In the case of the largest vessel, the production of this concrete produces approximately 5000 tonnes of CO_2. The smallest Ecovat produces 1500 tonnes of CO_2. Considering just the concrete components, this amounts to a CO_2 payback time of 1,9-2.5 years for respectively the smallest and largest Ecovat. With that, Ecovat scores -- on building emissions

Appendix 2: ATES

2.1 (Geological) Requirements and barriers to implementation

High-temperature storage of not-insulated systems is subjected to some legal restrictions:

- The first is that it is in principle not allowed to store energy at higher than 25 °C in the subsurface, regardless of depth.
- The second is that an energy balance is required (yearly) to prevent the soil from excessive heating or cooling. This is of course not feasible with high-temperature storage.

This implies that HT-ATES can only be permitted if an exception is made to standard legislation. This has happened several times in the past for research projects but it remains to see that will also be the case for commercial systems.

Geological requirements

Next to legal issues, some geological requirements have to fulfilled for ATES to be a possibility. A second requirement for ATES (in general) is the presence of a suitable aquifer, of suitable size which is located at reachable depth, where there is limited groundwater flow and where the heat is trapped by impermeable layers above and beneath the aquifer. Additionally, the aquifer should have a minimum thickness and suitable groundwater composition is necessary to prevent chemical problems. Additionally, there are requirements for the hydro-geological conditions that have to be fulfilled to check whether a HT-ATES system is possible.

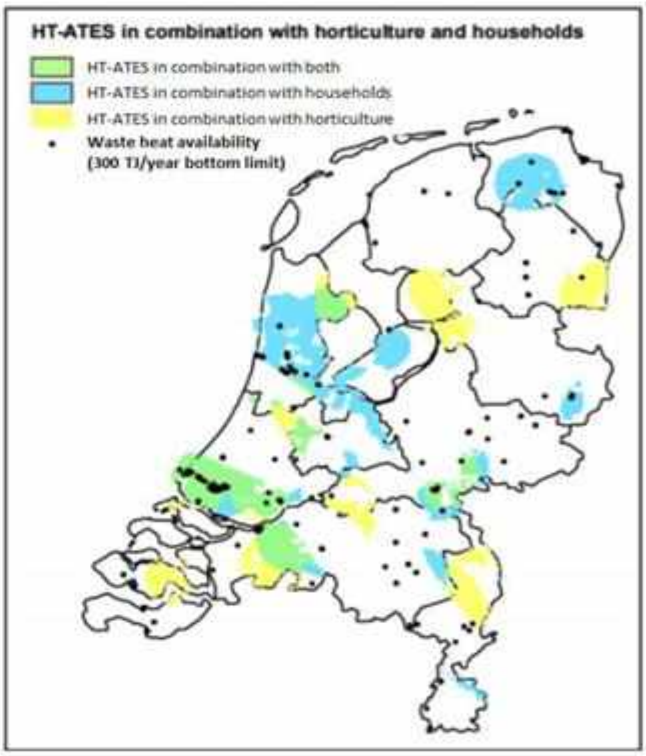


Figure 2: map indicating where suitable subsurface and surface conditions for HT-ATES overlap [14]

Luckily, the Netherlands has ample of such places. Still, HT-ATES is certainly not possible everywhere. Figure 7-1 indicates the places that have suitable underground for HT-ATES and have heat demand and possible supply overlapping. This does not mean that HT-ATES will only be feasible in these areas.

Despite the potential high profitability of an HT-ATES plant, the risks and barriers often seem to prevent investors from investing in MT-HT ATES systems. Possible explanations are:

- The risk of not getting a permit
- The geological risk of not finding a suitable aquifer in the area of interest
- A time-consuming test period and permitting procedure
- The risk that the system performs less well than expected and heat demand cannot be met

The risk of not getting a permit can be evaluated very early in the decision process and (in most cases) through a desktop study. The screening of the geological conditions is a more time-consuming process and crucial for a successful project. A time consuming permitting process can also pose a barrier to chose for an ATES system [5].
If these problems can be overcome, it is time to look at the technical and economic performance of the HT-ATES system.

2.2 Storage capacity

As mentioned, ATES systems are generally very large. Especially at high temperature, aquifers tend to lose a lot of heat due to the absence of insulation. To counteract high losses, a low surface to volume ratio is paramount. This ratio becomes more favourable as the aquifer increases in size. Previous HT-ATES projects have enables guidelines for the minimum sizes of ATES systems for different temperatures. It is worth noting that aquifers do not have to have lower efficiency at higher storage temperatures. If the buoyancy flow (convective losses) are prevented, the absolute amount of heat lost is larger but the relative losses (and thus efficiency) stays the same.

- *"The storage volume of an ATES cannot be thermally insulated against the surroundings. Thus heat storage at higher temperatures (above 50 °C) is normally only efficient for large storage volumes greater than 50,000 m³ with a favourable surface-to-volume ratio* [2]*".*
- *"An indication for the minimum storage volume of a HT-ATES with a temperature of 90 °C is between 250.000 and 500.000 m³/season (this improves the recovery efficiency and the economical feasibility)* [3]*".*
- *"Based on Dutch experiences Bakema & Drijver summarizes that if a specific aquifer storage volume is less than 100,000 m³ per season, the storage is very sensitive to variations in temperature and hydraulic conductivity. The consequence is likely to be a large differences between the theoretically calculated and actual recovery efficiency. Therefore Bakema & Drijver recommend aiming for systems that store at least 300,000 m³ of hot water* [5]*"*

These quotations are all from reports that looked at multiple HT-ATES projects and formulated conclusions based on the results retrieved from those projects. It may be clear that the minimum size of an HT-ATES should be very large. Smaller versions (near 50 000 m³) are possible but will suffer much greater losses when high storage temperatures are used. 250 000 m³ for 90°C storage is taken to be minimum. [3]

2.3 Storage efficiency

For MT- and HT-ATES systems that are commissioned in the '90s, the thermal efficiency of the systems was (much) lower than initially modelled (see *Table 2*).

This underperformance was due to various reasons, which will not all be mentioned here. With the experience

Project	Year of installing	Storage temperature [°C]	Design recovery efficiency (%)	Measured Recovery efficiency (%)
Utrecht University	1991	90	59	33
Heuvelgalerie Shopping Mall Eindhoven	1992	32	60	55
Dolfinarium Harderwijk	1997	40	55	40
Hooge Burch Zwammerdam	1998	88	49	10
NIOO, Wageningen	2011	45	45	15

Table 2: Designed and measured recovery efficiency of some MT and HT ATES projects in the Netherlands [6].

gained in the first HT-ATES projects, it is expected that these problems will no longer seriously degrade the performance of future HT-ATES systems that are yet to be built. Still, it is worth noting that there is much more uncertainty (and with that risk) involved in the thermal performance if a not-insulated system is used, compared to an insulated system and that the actual performance of the system might not live up to the expected (designed) performance.

As mentioned earlier, the system efficiency in ATES projects is very much dependent on the surrounding soil characteristics, as well as the presence of impermeable layers above and underneath the aquifer. Moreover, the groundwater flow should be negligible. If all these requirements are in place, the thermal efficiency mostly depends on the surface to volume ratio (geometry and size) and the storage temperature of the aquifer. For future HT-ATES projects, the aim is to get the recovery efficiency up to 60-70% [15].

It is worthwhile to note that this efficiency is the steady-state efficiency of the system, which will be reached after some 5 years or so of operation. The first years of operation, the surrounding soil needs to be warmed up, which causes larger losses and a significantly (i.e. ~20%) lower efficiency. After about 4-5 years, the soil has heated up and the system reaches its maximal efficiency.

To achieve this maximum efficiency, recommendations are given about the size and storage temperature. For 90 °C storage, 250 000 – 500 000 m^3 is regarded as the minimum size. For 50 °C storage, the minimal size drops to 35 000 – 180 000 m^3 [5].

Table 3 shows the relation between storage temperature and achievable efficiency.

temperature level	typical recovery efficiency*	heating	examples
< 30 °C (ATES)	70 - 90%	heat pump	> 1.300 systems in the Netherlands
30 - 60 °C (MT-ATES)	60 - 80%	direct / HT-heat pump	2 MW Haarlem, Heuvelgalerie Eindhoven, Dolfinarium Harderwijk
> 60 °C (HT-ATES)	40 - 70 %	direct	Utrecht University, De Bruggen Zwammerdam (near Gouda)

* ratio of the recovered amount of energy and the stored amount of energy, when equal amounts of water are injected and extracted. The amount of energy is calculated with respect to the ambient temperature.

Table 3: Recovery efficiency as function of storage temperature

Apart from these indications of efficiency, Schout and colleagues [16] modelled the recovery efficiency of an HT-ATES (90 °C) system and included an extensive sensitivity analysis. They performed model calculations from different hydro-geological conditions and found efficiency ranging mostly from 50-75 %.

2.4 Maximum temperature

In aquifers, the physical limit of the storage temperature is determined by the evaporation of water. Given the hydrostatic pressure at high depths, temperatures above 100 °C are possible if the aquifer layer is situated deep enough. However, such temperatures will lead to very high losses, are not necessary and do not offer many additional possibilities regarding the applications of the heat. Indeed, higher temperatures may even aggravate water chemistry problems occurring within the well.

For these reasons, the maximum temperature is more strongly determined by heat losses (efficiency) and available heat sources than it is determined by physical constraints. Common heat sources used in long term thermal storage include solar collectors, CHP, heat pumps and industrial waste heat. Solar heat is limited to about 80 °C and heat pumps generally don't produce very high-temperature heat (because of low efficiency). Industry waste heat can have any temperature and CHP plants also show variance in their waste heat temperature but this is almost always less than 100 °C. Given the fact that there are a lot of locations that will have to integrate thermal storage into their energy infrastructure and do not have access to higher than 100 °C sources, there will come a lot of projects that will have to rely on the local production of heat. This will rely mostly on solar collector heat and therefore the maximum storage temperature will be limited mostly by the maximum solar collector output temperature. In most studies, 90 C° is taken to be the maximum storage temperature for HT-ATES.

2.5 Levelized cost of energy storage (LCOES)

$$LCOE = \frac{\text{Discounted lifetime costs of an investment}}{\text{Cumulated energy generated by investment}}$$

To compute the LCOE(S), the lifetime, CAPEX, OPEX, WACC and costs of heat are needed. The energy output (denominator) is calculated using full-load hours, maximum power and the efficiency of the storage.

Lifetime

the economic lifetime determines the number of years – and thus the total amount of thermal energy - over which CAPEX can be amortised. There is little experience with the technical lifetime of HT-ATES installations as very few are operational today. The installations that were operational in the 1970s and 1980s generally had short technical lifetimes due to the issues such as corrosion [14]. As solutions to these issues exist today, these lifetimes are no longer representative. Regular ATES installations are generally designed to have a lifetime equal to that of the building it supplies heat and cold to, which is usually 30-50 years [17]. The main difference between ATES and HT-ATES is that the temperature of the water in the latter is higher, which was also the reason for most issues in the 1970s and 1980s. However, Kramers et al. [18] quote technical lifetimes of geothermal doublets – which produce water of temperatures in the same range as HT-ATES – of 30 years. Based on this, it can be assumed that the technical lifetime of a well-maintained HT-ATES installation is approximately the same, thus 30 years is assumed for the calculation.

Capital expenditure

Capital expenditure for ATES systems is mainly dependent on the power requirements of the system and depth of the suitable aquifer. Together these determine the number of wells and with that the drilling costs, which generally make up for the bulk of the costs. Rules of thumb regarding the CAPEX of (HT)-ATES systems are [19]:

- 4-15 €/m^3 storage volume
- 150 000 – 300 000 €/MW : peak power
- 6000 – 15 000 €/m^3/hr : maximal flow rate

The majority of the large-scale ATES systems have a peak power ranging from 5-30 MW [4]

Operational expenditure

The operational costs of a HT-ATES include system maintenance, monitoring, electricity costs (pumps) and potential heat purchase. The fixed expenditures (equipment maintenance and monitoring program) are less difficult to calculate than the more dynamic costs dependent on e.g. energy price levels. The main OPEX costs are estimated as follows[19]:

- Maintenance of wells and pumps: 35 000 EUR/doublet/year
- Electricity to drive the pumps: 17-20 kWh_e/MWh_{th} (price of electricity 0.22 EUR/kWh).
- Maintenance of residual components: 4 % of CAPEX/year
- Water treatment: 1 EUR/MWh_{th}
- Monitoring and reporting of the well conditions (mandatory by law): 30-40k EUR/doublet

2.6 Land use

One major advantage of an ATES system is that it takes up very little space above-ground. The system consists of a well, piping and some pumps. The above-ground impact is just the housing of the piping and pumps, which is typically a few m^2 per well. During construction, a little bit more space is necessary for the drilling machinery but this is also quite limited as you will see below. Therefore the land use is deemed negligible (0 m^2). The surrounding soil (above the aquifer) can be utilized for practically all purposes.

Figure 4: Well drilling site

2.7 Suitability for high-power application

The power of any water-based thermal system is dependent on the flow rate and the temperature difference between the stored water and the to-be heated medium. This means that for a fixed storage temperature, the flow is governing the maximal thermal power. For ATES systems, the max flow rate is dependent on characteristics of the aquifer, the strength of the pumps and the size of the pipes. For large diameter pipes, the pumping energy becomes too large to sustain a high flow rate and it becomes more feasible to use drill more wells. Since drilling amounts to the largest costs in ATES production (see Figure 5), the main determinant of ATES investment cost is the required power output. Apart from economic contemplations and the fact that the maximal power should be well-fitted to the storage capacity, there is no direct limitation to the power of an ATES system. It should be noted, however, that an ATES system is a slow-reacting system, meaning the power output cannot be changed very rapidly.

This has two reasons:
1. The heat has to be transported from large depth and
2. The pipe systems must be heated up.

This means ATES systems are particularly useful as baseload supplier but not so much so for peak buffers. ATES, therefore, scores a – on this indicator.

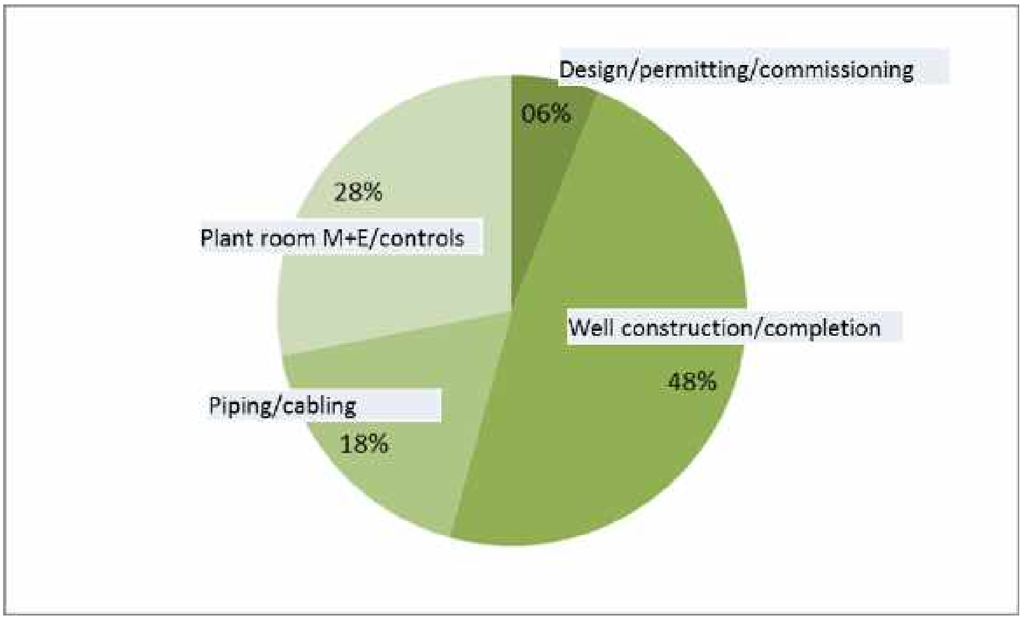


Figure 5: Breakdown of ATES investment cost [2]

2.8 Building emissions

Similar to the land use indicator, the not-insulated character of the storage means very little building material is needed in comparison to a tank or pit storage. This means the construction-related emissions are much lower than building material-intensive structures like PTES, TTES and Ecovat. ATES scores a ++ on this indicator.

Appendix 3: BTES

3.1 (Geological) Requirements and barriers to implementation

To successfully commission a BTES system, some geological and legal requirements have to be met.

Geological requirements

- drillable ground: the underground should be suitable for drilling to be able to place the ground heat exchangers.
- high heat capacity: the underground should have sufficient volumetric heat capacity so that sufficient heat can be stored in the vicinity of one borehole. If this is not the case, more boreholes are necessary and cost rise.
- high thermal conductivity: the underground should possess sufficient thermal conductivity to allow for fast heat transfer and with that high thermal power.
- low hydraulic conductivity: high hydraulic conductivity means that the stored heat will be quickly carried away from the storage side, resulting in high losses.
- Negligible natural ground-water flow: high groundwater flow will cause the stored heat to get out of the reachable extraction volume of the BTES system, rendering this heat lost.
- Groundwater level: the lowest part of the heat exchanger should be above the groundwater level to prevent convective heat loss.
- Depth: the minimum borehole depth is dictated by the seasonal variation in underground temperature. From about 15-20 metres depth (and more), the ground temperature is constant during the entire year, which is desirable for BTES. The maximum borehole depth is determined by the drilling expenses. Drilling is one of the main expenses of a BTES system, which is why boreholes are typically not deeper than 100-200 metres and most systems are in between 30-100 metres deep.

Since BTES systems are closed systems and solid material is the storage medium, the heat exchange is very different from technologies that use the storage material as the transport medium as well. For BTES, this means heat exchange takes place via conduction, which causes the many geological requirements of the soil. In BTES, there is a fundamental trade-off in the soil characteristic: thermal conductivity. High thermal conductivity facilitates fast heat exchange, allowing the total borehole length to reduce (which greatly determines the cost of BTES). On the other hand, high thermal conductivity will mean more losses to the ambient soil and thus a lower storage efficiency. Therefore, optimal soil has high volumetric storage capacity and moderate thermal conductivity. BTES scores a – on this indicator because of the many geological requirements necessary to successfully implement BTES.

Legal requirements

HT-BTES systems face the same set of restrictions as HT-ATES systems regarding the disturbance of the energy balance of the soil. An advantage of BTES is that it does not directly inject water into the soil, thereby facing no restrictions regarding the composition and quality of the injected water.

3.2 Storage capacity

For non-insulated technologies, the storage volume is not marked and with that neither the storage capacity. This goes for BTES even more so than ATES since an aquifer is confined by impermeable layers that somewhat mark the storage boundary. That said, the storage capacity of a BTES system has no upper limit as long as there is a sufficient amount of suitable soil available. There is, however, a lower limit for a BTES system to reach a minimally acceptable storage efficiency at high-temperature storage. In BTES, many design variables affect the efficiency of the storage, making it hard to name a lower limit valid in all cases. Looking at the realized HT-BTES projects that are fed by solar heat, the lowest observed storage volume is 10 000 m^3. Mangold advises a minimal size of 20 000 m^3 to reach financial feasibility [11] for BTES systems. 20 000 m^3 is taken as the lower limit of BTES storage as this is also the guideline given by Reuss et al, in which ground thermal energy storage is reviewed [20].

Table 4 & *Table 5* show the existing medium and high-temperature BTES installations and their storage volumes.

CSHPSS	Heated living area	Total heat demand, GJ/a	Solar collector area, m^2	Storage volume, m^3	Solar fraction, %	Maximum design storage temperature, °C	Solar heat cost at analysis date, MWh^{-1}
Neckarsulm, DE	20000 m^2	1663	5000	63400	50*	85	172 EUR
Crailsheim, DE	260 houses, school and gymnasium	14760	7300	37500	50*	85	190 EUR
Attenkirchen, DE	6200 m^2	1753	800	10000	55*	85	170 EUR
Anneberg, SE	9000 m^2	3888	3000	60000	60*	45	1000 SEK
Okotoks, CA	52 houses	1900	2293	35000	90*	80	

CA = Canada, DE = Germany, SE = Sweden. * Calculated values for long-time operation

Table 4: large-scale pilot plants for solar heating systems integrating borehole thermal energy storage [26]

Location	Years of operation	Storage volume [m^3]	Maximum storage temperature [°C]	Source of charge
Luleå, Sweden	1983-1990	115 000	65	Industrial waste heat
Emmaboda, Sweden	2010-	323 000	45	Industrial waste heat
Anneberg, Sweden	2003-	50 600	45	Solar thermal
Brædstrup, Denmark	2012-	19 000	60	Solar thermal
Necklarsum, Germany	1999-	63 360	65	Solar thermal
Crailsheim, Germany	2008-	37 500	65	Solar thermal
Okotoks, Canada	2007-	34 000	74	Solar thermal
Paskov, Czech Republic	2011-	Unknown	78	CHP

Table 5: Design parameters of existing HT-BTES [31].

3.3 Storage efficiency

HT-BTES systems generally have the lowest efficiency of all LSSTES systems. Typically, BTES systems lose about half of the energy that is injected into the ground and that is for optimistic scenarios in which more than 1 GWh/year is harvested.

– *"The efficiencies of the fully charged BTES in the existing installations are mostly in the range of 40–60%* [21]*".*

Note that this quote is for LT-BTES, so HT-BTES will have even lower efficiency.

– *"Even well-designed BTES arrays will lose a significant quantity of heat to the adjacent and subjacent rocks/sediments and to the surface; both theoretical calculations and empirical observations suggest that seasonal thermal recovery factors above 50% are difficult to obtain* [21]*".*
– *"Thermal storage efficiency increases as the size of the BTES increases. In Sweden, thermal recovery factors exceeding 50% are only predicted a heat extraction capacity of 1 GWh/year* [22]*".*

Reuss et al [20] state that the storage efficiency can reach up to 70% is the surrounding rock/soil has low thermal conductivity. This notion brings about a fundamental BTES trade-off that has been mentioned before. Lower thermal conductivity will yield high recovery efficiency but lower extractable power, which necessitates other investments in the energy infrastructure to compensate for the low thermal power of the system (buffer tanks mainly). In the calculations made for the comparison, the storage efficiency is 45 %.

Analogous to ATES systems, BTES systems do not operate at maximum efficiency from the get-go. The surrounding soil/rock must be warmed up first, which typically takes about 3 to 5 years [23]. *Figure 6* shows the soil temperature evolution of an ambient and medium temperature BTES system. For HT-systems, more heat will have to be injected to reach the steady-state temperature.

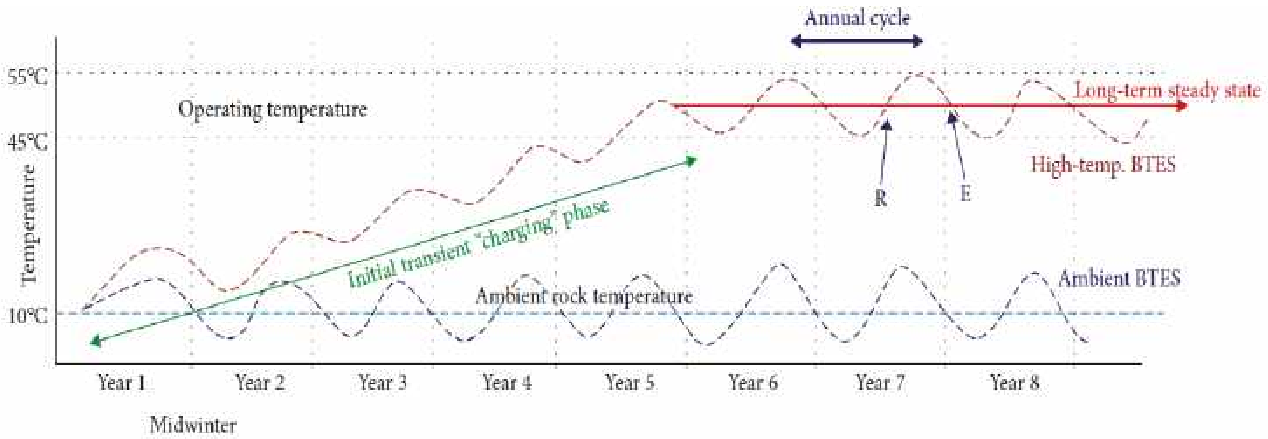


Figure 6: Temperature evolution of BTES for low and medium temperature BTES operation [21].

3.4 Maximum temperature

The maximum temperature of BTES systems has, like other non-insulated LSSTES systems, no hard physical limit as long as the fluid in the pipes does not boil. In BTES the maximum temperature is governed by:

1. The available heat sources (mostly solar thermal collectors (i.e. 85-90 ˚C), industrial waste heat and CHP.
2. Heat losses. As mentioned, BTES loses more heat than other LSSTES systems, which is amplified at higher temperatures. Therefore, BTES systems generally operate at somewhat lower temperatures than other LSSTES systems.

When looking at the commissioned systems, no HT-BTES has been designed for temperatures above 85 ̊C so far. So that will be taken as the hallmark here too.

3.5 Levelized cost of energy storage (LCOES)

The majority of the costs of BTES are upfront capital expenses. Drilling, workmanship, excavation and materials make up for the bulk of the costs. Operational expenses are quite low as the boreholes cannot be easily accessed for maintenance (and hence durable materials are chosen to prevent the necessity to do so). The lifetime of HT-BTES will most likely depend mainly on the piping material used for the ground heat exchangers. Mostly plastic materials are used for this, which are claimed (by manufacturers) to have a very high lifetime (although this is more dubious at higher temperatures). Since there are no HT-BTES systems in operation for as long as the expected lifetime of the pipes (PEX: 75 years), this cannot be validated and some uncertainty in lifetime remains.

Lifetime

The lifetime of BTES systems is determined by the lifetime of the pipes, which is normally produced out of plastic material, mainly HDPE, because of the low costs (low-temperature BTES). At higher temperatures, other materials must be used to guarantee a sufficient lifetime. Most often PEX (other plastic) is used for this, which can handle up to 99 ˚C but costs about twice as much. The service life of PEX is claimed to be 75 years [24]. This, however, this is a theoretical approximation as no HT-BTES systems have been around for that long to confirm this. The longest currently operating HT-BTES plant is commissioned in 1999 and is thus operating for 21 years. A conservative estimate for the PEX lifetime is taken to be 50 years.

Capital expenditure

The capital expenditure in case of BTES is made up out of:

- Site investigation and testing;
- Design;
- Site preparation and set up;
- Drilling;
- Pipework installation;
- Backfilling the borehole;
- Header and piping to energy supply centre; and
- Commissioning.

As with all LSSTES technologies, the investment costs show an economy of scale effect. The smallest systems (i.e. 10 000 m^3 water equivalent) cost around 50-70 €/m^3 while the larger systems are typically cheaper than 50 down to 20 €/m^3 [25]. Figure 7 shows commissioned LSSTES projects and investment costs as a function of the storage volume (water equivalents).

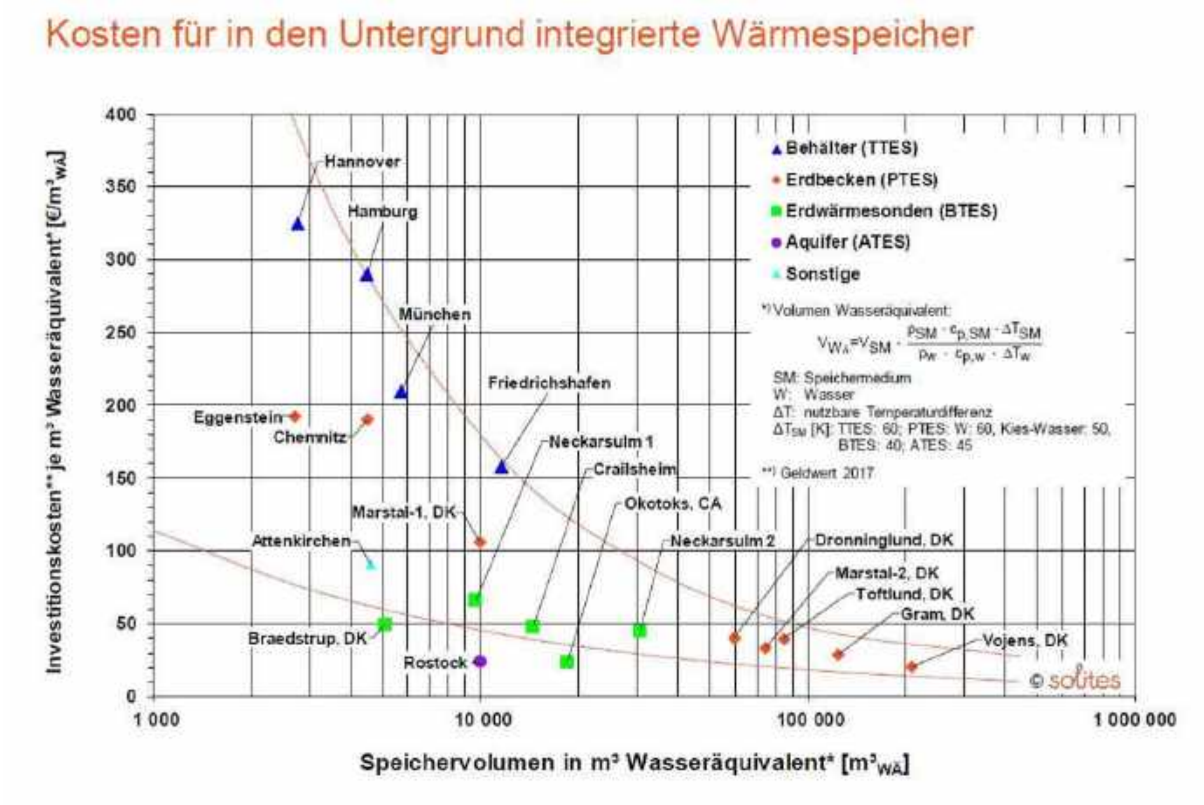


Figure 7: Investment costs for different LSSTES systems as function of system size [25]

For BTES the main costs are made upfront and are due to drilling, materials for the heat exchangers and groundworks (excavation and refilling). These sum up to about 70% of the total cost. The high installation expense of borehole heat exchangers and complex excavation work is the main obstruction to development to some extent [6].

The large contribution of drilling is confirmed by [26], who states that "the installation work for borehole heat exchangers, including material and drilling works, causes nearly half of the costs for borehole heat stores". The capital expenditure is thus dependent much on the design and depth of the BTES system, which is dictated by the geology.

Operational expenditure

There is not much data available regarding the operational costs of BTES systems. Luckily, BTES systems are quite alike other geothermal systems, for which data is more abundant. Generally, the expected OPEX is estimated as a percentage of the CAPEX. TNO estimated this for a specific deep BTES project to be 2% [27].

3.6 Land use

The land use of BTES systems is similar to ATES systems. Above ground, the impact is small as only the drilling sites will have to be freed during construction. After commissioning and restoring of the soil layer, the surrounding soil can be used for other means and there is no visual impact of the storage system left. Therefore, BTES scores 0 m^2 on land use.

3.7 Suitability for high-power application

BTES systems are not suitable for high power applications, because the heat transfer between the soil fluid inside the U-tubes is fairly slow. To enable the system to supply peak power, oftentimes an extra hot water buffer is included in the system. One could also choose to dimension the boreholes to allow for higher power (so there is no need for an extra buffer), but this would decrease the storage efficiency, which is why a buffer is oftentimes the optimal solution. BTES scores -- on this indicator.

3.8 Building emissions

The not-insulated character of BTES systems means very little building material is needed in comparison to a tank or pit storage. This means the construction-related emissions are much lower than building material-intensive structures like PTES, TTES and Ecovat. Compared to ATES, more building materials are necessary and more drillings have to be performed. BTES scores ++ on this indicator.

Appendix 4: TTES

4.1 (Geological) Requirements and barriers to implementation

When tanks are built above-ground, they do not pose any requirements for the underground other than it should offer a firm basis to hold the weight of the tank. In the case of (partial) underground commissioning, tanks merely need a stable underground. The legal restrictions are much less stringent since the vessel is insulated and the storage does not contact the surrounding soil. So in terms of legal and geological issues, tanks are much more desirable than BTES or ATES projects.

4.2 Storage capacity

As mentioned earlier, the storage capacity should be viewed in relation to the storage efficiency and maximum storage temperature. Like for all storages, bigger means more efficient and cheaper (more favourable A/V ratio). Bott et al [13] made an overview of all the large-scale TTES and buffer tank projects currently in commission (*Table 6*). The volume ranges from very small (580 m^3) till 12 000 m^3. Larger tanks can be built but since the investment costs are quite high other LSSTES technologies tend to be preferred for seasonal storage at high storage volumes.

#	name	year	country	storage type	volume (m^3)	water equivalents (m^3)
11	**Studsvik**	1978	SWE	**TTES**	800	800
12	**Ingelstad**	1979	SWE	**TTES**	5,000	5,000
13	**Särö**	1989	SWE	**TTES**	640	640
14	**Hoerby**	1990	DEN	**TTES**	500	500
15	**Rottweil**	1995	GER	**TTES**	597	597
16	**Cosenza (Calabria)**	1995	ITA	**TTES**	500	500
17	**Friedrichshafen (Wiggenhausen)**	1996	GER	**TTES**	12,000	12,000
18	**Neuchatel**	1997	SWI	**TTES**	1,000	1,000
19	**Ilmenau**	1998	GER	**TTES**	300	300
20	**Hannover (Kronsberg)**	2000	GER	**TTES**	2,750	2,750
21	**Rise**	2001	DEN	**TTES**	4,000	4,000
22	**Munich (Ackermannbogen)**	2007	GER	**TTES**	5,700	5,700
23	**Hamburg (Bramfeld)**	2010	GER	**TTES**	4,500	4,500
24	**Mühldorf**	2010	GER	**TTES**	16.4	16.4
32	**Aeroeskoebing**	1999	DEN	**Buffer**	1,400	1,400
33	**Attenkirchen**	2002	GER	**Buffer**	500	500
34	**Samsø**	2002	DEN	**Buffer**	800	800
35	**Linz**	2004	AUS	**Buffer**	34,500	34,500
36	**Braedstrup**	2007	DEN	**Buffer**	2,000	2,000
37	**Crailsheim (Hirtenwiesen)**	2007	GER	**Buffer**	580	580
38	**Salzburg (North)**	2011	AUS	**Buffer**	27,000	27,000
39	**Nuremberg**	2014	GER	**Buffer**	33,000	33,000

Table 6: Overview of all large-scale tank and buffer storages [13]

4.3 Storage efficiency

A major advantage of tanks is their high storage efficiency. Insulation can be applied relatively easy and the storage medium is out of contact with the surrounding soil, enabling high energy retainment. This means that for equal storage volumes, tanks will have the highest storage efficiency of all LSSTES technologies. This potentially high efficiency is not well reflected in the observed efficiency of active systems because most of those systems have a low storage volume and therefore a less favourable surface-to-volume ratio. The smaller storage volumes masks the high energy efficiency of the tank systems. *Figure 9* & *Figure 8* show (red diamonds) the thermal losses (1-efficiency %) of TTES systems according to their size. It is evident that most Tanks are quite small (a), which predicts the high thermal losses (b) [28][13].

For large storage vessels that are well insulated, 70-80 % storage efficiency at high temperature (90 °C) should be reachable.

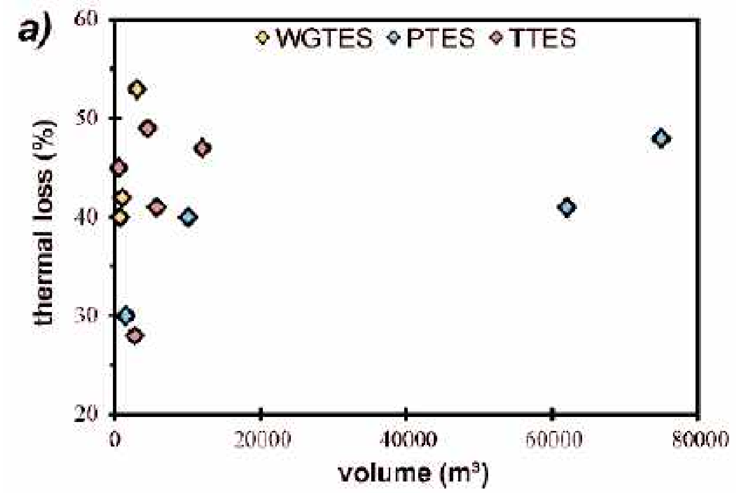


Figure 8: Thermal losses as function of storage volume for Pits, Tanks and Water-gravel storages

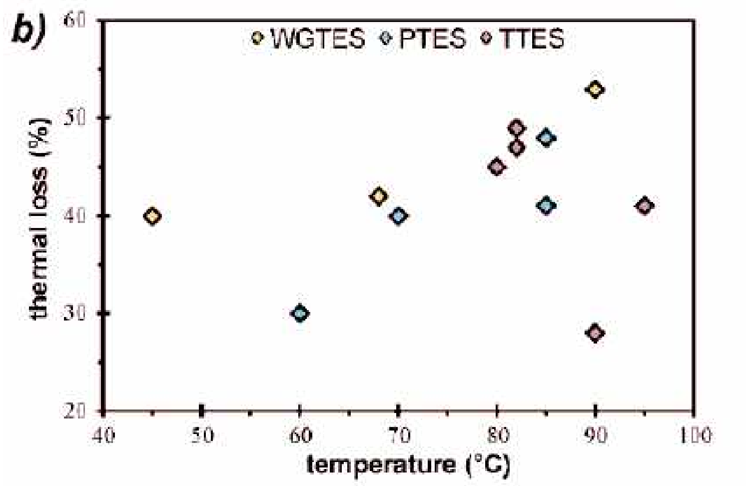


Figure 9: Thermal losses of Pits, Tanks, and Water-gravel storages as function of storage temperature

4.4 Maximum temperature

Tanks can store high-temperature heat with lower losses than the other systems, which is why tanks generally have a higher maximum storage temperature. For non-pressurized systems, the boiling point of water and the available heat sources are limiting factors. To stay away shy of the boiling point, 95 °C is often taken as a maximum.

4.5 Levelized cost of energy storage

TTES systems are characterized by high CAPEX and therefore also high interest costs. The OPEX and heat loss compensation are very low.

Lifetime

As mentioned, tanks are made out of concrete and/or steel. These materials are known to be very durable and characterise the durability of a storage tank. Concrete structures are known to last for 50+ years and typically last for as long as the building is functional. The durability of steel is much dependent on the kind of steel used and the conditions in which it is put. When the materials are chosen wisely, the lifetime of storage tanks can be easily 50+ years.

Capital expenses

Tanks are characterised by high investment costs, due to use of large amounts of building materials (concrete and often liners to reduce water permeability), construction, groundworks and insulation. These expenses can vary depending on whether the tank is built under- or above-ground. Above-ground tanks spare on

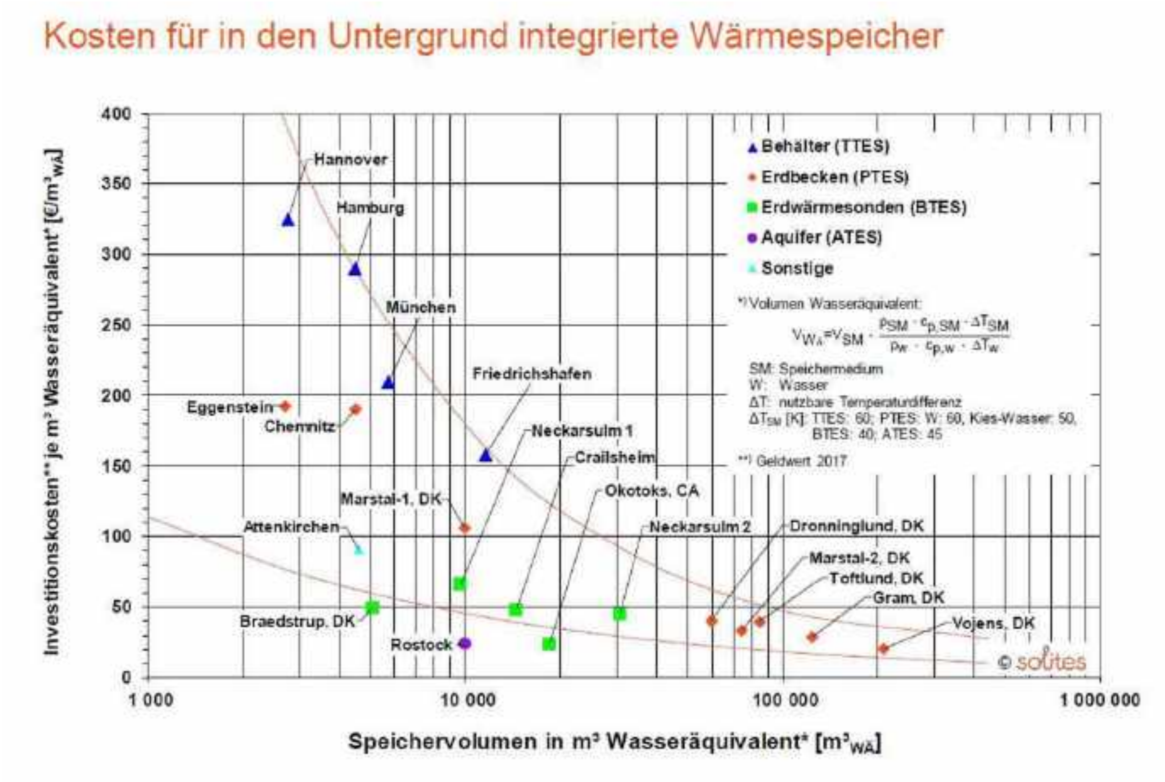


Figure 10: Investment costs for different LSSTES systems as function of system size [25].

excavation costs but miss-out on the insulating and constructive supporting properties of a partially dug in tank. Like all systems, the investment costs per unit of storage volume fall rapidly with increasing size. Unfortunately, there have not been built very large tanks (in the order of 100 000 m³) before, so there is no experience to fall back on. It is possible to extrapolate the trend in costs per storage equivalent, using data from previous projects, although this brings large uncertainty. Figure 10 shows in blue triangles a few tanks and their specific investment costs. No reports of plan or designs of TTES systems with lower specific investment costs than 100 EUR/m^3 are known. It is estimated that the trendline of the blue triangles can be extended to about 20 000 – 30 000 m^3 to arrive at approximately this price

Operational expenses

There is very little data concerning the operational expenses of TTES systems, although it is known TTES systems do not need much maintenance and have a low OPEX. The OPEX of TTES systems should be lower than PTES but since it also has similar costs like water quality treatment and temperature sensor replacement. The OPEX is estimated to be 50 000 EUR/year for 125 000 m^3 storage volume.

4.6 Land use

The land use of tanks is minimal in underground tanks. In such cases, the above-laying ground can be utilized for other purposes (although limited to parks, parking lots and the like). In case of partially dug-in tanks, the land use equals approximately the top surface area of the storage. Oftentimes, a downward slope is created at the sides of the tank by adding soil for insulating or constructive purposes. In this case, this ''soil area'' should be added to the land used. In the case of a fully above-ground tank, the land use is considered the top surface of the tank. For the above-ground tanks, the visual impact can be considered intrusive. Therefore it is recommended to integrate the storage tanks into the environment or to cover up the tank so that the space taken up by the tank is not considered 'wasted'.

4.7 Suitability for high-power application

Tank storages can either directly pump water out the tank to supply a heat demand, or they can let the water contained in the tank flow past a heat exchanger, delivering the heat to a secondary circuit. For both cases, high-power can be achieved due to the high storage temperature, fast response time and large possible flow rates (design parameter). For these reasons, tanks are excellent for high-power applications and are thus often used as 'peak demand buffers'. The ramp-up time can be low as long as the piping, pumps etc are designed to deliver high power. In contrast to other LSSTES technologies, this does not imply increased losses (as is the case for BTES) or higher investment costs (as is the case in ATES). That said, the maximum power is limited only by the maximum power the tank is designed for. TTES scores ++ on this indicator.

4.8 Building emissions

Steel and concrete both require a tremendous amount of energy to produce, especially when needed in large quantities. This makes the building emissions associated with the building of large-scale tanks very high compared to the much less energy-intensive non-insulated systems (BTES/ATES). The CO_2 payback time of tanks is in the order of a year to a few years. For ATES and BTES systems, this is probably in the order of weeks. TTES scores – on this indicator.

Appendix 5: PTES

5.1 Storage capacity

Pit stores show tremendous diversity in scale. The smallest pits are smaller than 1000 m^3, with the largest pit being over 200 000 m^3. Most of the smallest pits were pilot plants built in the '80s and 90's, as part of research projects in Sweden, Denmark and Germany. Some twenty years later, using the knowledge gained in these projects, a huge increase in the sizing of those stores is observed and multiple > 50 000 m^3 pit storages have been commissioned in the last decade. This does not go for the WGTES systems, which seem to have 'lost the battle' against PTES systems and did see through this tremendous increase in scale.

Pit stores now aim to compensate for their inferior shape (in terms of heat losses) and poor insulation with large size and relatively low construction costs. Since the size of pit stores is what makes them so competitive, it is probably unlikely to see future pit stores being built for smaller than 50 000 m^3. Larger volumes, even more than 200 000 m^3 are perfectly possible as long as there are no space limitations.

#	name	year	country	storage type	volume (m^3)	water equivalents (m^3)
1	**Lambohov**	1980	SWE	**PTES**	10,000	10,000
2	**Malung**	1989	SWE	**PTES**	800	800
3	**Herlev (Tubberupvaenge)**	1991	DEN	**PTES**	3,000	3,000
4	**Ottrupgaard**	1995	DEN	**PTES**	1,500	1,500
5	**Jülich**	1996	GER	**PTES**	2,500	2,500
6	**Marstal (SUN STORE 4)**	2012	DEN	**PTES**	75,000	75,000
7	**Dronninglund**	2013	DEN	**PTES**	62,000	62,000
8	**Gram**	2015	DEN	**PTES**	122,000	122,000
9	**Vojens (1+2)**	2015	DEN	**PTES**	203,000	203,000
10	**Logumkloster**	2016	DEN	**PTES**	150,000	150,000
25	**Vaulruz**	1983	SWI	**WGTES**	3,500	n.a.
26	**Stuttgart**	1985	GER	**WGTES**	1,050	725
27	**Augsburg**	1996	GER	**WGTES**	6,500	3,250
28	**Steinfurt (Borghorst)**	1999	GER	**WGTES**	1,500	1,000
29	**Chemnitz**	2000	GER	**WGTES**	8,000	5,300
30	**Eggenstein (Leopoldshafen)**	2008	GER	**WGTES**	4,530	3,000
31	**Sonderborg Vollerup**	2008	DEN	**WGTES**	4,000	n.a.

Figure 11: Overview of Pit and Water-gravel thermal energy storage systems[13]

5.2 Storage efficiency

Pit stores are generally badly insulated. The top is always insulated, while the sides and bottom have to do with just a liner separating the water inside the pit from the soil outside. So, even though the storage material of the pit is out of contact with the external environment, heat losses can still be severe. The surface to volume ratio, which is another important determinant for efficiency, is neither in favour of pits. Pits are generally quite shallow (5-15 metres) because the bottom of the pit should be well above the groundwater level (to prevent extra heat losses). This shallowness means there has to be a relatively large heat losing surface in relation to the storage volume. The only means for a pit store to counteract these negative effects on efficiency is to scale the pit to huge dimensions as to lower the surface to volume ratio, as Figure 6-13 depicts.

Figure 6-14 below shows in blue and yellow, the relation between thermal losses and storage volume (a) and

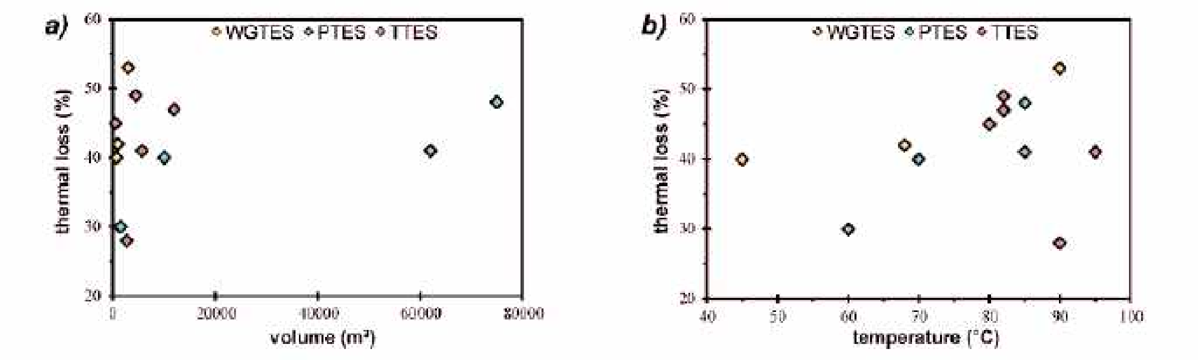


Figure 13: Performance of present storage systems in relation to volume (a) and operation temperature level (b). WGTES = Water-Gravel Thermal Energy Storage [28].

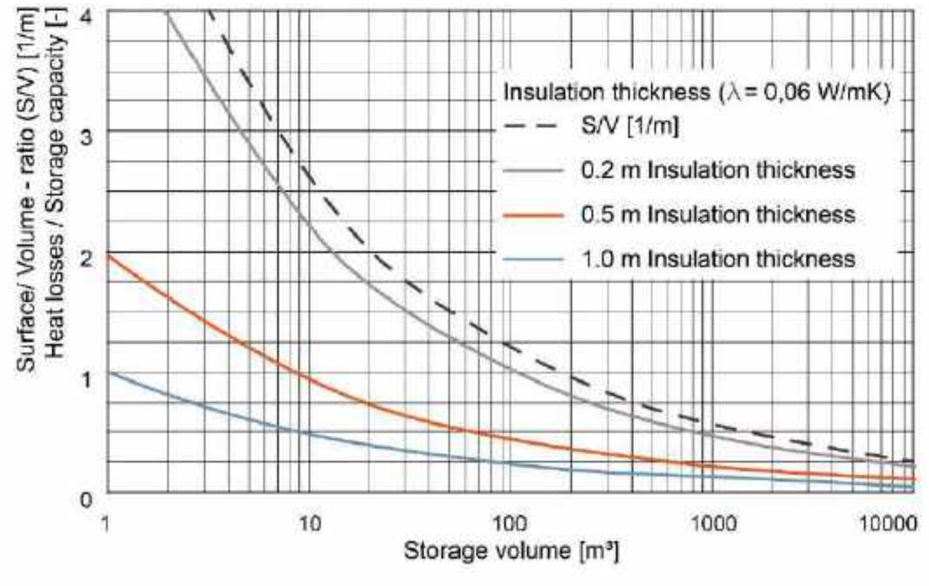


Figure 12: Ratio of heat losses to storage capacity ratio versus storage volume in m^3 for a storage duration of 6 months and a storage temperature of 40 K above ambient temperature [2]

the relation between thermal losses and temperature. One can see that for high-temperature storage, the pits lose between 30-55 % of the heat. WGTES seem to perform worse than PTES, although both perform badly. This is also noted by the authors, who stress that efficiency is still a key point of attention for improvement.

– *"Even though it is assumed that for optimal implementation, energy losses can be reduced to only 10 % the energy losses of existing storage systems are at least three times higher* [28]*."*

The heat losses observed in practice are much larger than expected (also for large systems of 60 000 & 75 000 m^3) and there is still plenty room for improvement in terms of efficiency for WGTES and PTES systems. For newly constructed large pits, 75 % efficiency seems an optimistic yet reasonable estimate.

5.3 Maximum temperature

Pit stores are limited in their storage temperature mostly by liner materials. Currently, research is ongoing into uncovering the most suitable liner material that can withstand high-temperature exposure for very long durations. Currently, most pits store heat no higher than 80-85 ˚C, primarily because of this limitation [2]. 80 ˚C is taken as maximal storage temperature for the comparison.

5.4 Levelized cost of energy storage

Lifetime

PTES systems are currently held back in either their storage temperature or lifetime by the insufficient lifetime of liner materials upon high-temperature exposure (i.e. 90 ˚C), which is why pits store up till 80 ˚C. But even at that temperature, the typically used HDPE liners show uncertain lifetimes in the order of 10 years. "Test results show liner lifetimes of 5-25 years at 90°C depending on oxygen content[5]".
With current projects using HDPE / Polymer liners there remains an issue with degradation over the installation's lifetime related to the condensation of vapours.

Generally, HDPE liners are used as liners. Metal liners are a possible solution to the limited lifetime of the plastic liners but metals are generally a few times as expensive as plastics, pushing up the investment costs. *Table 7* shows a typical service life of HDPE liners at different temperature.

	Service life (years)			
Temperature (° C)	Liner 1	Liner 2	Liner 3	Liner 4
90	2.5	3.2	2.9	4.3
80	6.1	7.2	10.0	10.0
70	25.9	17.0	15.6	23.0
60	43.7	42.4	35.9	52.9

Table 7: Service life of HDPE liners at different temperatures [2]

Currently, a liner with a lifetime of 20 years at 90 ˚C is under development. Until that time, the lifetime of PTES stores is only about 10 years at 80 ˚C when using standard HDPE liners. Employing different material or using multiple layers enables approximately double that lifetime, so 20 years.

Capital expenses

PTES stores can reach notoriously low specific investment costs due to their scalability. In the last 8 years, 5 large scale PTES projects have shown investment costs varying from 25-40 €/m^3 [2][10].

Given that the associated technologies and skills required are established, the cost reduction potential of PTES is primarily related to scalability. Additional cost reduction factors identified are primarily connected to the material of the lining and quality of insulation, which would reduce losses and offers some potential for reducing development/manufacturing cost. Interviews with industry indicated that should larger scale projects be realised and PTES becomes more established, costs could decrease below 28 €/m³. In the figure below the orange diamonds show investment costs as a function of system size.

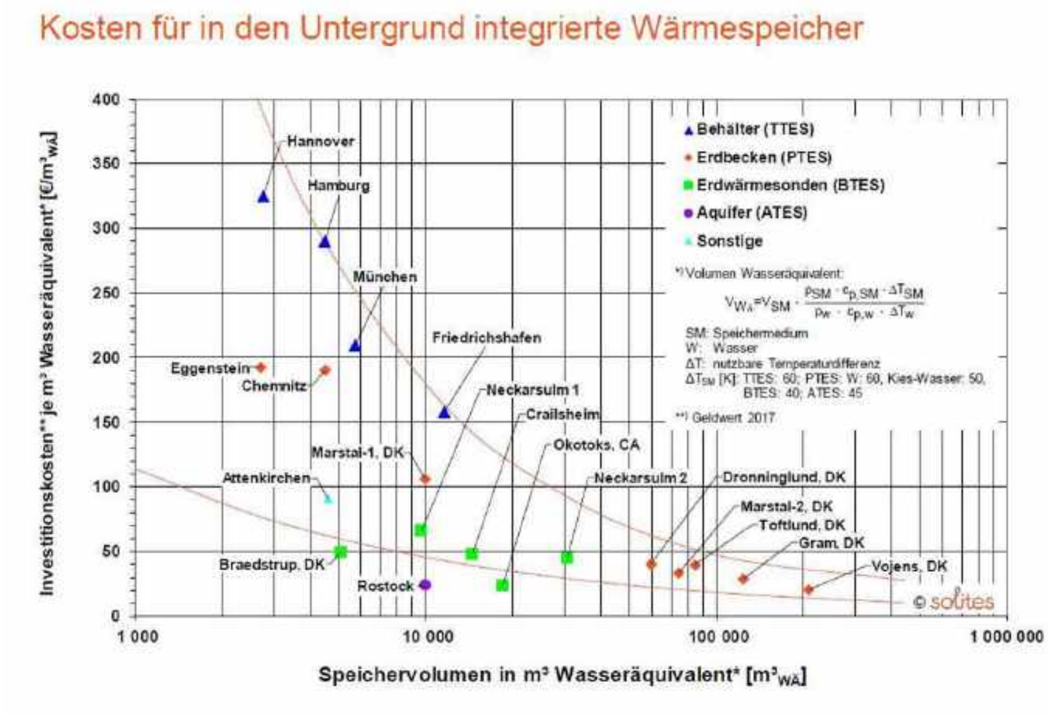


Figure 14: Investment costs for different LSSTES systems as function of system size [25].

Figure 15 shows the specific investment costs for different storage volumes. 30 €/m³ is assumed for the calculation of case 3 (140 000 m³).

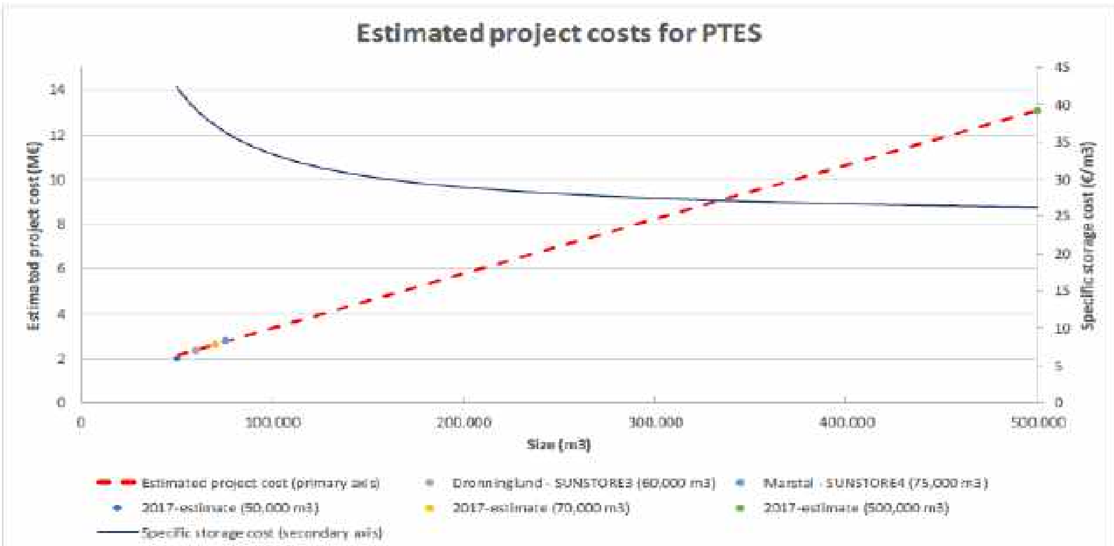


Figure 15: expected specific storage costs for PTES projects as function of system size [2]

Operational expenses

Data regarding the operational expenses of two large pit stores are public. For both the Marstal-2 (75 000 m^3) and Dronninglund (60 000 m^3) projects the yearly operational expenses amounted to 30 000 €/year [1]. A different [10] reports a lower yearly operational cost for the Dronninglund project to be 21 000 €. It is assumed that these costs will scale linearly with the size of the storage capacity of the pit store. And 30 000 €/year is taken as reference for 70 000 m^3.

5.5 Land use

The land use of PTES and WGTES systems is one of the prime barriers to implementation. Pit stores are generally no deeper than 15 metres (due to groundwater level), implying that scaling-up should come from larger width and length of the store, increasing the land demands for the storage pit. Especially for WGTES systems, the lower volumetric storage capacity aggravates this problem and increases the demand for land to achieve similar storage capacity.

Additionally, the pit is always elevated above ground-level, making the storage module quite obstructive and simultaneously rendering the entire surface area unusable. For the calculations, the pit is assumed to have 15 metres of storage height, with a square shape when viewed from the top. At the edges the storage is inclined at 45 ° to account for the reduced storage volume.

5.6 Suitability for high-power application

PTES storages are suitable for high-power applications as the design can easily accommodate a high heat exchange system to provide high power. WGTES storages have to rely mostly on conductive heat transport due to the solid storage material, which means troublesome heat exchange and less suitability for high-power applications.

The ramp-up time need not be high as the extracted volume can be adjusted fast by altering the pump power. PTES scores ++ for this indicator.

5.7 Building emissions

Among the insulated systems, pit stores use much less building materials than tanks of equal size, but more than non-insulated systems (ATES and BTES). PTES scores +-, in the middle ground

5.8 (Geological) Requirements and barriers to implementation

- One of the most pressing ‘issues’ with pit stores is their excessive land use, which is oftentimes a problem in urban areas.
- A second problem with pits is that there are no currently available cheap liner materials that can withstand high temperature (i.e. 90°C) for the intended lifetime of a pit store. This limits either the maximum storage temperature or the lifetime of the liners.

- Construction of pits in regions of high groundwater levels is troublesome if not impossible. Since the pits are not insulated at the bottom and sides, large heat losses are expected where the geological environment is not optimal.
- The volumetric storage capacity of pits (in the case of WGTES) is much lower than water, implicating even larger land-use necessary for WGTES compared to PTES. Moreover, since pits have limited maximum depth, the width and length of the store are the only means to increase storage capacity, further increasing the land-use necessary for pit stores.
- High groundwater levels and poor soil conditions directly affect construction costs. When groundwater almost reaches the surface PTES might not be an option at all, which is why PTES scores -- for geological requirements.

Appendix 6: input parameters

A lot of assumptions regarding the characteristics of the storage modules had to be made to enable the quantitative comparison, of which the results are presented in chapter 4, performance assessment. The main assumption and most important values taken as input parameters are displayed in the following tables below. The second table is valid only for the base case. Of course, the other cases used other values (but the same method. Some cells in the table are colour-marked, because they deviate from the standard cells. The explanation of this colour coding is given under the table on the next page.

Parameters	Value	Unit
Price of heat standard	10	EUR/GJ
Price of heat low	2,5	EUR/GJ
Costs of electricity (hydraulic & heat pumps)	0.1	EUR/kWh
groundwater temperature	10	°C
Coefficient of performance heat pump	5	-
Return temperature DHN	30	°C
Average supply Temperature DHN	50	°C
WACC	4	%
Cp soil	2100	kJ/m3*K
Cp water	4200	kJ/m3*K
Peak heat demand per house	3	kW
Heat demand / household * year	30	GJ
Percentage of heat demand supplied by storage	25	%

Parameter	Unit	Ecovat	HT-ATES	HT-PTES	HT-BTES	HT-TTES
Volume	m^3	Determined by efficiency and energy density storage				
Storage temperature	°C	90	90	80	80	90
Discharge temperature	°C	20	50	20	20	20
Energy density	GJ/m^3	Cp storage medium * (T storage – T discharge)				
Thermal Power	MW	12	6	12	6	12
Efficiency (final)	%	90%	70%	75%	50%	70%
Specific investment costs	€/m^3	150	10	30	50	110
CAPEX	€	€/m3*storage volume		€/m3*storage volume		
OPEX	%/€	50 000 €		60 000 €	100 000 €	50 000 €
Costs of heat compensation	€	(Heat lost more than Ecovat over lifetime + start-up losses) * price of heat				
Total Costs of heat pumps	€	--->>>	€ 0	(T return – T dis) / (T stor-T dis)* Storage cap/ (COP heat pump * price of electricity)		
Lifetime	Years	50	30	20	50	50
Financing period	Years	40	30	20	40	40
Total cost of ownership	€	CAPEX + (OPEX * Lifetime) + (Financing period * yearly interest) + Heat pump costs + Heat loss compensation				

(orange)	(HT) ATES and (HT) BTES are not suitable for peak power delivery. Therefore, it is assumed that these systems deliver half of the peak demand as maximum power
(purple)	Multiple methods were used to determine the CAPEX and OPEX. The used values are weighted averages of those methods
(green)	When the discharge temperature is higher than the initial groundwater temperature, the start-up losses are the difference between the discharge temperature and groundwater temperature
(light green)	In these cases additional start-up losses are accounted for, for heating of the surrounding soil. The efficiency starts at 40 % lower than end efficiency and linearly rises in four years to eff end -5. The last five years each year 1% increases
(yellow)	The specific investment costs here are for one water equivalent, so that is about 25 EUR/m3 since Cp soil ~= 1/2 Cp water.

Financial assumptions

The case examined in the comparison assumes a yearly heat demand roughly equal to that of 1000 households (7216 MWh). The storages are dimensioned in a way that allows the storage to retain that heat after storage for a full season (6 months).

The costs for the storage are built up of 5 components.

1. CAPEX: these are the total investment costs for the storage module that are paid of using a loan with a duration of the financing period. The financing period is equal to the lifetime of the storage module with a maximum of 40 years.
2. OPEX: yearly costs as a percentage of the CAPEX. Contains maintenance costs but excluding the costs of heat.
3. Heat loss compensation: all storage modules are assumed to be filled with 'free heat'. This is because the aim is to quantify the costs of STORING energy. These costs should be added to the production costs of heat to get to the total heat costs. Some storages will lose more heat than others, meaning that more heat will have to be put into the storage in the beginning. The amount of heat that is lost during storage equals the amount that has to be produced extra and is therefore an extra cost (compared to no storage). This term is called 'heat loss compensation'.
   The price of heat is assumed to be 10 €/GJ.
4. Interest: the interest is the cumulated WACC over the financing period. Different values for WACC per project hold.
5. Start-up losses compensation: apart from standard thermal losses, ATES and BTES systems lose more heat during the first years of operation. This excess heat is lost and, like 'normal' losses has to be compensated for.

Land-use: required space

For each of the technologies a storage capacity is fixated, after the losses have occurred. The required space for a storage system, then, is amount of land occupied by the storage module. In other words, how much land is used by this project. Some projects completely render the space over which they are built useless, like in cases where the systems sticks out above the soil (pits and some TTES projects). Ecovat is built completely underground and the above-lying area can still be utilized. However, the applications are limited. As such, we assume for the time being that the surface is useless afterwards, and that the possible usages of the room can be considered a bonus.

For Ecovat, the top surface area of the entire construction is used as required space. A Large Ecovat has a height/diameter (H/D) ratio of one (50/50 metres storage volume). To this diameter, the width of the outer wall is added. Different height/diameter ratios are not possible due to the construction method of the vessel.

For conventional TTES systems, the H/D ratio can be varied to produce a flat or long cylinder, according to the constraints of the construction site. For seasonal storage applications, minimizing the heat losses is one of the prime concerns. When there are no limitations regarding space usage, the optimal geometry to minimize heat loss is a 1 tot 1 H/D ratio. In commissioned seasonal storage systems, there are deviations from this optimal geometry but they tend to be mild. Therefore, this comparison assumed that a tank with equal storage capacity of Ecovat will have a minimal height to diameter ratio of 2/3 and maximal ratio of 3/2. This yields a surface area range for TTES. Oftentimes, when, TT/ES systems are (partially) built above ground, a sand layer is added at the top and sides to support the structure and reduce the visual intrusiveness of the storage unit (see figure 6-17). In that case, the 'used' area is much larger than just the top surface area of the storage vessel. For the calculations, it is assumed that this layer of sand is inclined at 45° from the horizontal and the range over which the sand extends is added to the diameter of the tank.

Figure: Sand layer at above ground TTES system

For PTTES systems, case studies of storages with similar heat storage capacity where analysed (Marstal-2,Toftlund, Gram and Vojens). These systems are typically 10-15 metres deep. 15 metres is assumed in this calculations (10 metres below ground level and 5 metres above). The shape of the storage pit (from top view) is assumed square and the walls inclined at an angle of 45° (both inner and outer wall). From this information, the length (and thus width) of the storage vessel is calculated. Similar to the TTES systems, the side sand layer is adds to the surface area of the storage unit.

Appendix 7: Sensitivity Analysis

To gauge the effect of the uncertainty for each project on the LCOES a sensitivity analysis is performed for the main case (7200 MWh) for each technology. The calculations are made for three values:

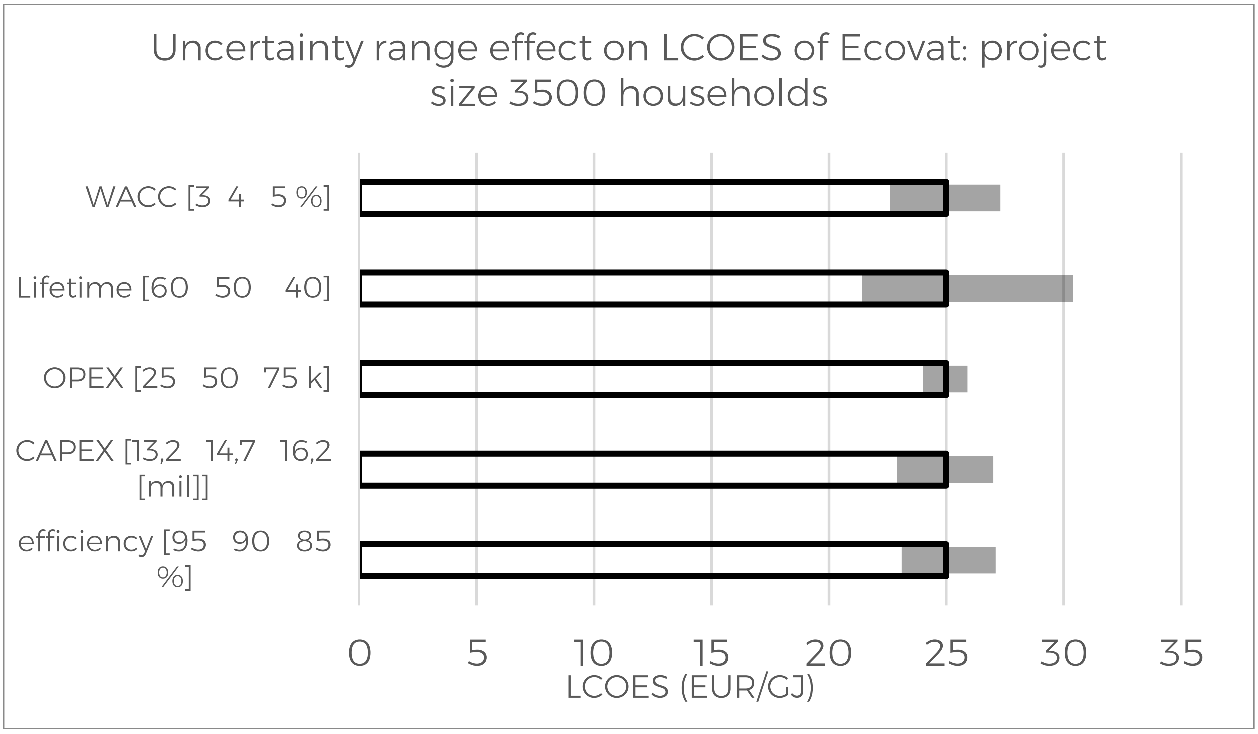
1. A low estimate
2. A middle estimate (used in main calculations)
3. A high estimate

The three estimates are considered to contain 95% of the occurrences in real-life.

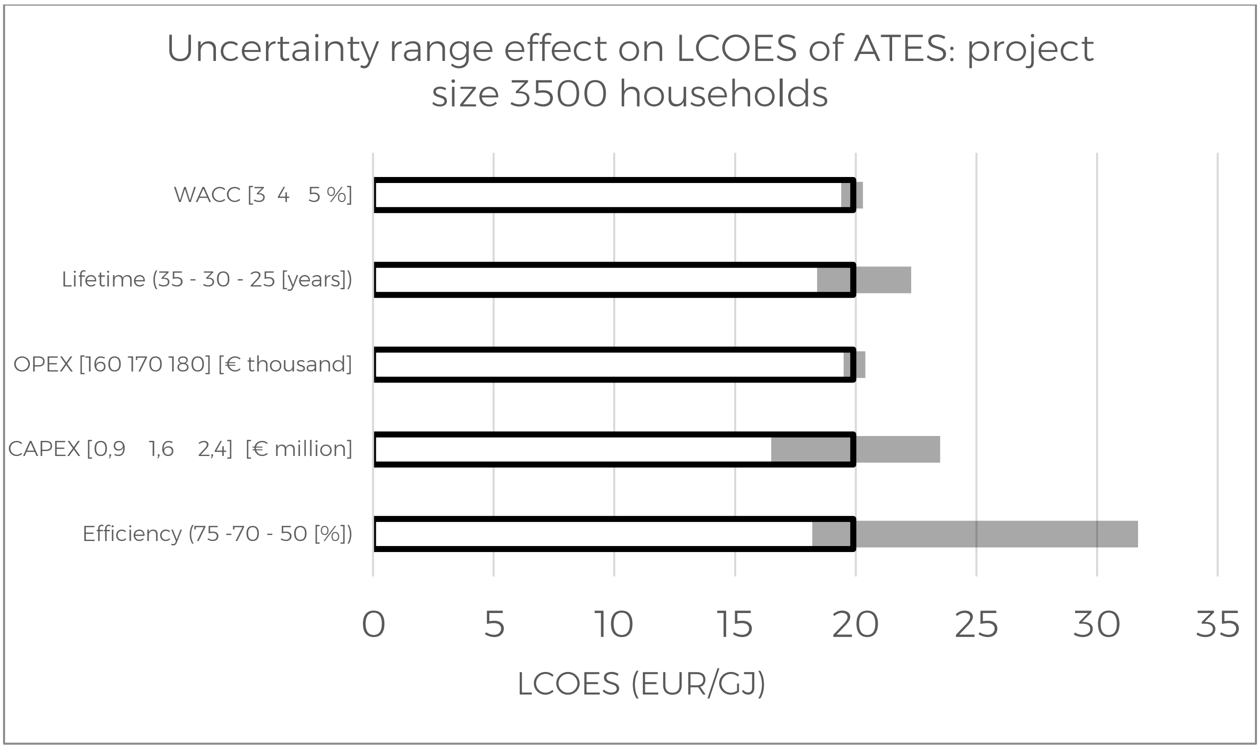
The next paragraph presents an overview table in which the final two columns display the effect size of the low and high estimate on the LCOES for that specific technology.

The remaining paragraphs display bar graphs of the uncertainties and the effect on the LCOES. The low-cost estimate is displayed as the first number in brackets, the middle estimate the second and the high-cost estimate as last value in brackets. The white bar with black contour displays the standard calculation and the grey bar is the uncertainty bar. The left edge of the bar is the LCOES had the low-cost estimate been correct, analogous for the right edge of the grey error bar. The table below is an overview of all the individual uncertainties and effects on the LCOE per technology.

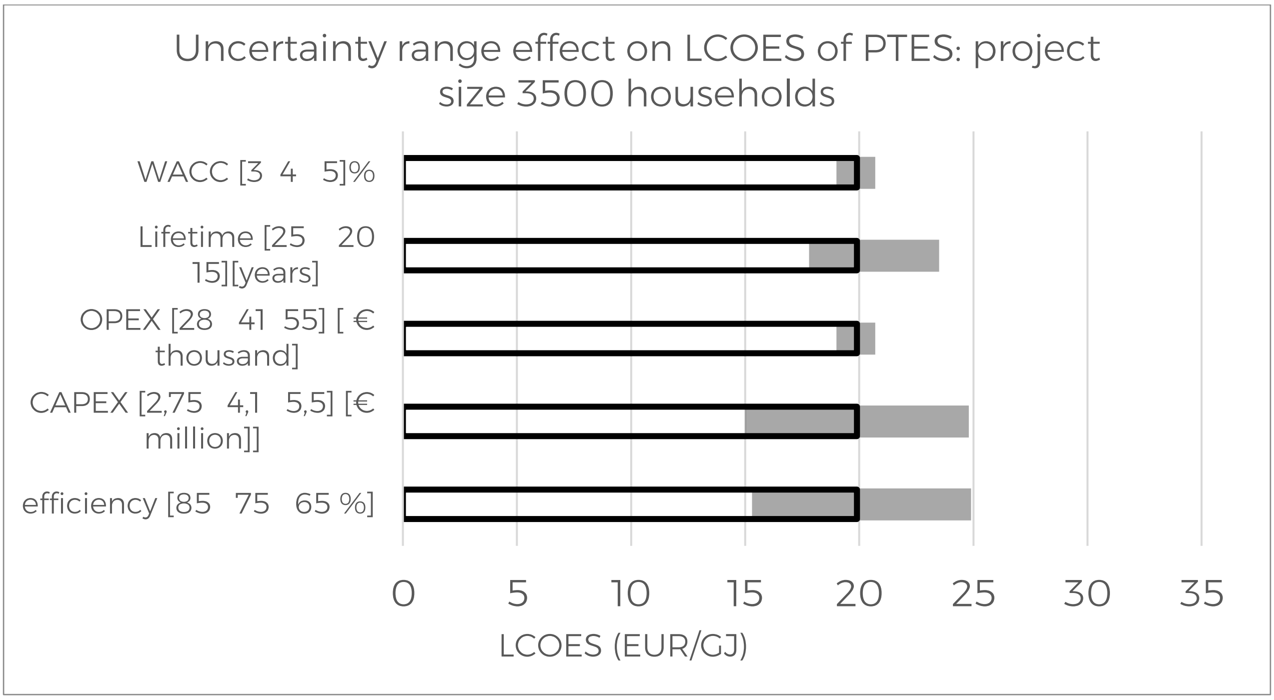
ATES	**Low estimate**	**LCOES standard**	**high estimate**	**Decrease**	**Increase**
Efficiency (75 -70 - 50 [%])	31,7	19,9	18,2	1,7	11,8
CAPEX [0,9 1,6 2,4] [€ million]	16,5	19,9	23,5	3,4	3,6
OPEX [160 170 180] [€ thousand]	19,5	19,9	20,4	0,4	0,5
Lifetime (35 - 30 - 25 [years])	22,3	19,9	18,4	1,5	2,4
WACC [3 4 5 %]	20,3	19,9	19,4	0,5	0,4
Ecovat	**Low estimate**	**LCOES standard**	**high estimate**	**lesser costs**	**added cost**
efficiency [95 90 85 %]	27,1	25	23,1	1,9	2,1
CAPEX [13,2 14,7 16,2 [mil]]	22,9	25	27	2,1	2
OPEX [25 50 75 k]	24	25	25,9	1	0,9
Lifetime [60 50 40]	30,4	25	21,4	3,6	5,4
WACC [3 4 5 %]	22,6	25	27,3	2,4	2,3
PTES	**Low estimate**	**LCOES standard**	**high estimate**	**lesser costs**	**added cost**
efficiency [85 75 65 %]	24,9	19,9	15,3	4,6	5
CAPEX [2,75 4,1 5,5] [€ million]]	24,8	19,9	15	4,9	4,9
OPEX [28 41 55] [€ thousand]	20,7	19,9	19	0,9	0,8
Lifetime [25 20 15][years]	23,5	19,9	17,8	2,1	3,6
WACC [3 4 5]%	20,7	19,9	19	0,9	0,8
TTES	**Low estimate**	**LCOES standard**	**high estimate**	**lesser costs**	**added cost**
efficiency [80 70 60 %]	33,5	27,7	23,3	4,4	5,8
CAPEX [12 12,6 15,1] [€ million]	31,3	27,7	26,8	0,9	3,6
PEX [50 100 150] [€ thousan	29,6	27,7	25,7	2	1,9
Lifetime [75 50 40][years]	32,4	27,7	21,4	6,3	4,7
WACC [3 4 5]%	29,7	27,7	25,7	2	2



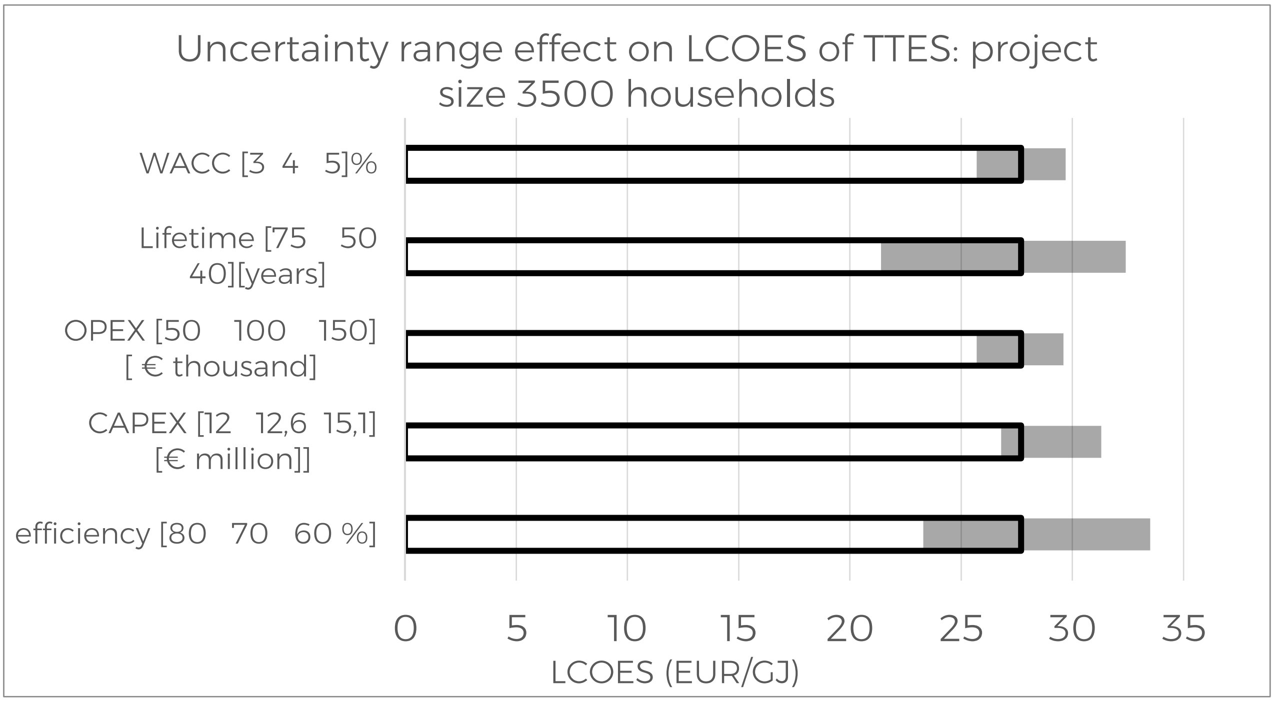
For Ecovat, discrepancies in lifetime have the largest effect on the LCOES.



For ATES, the spread in efficiency is large. Systems can perform much worse than designed and therefore the efficiency can be much lower. This means costs can be much higher for ATES is efficiency is lower than expected. CAPEX is also a source of considerable variance. Since the CAPEX is relatively low, the WACC is only of small influence.



PTES has quite a large spread in lifetime (relatively), because the liner materials are currently not sufficiently resistance to high-temperature exposure. The low lifetime also causes the uncertainty in CAPEX to have a strong effect on the LCOES. PTES systems also show high variance in efficiency, which also causes high variability in the LCOES.



TTES is similar to Ecovat in terms of the high spread in costs due to lifetime uncertainty. TTES systems have a larger spread in the efficiency, which is also a source of large cost variability.

Appendix 8: Different project sizes

This research aims to compare Ecovat to its potential competitors. As mentioned in the main text, 4 different project sizes have been defined, ranging from the smallest Ecovat to two of the largest Ecovat vessels. The table below displays the accompanying heat supply from the storage and how many houses can be connected (when 25% of the heat demand requires storage). Case 3 is the main case.

Case #	Ecovat Storage Volume (m^3)	Heat delivered from storage	Number of houses connected	Fraction of heat demand from Storage
1	20 000	1500 MWh	700	25%
2	50 000	4000 MWh	2000	25%
3	100 000	7220 MWh	3500	25%
4	2* 100 000	1440 MWh	7000	25%

Table 8-1: Heat demand and households per case for 25 % of heat demand requiring storage

Table 8-2 shows which technologies are applicable for the cases defined in the comparison.

Suitable	Not ideal	Not suitable

Legend Table 8-2

Case	Heat (MWh)	Ecovat (#)	ATES	BTES	PTES	TTES (#)
1	1500	(1)	Low efficiency			(1)
2	4000	(1)	Low efficiency	Power too low		(3)
3	7220	(1)		Power too low		(6-7)
4	14400	(2)		Power too low		(13-14)

Table 8-2: Suitability of each technology per case and number of systems required.

The table below indicates what values are used for the calculation of all the cases. Only the parameters that have different values than the main case are mentioned here (see appendix 6: input parameters). The light red colour indicates that the analysis is skipped for that technology and case combination. The table above explains why. The purple marker refers to a deviating method for the CAPEX calculation. See appendix 6 for explanation.

Case 1: 1500 MWh	Volume	Efficiency	CAPEX
	m^3	%	€/m^3
Ecovat	21 000	85%	€ 280
HT-ATES	-	-	-
HT-PTES	32 500	65%	€ 40
HT-BTES	84 000	50%	€ 50
HT-TTES	25 000	70%	€ 110
Case 2: 4000 MWh			
Ecovat	50 0000	87,5%	€ 210
HT-ATES	-	-	-
HT-PTES	80 000	70%	€ 40
HT-BTES	-	-	-
HT-TTES	70 000	70%	€ 110
Case 3: 7220 MWh			
Ecovat	98 000	90,0%	€ 150
HT-ATES	220 000	70%	
HT-PTES	140 000	75%	€ 30
HT-BTES	-	-	-
HT-TTES	125 000	70%	€ 110
Case 4: 1440MWh			
Ecovat	196 000	90,0%	€ 150
HT-ATES	410 000	75%	
HT-PTES	260 000	70%	€ 40
HT-BTES	-	-	-
HT-TTES	-	-	-

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