Seasonal thermal energy storage as a complementary technology

Case study insights from Denmark and The Netherlands

Citation for published version:
Bolton, R, Cameron, L, Kerr, N, Winskel, M & Desguers, T 2023, 'Seasonal thermal energy storage as a complementary technology: Case study insights from Denmark and The Netherlands', *Journal of Energy Storage*, vol. 73, no. Part D, 109249, pp. 1-15. https://doi.org/10.1016/j.est.2023.109249

Digital Object Identifier (DOI):
10.1016/j.est.2023.109249

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Journal of Energy Storage

Journal of Energy Storage 73 (2023) 109249

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Research Papers

Seasonal thermal energy storage as a complementary technology: Case study insights from Denmark and The Netherlands

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ARTICLE INFO

Keywords:
Seasonal thermal energy storage (STES)
Energy storage
Sustainable energy systems
System transition
Technological complementarities
Institutional complementarities

ABSTRACT

Seasonal thermal energy storage (STES) has potential to act as an enabling technology in the transition to sustainable and low carbon energy systems. It is a relatively mature technology, providing a reliable and large-scale solution to seasonal variations in energy supply and demand where it has been deployed at scale. In practice, however, there remains minimal deployment of STES internationally, with only a small number of countries being exceptions. Here, we analyse STES development in two of these exceptions: the Netherlands and Denmark, and we consider the relevance of the Dutch and Danish STES experiences for other countries, such as the UK, where STES is currently marginal. In explaining the diffusion of STES in leading countries, and its limited uptake elsewhere, we pay attention to energy system context by investigating the complementarities – or misalignments – between different parts of energy systems which have influenced STES deployment. The contribution arising from our mainly qualitative and historical analysis is to demonstrate the importance of contextual factors such as national policy and complementarities between technical and social factors in influencing STES deployment. This approach, we argue, can complement and enrich engineering and economic perspectives on STES.

1. Introduction

Future heating systems running on low carbon electricity, low carbon fuels, or a mix of the two, will have to consider various modes of energy storage. There is a wide variety of storage technologies competing to fulfil the requirements of a low carbon energy system. Thermal energy storage (TES) is the simplest and most well-established form of accommodating highly variable energy and demand in the transition to sustainable energy systems. The most common forms of TES are currently at the building-level and provide diurnal (within day) storage. Alongside short-term fluctuations, there is also a need to address seasonal variations in supply and demand [1]. Seasonal thermal energy storage (STES), which can provide interseasonal balancing, is seen as increasingly important enabler for low carbon transitions as natural gas reduces in the overall energy mix [2]. In a low carbon system, STES applications can offer flexibility by shifting heat demand to off-peak periods, reducing overall capacity requirements, improving the utilisation of renewable energy sources, and lowering system operating costs [3,4].

However, there is little deployment of this form of energy storage globally; for example, 93 % of global storage capacity is under 10 hours [5]. For some of its proponents, the neglect of STES arises from a preoccupation in energy policy on electrification and electricity storage as the engine of the energy transition [3,6]. Electricity storage has greater functionality (higher exergy) than thermal storage and is often seen as a key enabler of energy system integration across multiple vectors and services [7]. However, in countries such as the UK, there is an increasingly urgent need to address long-term (10 hours plus, including interseasonal) variations in demand for building-level heating so far resolved by fossil fuel stocks and reserves, especially natural gas [8]. Different forms of STES could help to address these challenges [9–11], but in practice there are few examples of deployment at scale [1].

In order to better understand the mismatch between STES as a potentially important enabling technology, and its marginal current role, we consider two of its most well-developed technological forms and country contexts: aquifer thermal energy storage (ATES) in the Netherlands and pit storage (PTES) in Denmark [8]. These countries are world-leaders in these respective forms of STES, with heating and cooling demand variations comparable to many mid to high-latitude countries, such as the UK, and thus offer useful case studies to

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https://doi.org/10.1016/j.est.2023.109249
Received 15 May 2023; Received in revised form 4 October 2023; Accepted 7 October 2023

examine the factors which influence successful STES deployment.

To understand the pattern of STES deployment in these countries, we consider the importance of energy system context, particularly the complementarity (or otherwise) of different parts of the system at the local level, and how this is shaped by sector structures and national policy. Drawing from the innovation studies literature, we propose a framework for analysing STES deployment which considers complementarities across three interlinked domains: technology, sector and institutional levels.

The paper is structured as follows: Section 2 sets out the background literature. Here we review two major strands of literature on STES. The first, and most extensive, covers anticipated deployment and costs. These are primarily pre-deployment studies including energy system modelling and a number of technoeconomic appraisals. The second strand focuses more on real-world deployment, but this literature is limited to a small number of studies. What the existing literature on STES points to, but rarely investigates in-depth, are the ways in which systemic interdependencies and contextual factors influence real-world deployment prospects. Through our in-depth case studies set out below we seek to address this gap in the literature. Section 3 describes the analytical approach which is based on a complementarities framework, and the empirical methods. Section 4 presents a comparative analysis of the diffusion of STES technologies in the Netherlands and Denmark highlighting the role of socio-technical context and complementarity in its development and diffusion. In Section 5 we analyse the cases using the complementarities framework. In Section 6 we conclude the paper, and highlight the potential for contextualised and qualitative-historical accounts such as our own to inform and enrich and technoeconomic studies of STES.

2. Literature review

2.1. Thermal energy storage

The main strand of the academic literature to date on STES is techno-economic feasibility studies. These focus on assessing the energy [12] and economic performance of certain heat sources, stores, and combinations thereof [13–17]. Most studied and promising combinations include solar thermal-PTES [17], solar thermal Tank-TES [18], and energy from waste (EfW)-combined heat and power (CHP)-PTES. Heating network research is also a well-developed component of this literature, such as techno-economic analysis of PTES and Tank-TES with district heating systems (DHS) [19].

The primary methods techno-economic studies employ are literature reviews [18,20] and quantitative computer modelling [21]. Analysis tends to be rather abstract [19], but some techno-economic studies are contextualised, variously at country-level [22], building-level [23], project-level [24], city-level [17], or regional and district level [25].

Characterising STES costs can be challenging, as cost analysis and options appraisal are both highly context-dependent (in Appendix A we present further data on techno-economic variables for STES which discusses these issues more extensively).[1] As a result, direct comparisons between STES and other energy storage types can be problematic. These issues of context dependency and coupling at the local level are less problematic for electrical storage options which are more globally developed, have faster installation times and are better supported in policy, planning and market frameworks. They are thus more systemically embedded.

Within techno-economic STES studies, four areas of empirical focus have emerged: technical appraisals and modelling studies in relation to optimisation and coupling; smart energy systems [26]; advanced district heating systems (5GDHS); and the influence of policy mechanisms on the techno-economics of STES [17]. Lyden et al. [26], for instance, analyse STES in smart energy systems at the district-level, providing a review of various modelling approaches. Lund et al. [27] provide a techno-economic study of STES combined with advanced heat networks; they find that the ability to connect to a heat network improves the economic viability and performance of STES.

Lund et al. [28] advance this further by showing that as heat networks continue to improve their efficiency, so does the viability and systems-level value of STES, indicating an important coupling between the two technologies. Renaldi and Friedrich [17], in a rare example of grounding energy modelling with contextual real-world data, develop a model using data from Drake Landing solar thermal in Canada and socio-technical data for two cities in Scotland, including climate, heat demand and building stock. They find that it is technically possible to achieve over 95 % solar thermal efficiencies if coupled with heat networks and borehole-TES or PTES.

Thermal storage of some type and scale is quite common in heat network schemes – 15 % of district heating globally [29] – as it enables a range of benefits for the whole system it is integrated with. These include enabling systems to be optimised, integrating greater shares of renewable thermal energy and power and local sources of heat and cooling, improved balancing, and improved system decarbonisation, sustainability and resilience. The extent to which these benefits are achieved will depend on how well managed the system is, and the extent to which markets and regulation value these benefits over systems without large-scale TES or STES. The techno-economics of large-scale TES or STES also depend on the extent to which a locality has natural resources which favour the lowest cost and most efficient forms – such as shallow aquifers with low flow rates for ATES – and on wider socio-technical capabilities such as skills, know-how, low-cost finance and efficient planning and permitting (see Appendix A).

While these findings underscore the contextual dependency of STES, the multi-dimensionality of context and its role in shaping technical systems is rarely captured in conventional techno-economic analyses – the dominant strand of the literature on this technology. Techno-economic studies may omit many of the socio-technical factors that affect STES, including market structures, business models, investor trust, and public and end-user acceptance. Other important contextual variables impinging on the viability and costs of STES are the proximity of existing assets that can be repurposed, such as caverns, abandoned mines, industrial sites and power plants, the presence of heat networks and the availability of data that is otherwise expensive to obtain, such as high-quality subsurface data from borehole sampling. Such contingencies underpin calls for STES to be studied in a range of contexts, such as via case study analysis and demonstration projects, and for analysis to include a wider range of relevant dimensions [30].

A small number of recent studies have sought to develop such an integrated socio-technical approach. Bertelsen et al. [6], for example, analyse the planning and investment process for STES in the Greater Copenhagen heat network. Combining stakeholder interviews, actor activity mapping, and analysis of wider energy plans and institutional settings, they demonstrate that energy planning and investment decisions, in various ways, are not neutral, and to become effective, they require ‘translation’ by collective and contextual social processes such as long-term trust-building, cooperation and compromise.

Another comprehensive socio-technical study, by Barns [31], draws attention to a key conceptual barrier to STES in Britain and beyond: an institutionalised approach which considers energy *sources* and *stores* as

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[1] Appendix A includes a comparative summary of key techno-economic characteristics of STES (Table A), Typical economic boundary conditions for STES (Table B), Typical technical boundary conditions of STES (Table C), and real-world techno-economic performance results for world-leading Danish PTES and Dutch ATES. We present these in the appendix because the focus of this paper is on the qualitative factors that influence STES growth in specific contexts because this focus, an issue which is relatively neglected in the STES literature. A techno-economic consideration, however adds to the robustness and added-value of this paper by supporting our qualitative analysis, data and arguments with quantitative data and techno-economic analysis.

distinct, rather than coupled. This segmented approach to planning, Barns argues, can be attributed to path dependency and the structure of the British gas-based heating regime, with its 'single-endowment' dominance of gas networks for heat. This hinders recognition of STES complementarities in the UK [32].

An additional relational effect is highlighted by Lund's work on the coupling of STES with heat networks. This emphasises complementarities between existing cooling demand and relevant actors [27,28]. Lund, Barnes and Collier all highlight that high levels of coupling across sectors and policies are necessary for deployment of STES, but this is unlikely to develop without considerable policy intervention to ensure that the system benefits of thermal storage can be captured.

While the issue has been highlighted in a number of STES-based studies, a contribution of this paper is to develop a more structured and systemic approach to analysing contextual factors and complementarities influencing STES deployment. We do so in the next section by drawing on the technological innovation systems literature.

2.2. Analysis of STES complementarities

As has been highlighted in the existing literature, patterns of STES deployment are strongly influenced by complementary relations between technologies. Thermal storage technologies of different types have tended to be coupled with heat networks and provide an important means of balancing loads and optimising these local systems. In a more general sense, such *technological complementarities* have been highlighted as an important feature of technology innovation systems (TISs). The TIS literature has emphasised how interactions of actors, institutions and technologies shape innovation processes at the development, deployment and wider diffusion phases of emerging niches, but empirical studies have tended to focus on single technology cases [33,34]; relatively few studies highlight cross-technology and multi-sectoral interdependencies and interactions [35], and there has been little or no work specifically on STES.

According to the TIS framing, interactions between energy technologies can be complementary or competitive – though these often co-exist in practice. For example, wind and solar PV may compete for market share, but deployment support policies may also benefit both [122]. In a narrowly technological and operational sense, STES technologies are embedded in wider energy system contexts and depend on complementary relations with other parts of the system: they require charging from energy sources and often rely on heat networks to discharge. In this sense, they can be seen as 'enabling' [36] or 'bridging' technologies [37].

While the literature reviewed in the previous section identified important complementarities and the enabling role that STES can play in low carbon systems, this work has primarily been from a techno-economic perspective, so omits actor and institutional dynamics. Social science and interdisciplinary research on this technology has begun to address this gap, however, empirical work has been primarily at the local level, with less emphasis on broader policy and regulatory frameworks. There is a need therefore to broaden research scope by paying attention to complementarities at different levels, from local technology linkages to broader national policy frameworks and institutions.

Markard and Hoffman offer a framework for this [38] highlighting *technology*, *infrastructure*, *organisational* and *institutional* complementarities affecting socio-technical systems. Linking this to the techno-economic literature on STES deployment reviewed above suggests the need for more attention on sectoral and institutional linkages. *Sector complementarities* include market and contracting structures which enable the value of thermal storage technologies to be realised [38], and also cross-sector linkages which facilitate the transfer of knowledge and capabilities across technology domains, enabling system economies to be exploited [39].

Institutional complementarities relate to policies, standards and regulations affecting an entire sector, and how they enable or constrain the deployment of certain niche technologies. These are particularly important for integrative technologies such as STES which are not viable as stand-alone investments, and thus need to align with prevailing rules and structures governing a large technical system such as electricity supply. In our analysis therefore, alongside technological complementarities, we highlight sector-level and institutional complementarities; we identify the processes and conditions of complementarity within and across these levels, and their influence on the deployment of STES.

In studying STES through this analytical frame, we also contribute to innovation studies research on complementarities and energy systems. Markard and Hoffmann's work mostly focuses on supply side technologies, with storage technologies analysed as part of the broader systems in which these focal technologies operate. Taking storage as the focal technology brings to the fore the temporal dimension of complementarities, an issue of growing importance as systems are increasingly dominated by variable renewables. Technologies which support system integration and managing variability across different timeframes, particularly seasonal variability, will play an increasingly important role in future energy systems. Another relevant feature of this technology is its 'local' character. STES is linked to individual end-use sites and/or heat networks which are often small scale and isolated. The study of STES complementarities should therefore bring to the fore multi-scale interactions, from national to very local sites.

3. Methodology

An emphasis on complementarities requires contextual analysis of deployment over long timescales. Case study research is therefore a suitable method for analysing complementarities as this approach enables insight into the pluralities of situated systems [40], how complex systems are 'constructed' by socio-technical processes [41], and the contextualised 'thick descriptions' of multi-dimensional, relational and processual data to best account for them [42]. The term for such data is often 'rich' or 'social' data, acknowledging its social or socio-technical construction. Case studies enable the capturing of such data by approaching phenomena 'in the wild', in real-world settings of interrelating, unfolding processes.

A comparative case-study approach helps to reveal a greater range of complementarities that may occur in STES technological configurations, and more effectively assess the conditions for, and influence of, those complementarities. While existing socio-technical studies of STES have developed localised case studies, we take a national-level comparative approach to more fully investigate the broader policy, market and regulatory environments shaping local contexts, enabling analysis of system level interactions.

Based on a review of existing datasets, we found thousands of installed STES projects, in countries such as Germany, Denmark, Sweden, Finland and the Netherlands. By contrast, there are only tens of installed STES systems in the UK [8]. Of the installed capacity of TES – both short and long duration/seasonal – worldwide in 2020 – totalling 234 GWh – the bulk is located in Germany, Denmark, and Sweden [43]. This trio dominates global TES deployment both in installed capacity and the number of schemes built [44]. On seasonal storage, Germany and Denmark have the majority of installed STES.

We selected Denmark and the Netherlands as national case studies due to their extensive deployment and specialisation in two particular forms of STES: PTES and ATES. Pit thermal energy storage (PTES) – seen mostly in Denmark – involves the use of a large hole in the ground where water (or water with gravel or sand) is used as a thermal storage medium. It is most commonly used alongside heat networks with large solar thermal arrays, but combined heat and power (CHP) and waste incineration plants have also been used as heat sources. Solar-PTES systems charge the store during the summer; at the beginning of winter the heat stored is at around 90 °C, so can be used directly in the heat network.

Low temperature aquifer thermal energy storage (ATES) is more common in the Netherlands. These systems provide both heating and cooling in a cyclical service, with the heat extracted in the summer for cooling purposes and stored to provide heating services in the winter. ATES systems consist of two wells – one cool, one warm – a heat pump and a dry cooler. A gas boiler is often also present to meet peak demands.

PTES and ATES both couple with their geological and hydrological contexts: PTES uses a low-cost and locally abundant thermal storage medium, and low-cost and locally abundant insulation (the surrounding ground). ATES utilises the thermal properties of water (high specific heat) and the storage properties of natural underground formations (vast storage capacities, excellent insulation), which are ubiquitous characteristics of aquifers.

Our unit of analysis in the cases is the whole STES system, incorporating all the components necessary for energy storage and discharge. Analysis of each case began with a literature review incorporating academic and grey literature; this was followed by interviews with relevant actors in each context, from which further literature was identified and the cases refined. (See Appendix B for an anonymised list of interviewees.)

On the basis of this documentary analysis and series of interviews, we detail the history of STES deployment in the two countries in the next section of the paper. These cases provide an overview of our two national cases, detailing significant aspects of their socio-technical contexts, and notable examples of technological, sector and institutional-level complementarities which influenced the deployment of STES in these countries since the early 1980s. In Section 5, we draw on the results to compare the cases and analyse the role of context and complementarities which have influenced technology diffusion in each case.

4. Case studies

4.1. ATES in the Netherlands

Pioneering and piloting work on ATES in the Netherlands began in the early 1980s [45]. Initial motivations were arguably more environmental than economic [45], related to early interest in low carbon energy (Interview, NL#4). The Dutch history of subsurface industries helped stimulate ATES deployment; a well-established Dutch groundwater extraction industry meant there was already established expertise in drilling and water extraction [46] (Interview, NL#4, 6, 7). A legacy of data collection on the location and type of aquifers from water and gas extraction was also important to the early development of the technology (Interview, NL#6). Firms involved with heating ventilation and cooling systems also brought knowledge and experience to the sector [45,46]. Larger design consultancies were initially more reserved about ATES, so smaller firms took the lead on the early projects [45,47].

Alongside enabling regulation, government financial support was made available for ATES demonstration projects [45] due to the relatively high risks and costs associated with monitoring impacts [48]. Early promotion and demonstration projects were also supported by the Environment Ministry who were looking to find new, sustainable uses for the subsurface (Interview, NL#3). Some early demonstration projects were also funded via the National Research Programme on Solar Energy [45], and an International Energy Agency research programme [47,48].

In the earliest stages, technology development ran ahead of governance arrangements [49,123], with limited regulations and higher temperatures than are currently permitted [48]. Many of the earliest projects ran into technical difficulty and were abandoned [45]. As uptake increased in the 1990s, regulations were introduced on a province-by-province basis, such as limits on injection temperature (Interview, NL#5). Communication and collaboration between developers, government departments and groundwater authorities was critical to development at this stage (Interview, NL#4).

Dutch ATES projects moved on from the demonstration phase and became commercial in the early to mid-1990s [46]. While some of the earliest systems were thought overly complex [45], a standard technique was established around 2000 [45,48] and the basic system design has been largely unchanged for many years (Interview, NL # 2, 4). This dominant design is for relatively small scale low temperature ATES. See Table E in Appendix A for details of this design and others used in the Netherlands.

Low temperature ATES became regarded as a mature and well understood technology [45,47,50]. There have since been incremental improvements in efficiency, with a minimum required seasonal performance factor (SPF) in place since 2013 [50]. The seasonal performance factor (SPF) is the average coefficient of performance (CoP) of a heat pump over the full heating season. The CoP is the ratio of heat output over the electrical input at any one time. ATES can be used as a heat source for a heat pump in order to increase the CoP of the heat pump and reach the required temperature level for a system. While it is possible to add a heat pump downstream of a STES, as this would require, one drawback of doing so is that it undermines the purpose of storage. Indeed, storage units decouple energy production from demand, but adding a heat pump means that electrical power would be required at times of energy extraction, which cannot be guaranteed to be available from variable renewables, thereby recoupling production and demand.

By 2000, there were around 100 ATES projects in the Netherlands [45], mostly in large non-domestic buildings; by 2005, this had grown to 550 installations [8], and 3000 in 2020 [51]. This was achieved despite the dominance of gas heating in the Netherlands, and low penetration of district heating (supplying just 4 % Dutch heat demand in 2017).

In order to understand the accelerated deployment of ATES in this case one needs to look at a broad socio-technical level, particularly the complementarities between energy and sustainability regulations across sectors and at a national level. In 2008, a Dutch Government taskforce was created to promote the ATES industry and recommended the adjustment of legislation to aid deployment. Two major research projects into the environmental impacts concluded that under certain conditions impacts were limited [52,53]. As a result, in 2013 a coordinated national regulatory framework was adopted [48]. The permitting process was streamlined and a licensing regime was introduced (#NL7). One interviewee suggested that the requirements for certification had made systems more expensive to install but had resulted in the improved efficiency and lower operational costs (Interview, NL #2). However, growth slowed after 2013 [46], with one interviewee suggesting that not enough government attention was given in this period (Interview, NL #3).

There is little public opposition to ATES, in-part due to its subterranean nature and a lack of public awareness (Interview, NL #1,4). One interviewee, however, observed that there was some resistance to drilling due to concern over groundwater pollution (Interview, NL #3), while another (Interview, NL #6) suggested there is a 'sensitivity to geothermal energy' due to the history of earthquakes in the province of Groningen related to gas extraction (see [54]).

Alongside central government, Dutch provinces and municipalities have played a significant role in STES deployment, through the permitting and licensing of groundwater extraction. While the provincial government provides licensing, municipalities are more influential in determining deployment, as they control local development plans and the placement of new buildings (Interview, NL #4). As a result, ATES master planning tends to take place at a municipality level (Interview, NL #7). Some municipalities – typically those with higher population density and existing schemes – have commissioned subsurface masterplans to encourage more efficient deployment. Subsurface masterplans are seen by some as critical to future development [50,55]. Historically, rights to abstract and inject heat have existed on a first-come first-served basis [48]. There remains a need to better coordinate and plan the deployment of ATES systems to make the most efficient use of available aquifers.

In the Dutch case, larger non-domestic ('utility') buildings with high energy and cooling demand are most suitable for ATES. Some projects connect to the Dutch horticultural sector, where ATES is often well-suited due to the temperature requirements of greenhouses. Even though the vast majority (80–90 %) of ATES globally is located in the Netherlands [43], it remains marginal at the national level: it is used in <1 % of Dutch non-domestic buildings [50]. For domestic buildings, ATES provides only 2 % of the country's heating and cooling demand (127 TWh) [56].

The Dutch case also paints a representative picture of the data quality and availability for installed STES. Data on techno-economic performance of STES in a range of the real-world settings is a significant gap in the knowledge base. Most countries also lack accurate data on the exact fraction of domestic buildings equipped with STES, and the aggregated storage capacity of STES. This data is very challenging to locate as it requires being aggregated to national-level from local-level systems which are typically not standardised and very bespoke. Important techno-economic data is often not monitored uniformly, and not always compiled and published frequently.

In the Dutch case, The Netherlands Central Bureau of Statistics reviews and publishes the country's energy balance, but the last three reports were in 2005, 2011 and 2015. Annual updates are provided but aggregate all renewable energy sources, with only disaggregated renewables data for total solar and wind [57]. Annual country energy balance data is provided by the IEA, but this database also does not include specific data on ATES. For renewables its categories are Geothermal, Solar/wind/other, Biofuels and waste, and Hydro [58]. For heat generation from renewables and waste by source, the only source categories are primary solid biofuels and biogases [59]. For the Netherlands, the aggregated storage capacity of ATES is unavailable. Dutch ATES systems monitor their data individually and are collectively not publicly available. Capacity analysis is therefore available at the individual ATES level, and in a few instances at the city and regional level for a selection of ATES systems.

Looking ahead, Dutch heat decarbonisation policy involves plans for significant heat network expansion [60]. Although there has been little connection of ATES to heat networks to date, there is potential for its integration with low carbon heat networks. Due to the unsuitability of lower temperature ATES with more conventional higher temperature heat networks, and the technical challenges of higher temperature ATES, there is a need for strategic planning to ensure alignment between future heat networks and STES. Municipality level STES plans are well-placed to coordinate with prospective Dutch heat zoning initiatives [61,62].

4.2. PTES in Denmark

At roughly the same time as ATES was developing in the Netherlands, another distinctive form of STES was emerging in Denmark: Pit thermal energy storage (PTES). Some small PTES demonstration projects were constructed in Denmark in the 1980s [63], but it was not until the early 2000s that larger PTES projects were developed by a joint Danish and European programme [64–66]. These larger projects served towns with populations of a few thousand people and existing heat networks using large solar collector plants. [67] (Interview, DK #1).

Early PTES projects were instigated by the engineering boards of small heat networks in towns such as Marstal and Dronninglund, drawing on the expertise from the Danish Energy Agency (Interview, DK #1). These early projects had straightforward ownership models, led by the district heating utility, often municipally owned. This leadership from a very well established and trusted institution in Denmark is likely to have been significant. EU funding and piloting support was also available at the early stage of PTES development in Denmark.

Multiple forms of favourable financing have key institutional factor in the development of PTES and heat networks in Denmark [68,124] (Interview, DK #1). Investment in PTES – and Danish energy infrastructure more widely – is supported by a socio-economic approach to accounting, and low-interest, long-term financing provided by municipality owned financial institutions, with the municipalities guaranteeing loans.

All early PTES projects in Denmark were coupled with heat networks and solar thermal collectors. District heating has a long history in Denmark, with over 60 % of Danish properties now connect to a heat network [69,70]. The higher storage temperature of PTES technology, compared to ATES, complements the widespread existing district heating [20]. Combined heat and power generation provides over two thirds of the heat requirement for these networks. PTES combined with district heating is thus a key technological complementarity in the Danish context.

Another technological complementarity is solar thermal generation coupled with heat networks. Solar District Heating has been implemented in Europe since the 1970s and is now established in a number of countries, including Denmark (1128 MW Solar District Heating), Germany (102 MW), Austria (34 MW) and Sweden (24 MW) [58,59]. Denmark has the highest level of solar heat networks internationally [67], with current estimates of about 120 networks [68]. This was enabled by a market intervention from 2005 that made the electricity pricing regime for CHP plants more favourable, which greatly increased interest in solar thermal [68,70]. Solar heating has also offered a way for heat networks to achieve energy savings as a part of energy efficiency obligations [71].

The technological coupling of PTES with solar heating, however, is patchy and fewer than ten solar heat networks currently have PTES [67]. While the first solar PTES projects were supported by public funding, unsubsidised, fully-commercial projects were subsequently developed, although none since 2017 [72].

Available and affordable land is key for PTES [67]. For solar PTES systems, land requirement is even greater due to the need for solar collectors. Solar PTES systems have generally been deployed with heat networks in small towns, which have more readily available land [67]. Some PTES have also been deployed at sites with existing excavations [67] (Interview, DK #2), which helps to smooth the planning process and reduce construction costs.

The technological simplicity of PTES means that there is relatively little scope for technological innovation [73], other than insulation improvements (#DK5). Larger PTES systems generally offer economies of scale and lower cost per kWh. While some sources suggest scale economies might level off [72], this may be offset by the potential for increased revenue streams and services achieved through greater scale.

Approximately two thirds of households in Denmark have their space heating and domestic hot water supplied by district heating [68]. Danish heat networks now have renewable energy sources contributing 65 % of the energy share, up from 20 % in 1990. This transition in the Danish district heating systems is due mostly via biomass (43 %), solar thermal (6 %) collectors and waste heat from industry (21.5 %), with natural gas, coal & coal products (21.5–30 %) making up the remaining amount [74]. These percentages vary annually and biofuels shows the most consistent and largest annual increase in share of energy sources to the annual heat generation in the Danish district heating systems.

Danish heat networks with CHP typically operate with a large amount of non-seasonal thermal storage in the form of steel water tanks. In 2013, this was estimated to have a thermal capacity of 50 GWh [75], while in 2018, seasonal storage capacity (almost entirely PTES) was estimated to be 14 GWh. Due to the high and increasing levels of renewables on the Danish electricity system, CHP plants have evolved from only providing baseload to also being a key source of flexibility [76]. CHPs and heat networks can accommodate more renewables with the use of STES [77]. It is, however, anticipated that heat pumps will become the main source of heat for DH in the long-term (Interview, DK #2)[76].

In a future 100 % renewable energy system, it is estimated that demand for non-seasonal storage would be 320 GWh and seasonal storage 30 GWh (ibid). Thus, while STES is seen as having a growing role, there ultimately may be a much greater focus on non-seasonal thermal storage. This highlights the importance of systemic and relational factors: STES aligns less well with the current socio-technical regime, than other energy technologies with faster or more guaranteed pay-back times, faster build-times, more standardised, assured and clearer permitting processes and regulatory frameworks, clearer incentives for short-term storage, and more available supporting technical infrastructure, such as a lack of heat networks.

A new model of PTES is currently being demonstrated by the Greater Copenhagen heat network. This differs from conventional PTES in that it charges using biomass and waste incineration CHP rather than solar thermal. It also discharges much more frequently – fortnightly rather than seasonally – with 25–30 charge-discharge cycles annually. This combination optimises energy production and provides utility-level balancing [78]. The relatively large number of cycles makes the storage duration not interseasonal, although the technology is still defined as STES and part of the store will often still be used on an interseasonal basis.

5. Analysis and discussion

The case studies demonstrate the development of two different forms of STES: ATES in the Netherlands and PTES in Denmark. In this section we conduct a cross-case comparison by analysing the common themes related to context and complementarity that emerge from the cases, and the analytical and policy implications these suggest for STES specifically, and energy system decarbonisation more broadly. This draws on the complementarities framework outlined in Section 2 of the paper. This framework helps understand the progress of STES in the Netherlands and Denmark in terms of how well it integrates with other energy technologies and changes in the wider energy system context [79]. The analytic of context and complementarity helps focus attention on these system processes.

5.1. Technological and infrastructural complementarities

Our two case studies demonstrate the strong influence of technological complementarities on STES development, deployment and commercial viability.

First, there are strong and close relationships between heat sources and storage technologies in our cases: solar-PTES and CHP-PTES in Denmark, and geothermal-ATES in the Netherlands. This is consistent with studies emphasising a key advantage of PTES and ATES; their ability for system integration with multiple complimentary technologies, especially heat pumps, CHP, and renewable and waste sources of heat [80]. ATES in the Netherlands is predominately smaller scale and for heating and cooling of individual buildings, greenhouses and communities up to 500 houses, usually utilising heat pumps, while PTES in Denmark are large scale heat storage for centralised systems providing heating and cooling to very large buildings such as universities and city-scale housing.

In all cases, there are also close technological couplings of STES with district heating. District heating makes STES more commercially viable as more revenue can be secured for the heating and cooling services. The supporting practices, norms, business models, investor certainty and long-term contracts for DH are already established and trusted, especially in Denmark. Technological coupling can thus also reinforce strong sectoral and institutional complementarities, and vice versa.

This coupling effect is enhanced by expanding and increasingly efficient networks. In Denmark, DH and STES have been deployed at considerable scale because they combine multiple complementary heat sources (EfW, biomass & solar) with a complementary store (PTES), a large-scale, low-temperature heat network, and additional complementarity technologies, such as heat pumps and CHP – a system known as advanced 5th generation DH. Such positive feedback loops in terms of network scale, diversity of heat sources and system flexibility point to the need to consider the scope for technological complementarities in energy planning.

Despite these possibilities, STES deployment faces particular challenges given its reliance on cross sector coupling and its bespoke nature. These technical and economic properties manifest in organisational and institutional ways: for example, STES tends to have a limited advocacy base and lacks wider stakeholder understanding and public awareness. Our STES case studies therefore support the suggested distinction between technological and sectoral complementarity [38].

5.2. Sectoral and institutional complementarities

Understanding the limited deployment of STES requires consideration of its limited complementarity with local, regional and national institutions, and the wider energy sectoral context.

The Dutch case highlights the importance of institutions and legislation in enabling cross-sector interactions. For example, a key indirect policy driver for ATES was the gradual tightening of building energy regulations. Deployment was stimulated by increased demand for cooling due to better insulation and higher frequency of summer heat waves. Cross-sectoral interactions with water industry environmental regulations and licensing frameworks were also influential in creating market confidence. While there was some caution from authorities and groundwater industries toward ATES, this was ameliorated by respecting groundwater protection zones around extraction points [48].

In terms of wider sectoral context, the limited use of solar PTES in Denmark means there are few sector-level complementarities and benefits. Our case studies suggest that without these, STES deployment can be highly vulnerable to external shocks. This is illustrated by the stagnation of solar-PTES in Denmark following falling electricity prices from 2017, despite projected strong growth. Larger-scale CHP-PTES is anticipated to provide greater sector-level complementarity and consequent positive knock-on effects at the system-level, including wider stakeholder interest and recognition of its benefits across the system. Large-scale hybrid STES systems may enhance diversity, innovation and efficiency of wider energy systems. However, moving from localised to larger scale systems presents the challenges of increased project complexity and transaction costs.

Across the two cases, early-stage government support was essential to overcome barriers, especially upfront financial support. Thereafter, wider, non-fiscal measures such as progressive building energy regulations and clear environmental standards were needed to accelerate the growth of STES. Our study also highlights important knock-on system effects: for instance, wider changes to energy systems, such as the increasing influence of variable renewables on electricity markets, means that STES may become increasingly cost-effective if used over shorter timescales, such as fortnightly. However, these emerging complementarities are fragile: the viability of STES in markets lacks scale, prices are increasingly volatile, and investment is strongly dependent on government support as a means of reducing risk and accessing debt financing.

Drawing from the cases, in Table 1 we summarise key complementarities and the key policy and market mechanisms responsible for achieving STES diffusion in both Denmark and the Netherlands.

The table illustrates both the unique and shared nature of the STES complementarities. In the Netherlands, for instance, STES deployment accelerated by coupling it with already highly established and complimentary industries (e.g. horticulture), technologies (drilling, groundwater extraction, distribution, heating) and related supply chains, skills and markets. In Denmark, technological, sectoral and institutional complementarities were also instrumental, but came from different origins: strong district heating, solar thermal and PV industries built socio-technical complementarities that aligned well with PTES and supporting regimes such as energy from waste technology, high landfill tax and high building energy performance standards and regulation.

The case studies also reveal that the policy and market mechanisms

Table 1
A summary of the key complementarities for STES in Denmark and the Netherlands.

	Netherlands	Denmark
Technological and infrastructural complementarities	• Competencies in supporting technologies (e.g. drilling, groundwater extraction) • Scaling limited by lack of DH	• Municipal heat networks developed at scale • Hybridity (biomass & EfW CHP & heat pumps, 5GDHS)
Sectoral complementarities	• Strong horticulture sector coupled with ATES • New builds (commercial and public) coupled with ATES	• Established solar thermal and PV installation industry • Cross-sector skills base and financing capability from municipal heat supply chain
Institutional complementarities	• Multi-level energy planning & powers (devolved to municipal & council levels) • Subsurface masterplans to improve information and optimise A-STES resource • Clear & streamlined permitting process & licensing regime • Early-stage grants & subsidy for ATES	• Multi-level energy planning & powers (devolved to municipal & council levels) • Well developed supporting legislation (e.g. high landfill tax & building energy performance). • Centralised expertise available to local projects resource of expertise • Support for experimentation and trials

responsible for this success were relatively consistent across these different contexts. In particular, our study reinforces the value of demonstrator projects within and across technologies, sectors and institutions. These help to capture economies of scale, develop partnerships, financing structures and business models. At the early stage of projects across the two country cases, public policy was crucial in the provision of data, building expertise, and financial support for risky projects. Later, as the technology progressed through the innovation chain, environmental regulations and technical standards became important for enabling the development of replicable project designs.

Creating networks and collaborations were also important in this phase of the innovation system. In the Dutch case, a national regulatory framework emerged as the sector matured during the 2010s, streamlining planning, permitting, and licensing. Regional and local authorities were important too, across both country cases and at all stages of the innovation system. This was especially in relation to the enabling role of planning and consenting, but also in relation to the development of municipal level energy masterplans which helped to identify local opportunities and complementarities with other parts of the heating supply and distribution regime. Across these different stages of the innovation system, we can see the crucial role played by cross-sector and institutional complementarities in creating positive feedbacks as the technologies progressed from early-stage demonstration to broader diffusion.

6. Conclusions

As part of sustainable energy transitions, STES can offer a low cost and reliable response to the challenge of interseasonal variations in demand and supply. However, despite its potentially valuable role in low carbon systems, in most countries STES has been largely ignored to date and faces uncertain prospects. In part the reasons for its niche status relate to its techno-economic properties: like other storage technologies, STES is dependent on supply and demand patterns, existing and planned infrastructures, and on developing complementary relations with these. Unlike dominant storage technologies such as electrical battery storage, STES and large-scale TES are also highly context-specific, requiring local, regional and national regulatory frameworks, regulatory and market capacities, supply chains and expertise that is unevenly distributed across and within countries.

The case studies investigated here show that the techno-economic feasibility and prospective role of STES in net zero energy transitions varies greatly between different contexts. Key contextual factors include national energy market and regulatory frameworks, more regional and local energy planning arrangements, and the presence or absence of complementary infrastructures, such as heat networks. STES assessment methods and policy incentives must recognise these socio-technical specificities.

As low carbon energy systems increasingly involve more flexible and distributed technologies, technology integration and complementarity will become more important considerations. Energy research and policy should therefore consider impacts across the system, and not just on particular technologies.

In this paper, drawing on an emerging theme in innovation and transitions studies, we addressed these wider impacts in terms of technological, infrastructural, sectoral and institutional complementarities. Our main contribution to research on STES has been to draw on the innovation systems literature to identify and analyse the systemic complementarities which influence the diffusion of this technology. While the challenges facing STES as an enabling technology which improves the functioning and efficiency of wider systems has been noted, much of the techno-economic literature focuses at the project-level. Our case studies show how sectoral and institutional complementarities can facilitate experimentation and learning, and are crucial in supporting subsurface resource knowledge and infrastructure development.

Our findings also suggest that, for large-scale TES and STES deployment and optimisation, conventional business models and economic boundary conditions may play secondary roles to wider socio-technical influences: regulatory, institutional, and market-related. The presence or absence of complementarities across technologies, infrastructure, sectors, and institutions over multiple spatial levels and time periods play the major role in STES techno-economics and deployment levels. Based on these findings, we recommend further research on the factors that influence the deployment and contributions of STES and large-scale TES, and how these factors can be best stimulated.

In parts of the UK, for example, there has in the past number of years been a greater emphasis on local energy planning, including heat network zoning [81] and local heat and energy efficiency strategies [82]. These changes resemble more local and place-based energy governance seen in Denmark and the Netherlands, where STES is now a relatively normalised investment, with supporting sectoral and institutional cultures, infrastructures and practices, with multi-partner coordination, experimentation, funding and planning.

A key lesson from the frontrunner countries is that the widespread diffusion of STES in the UK will require a high degree of system orchestration and planning. National and local policymakers have a key role in recognising the value of STES and identifying suitable areas for its different forms [83]. STES also requires bespoke consideration of local geological and hydrogeological conditions, as well as the local energy system contexts –features which are becoming more important in countries unfamiliar with multi-partner and cross-sectoral co-ordination. A national STES strategy will also need to be aligned with wider patterns of changing energy supply, demand and infrastructure, as systems are decarbonised and variable renewables become the backbone of electricity supply.

Author statement

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

CRediT authorship contribution statement

Bolton – conceptualisation, writing and editing; Cameron – document research, writing and editing; Desguers – techno-economic research and editing; Kerr – conceptualisation, interviews, document research and drafting; Winskel - conceptualisation, writing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

Funding for this research was provided by the UK Engineering and Physical Sciences Research Council (grant number EP/T023112/1).

Appendix A. Techno-economic factors affecting STES

Summary of the techno-economics of STES in 5 tables

The primary contributions of this paper focus on context-specific factors that underpin STES growth because context-specific factors are influential to STES growth yet are relatively neglected in STES literature. Our analysis is primarily supported by qualitative methods, data and analysis, however we add to the robustness and added-value of this paper by supporting our analysis and arguments with quantitative data and techno-economic analysis. This analysis includes an overview of both typical values and assumptions used in theoretical techno-economic studies, and project-specific values used in more grounded techno-economic assessments. This quantitative and techno-economic contribution is presented below.

We present this in five tables:

Table A: Comparative summary of key techno-economic characteristics of STES.
Table B: Typical economic boundary conditions for STES.
Table C: Typical technical ‘boundary conditions’ of STES: key factors influencing the technical requirements & performance of STES.
Table D: Techno-economics for a leading STES model & example: Vojens, Danish PTES
Table E: Techno-economics of STES for a world-leading model & example: Dutch ATES.

Table A
Comparative summary of key techno-economic characteristics of STES & other energy storage technologies (EST).

EST type	Storage duration	Storage efficiency (η) (round-trip)	Storage volume cost[a] €/m^3	Lifetime (years)	Energy storage density (kWh/m^3)	Operating temperatures (°C)	Power capacity cost (€/kW) 2025	Energy capital cost (€/kWh) 2025	References	Model assumptions
PTES	Weeks - many months (seasonal)	>90 % 54–94 %	Range: 24.0–456.8[a]	30	60–80 (water) 30–50 (gravel/water)	Typically <90, limited by material of floating lid	Range: 245–410	Range: 0.46–2.91[a]	[4,18,20,84,85]	Insulated shallow large-scale PTES (200,000m^3) achieves 79 % efficiency [86]. 50 MWh storage capacity [84]. Various storage sizes [18]
ATES	Seasonal	67.5–93 % HT-ATES 40 % to 80 % η with an average η of 56 %	[a]	25 (20–40)	30–40	Low-temperature ATES: <30 (for heat and cold storage) High temperature: 40–80 (for heat storage only)	[a]	[a]	[87–91]	Bakr et al. [92] analyse the real-world η of 19 ATES in the Netherlands, finding their average at year 10 is 87 %. Drijver et al. [125] state values between 70 and 90 % as typical range of thermal recoveries for LT-ATES systems in aquifers with low flow velocities.
BTES	Seasonal	20–65 % for	Range: 2.8–16.5[a]	25	15–30	Ambient – 90, depending on heat source	See comment	Range: 0.41–0.80[a]	[20,55,66,93–95]	76 % reported for shorter cycles [96]

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Table A (*continued*)

EST type	Storage duration	Storage efficiency (η) (round-trip)	Storage volume cost[a] €/m^3	Lifetime (years)	Energy storage density (kWh/m^3)	Operating temperatures (°C)	Power capacity cost (€/kW) 2025	Energy capital cost (€/kWh) 2025	References	Model assumptions
		seasonal storage				type and temperature				
TTES	<4 h–seasonal	Up to 90 %, with 55.4 % reported for seasonal	Range: 108.1–5439.4[a]	20	60–80	<100 for unpressurised systems Typically <90 for buried tanks		Range: 0.69–5.55[a]	[20,97,98]	Insulated large-scale TTES (200,000 m^3) achieves 93 % efficiency [86]
CAES	<4 h–seasonal	<60 %	0.45–161.6	30	0.5–20	N/A	Mean: 817 Range: 434–984	Mean: 34.9 Range: 9.1–80.8	[5,99]	80 % variable renewable energy (VRE) share.
PHS	<4 h–seasonal	80 %	11.5–487.0	55	0.2–1.5	Ambient	Mean: 1156 Range: 573–1819	Mean: 50.9 Range: 17.3–97.4	[5,99]	80 % VRE share.
Hydrogen	<4 h–seasonal	40 %		18		N/A	Mean: 3013 Range: 1507–4520	Mean: 3.7 Range: 1.8–5.5	[5], assumes a system with 80 % VRE share.	Hydrogen storage is influenced by its type (gas, liquefied, fuel cell). Koohi-Fayegh and Rosen [99] have data on this for different types.
Li-ion battery ES	<4 h	85.0–98.0 %	0.3–4600		30–300	N/A	Range: 300–3500	Range: 100–20,000	[99]	

Comparative summary of key Techno-economic characteristics of STES & other energy storage technologies (EST).

Power and Energy capacity costs: Mean and/or range is provided where available. Power capital cost refers to the total capital cost per unit of rated power output. This is a common metric in techno-economic assessments, but does not include the OPEX, which is the annual operation & maintenance costs over the system lifetime. Not all studies include both. A third key metric is the energy capital cost: the total capital cost per unit of energy storage capacity. For all these STES, storage efficiencies increase with storage volume [87,88].

Power capacity costs is difficult to summarise in one single number because the charge and discharge capacity of a STES depend on its operating temperature, but also on the total length of boreholes, which is not fixed even for a given BTES volume, and also depends on the depth of the boreholes, their number, their spacing and the total STES volume. For a given volume, a wide range of powers can therefore be obtained, depending on the design, as well as its construction and operation.

The techno-economic calculations presented in this table are averages from multiple sources, depending on the number of sources found for each technology using recent data, since 2015. The range of values found across the studies is also presented. The results can be used as techno-economic assumptions of the main parameters for ES technologies used in techno-economic analysis.

Storage Duration: A range of durations is given because STES can provide a range of storage durations, from multi-year to multi-week.

Storage Efficiency: Depends on the storage duration and how the system is used, such as heat to heat or also power components. Where heat-to-heat, which is most STES, η will be closely tied to the storage duration. The wide range of η presented illustrates the range of factors that influence η. Project-level analysis should include the exact number of cycles in their calculations of storage efficiency to improve accuracy.

Lifetime: The values provided are for modern STES, some of which their lifetimes to these ranges have not yet been proven. This is the case for PTES.

[a] Useful correlations for storage volume costs (V_{eq} is the store water-equivalent volume, in m^3): PTES: $C_{PTES} = \left(1944 \times V_{eq}^{-0.29} - 43.04\right) \times V_{eq}$ (€) [118]; ATES: ATES costs have very strong variability as a big share of the cost is due to non site-specific components [119]. Capital costs (per unit power) can be estimated either from a Monte Carlo simulation [119] or from the following correlations, depending on ATES size [120]: $C_{ATES} = 1000$ € + 252 €/kW (<100 kW), $C_{ATES} = 69{,}860 \ln(\text{kW} / 6.69) - 109{,}000$ (€) (>100 kW); BTES: $C_{BTES} = 2600 \times V_{eq}^{0.53}$ (€) [121]; TTES: $C_{TTES} = \left(2893 \times V_{eq}^{-0.22} - 247.5\right) \times V_{eq}$ (€). Similar correlations for the "Energy capital cost" column can be obtained by dividing the above equations by the energy density.

Sources: Listed in table.

Table B

Typical economic boundary conditions for STES.

Parameter	Unit	Example
Life time	Years	Varies with quality of construction & O&M
Build time	Months or years	Technology-dependent. PTES has simple construction while TTES has complex construction but easy installation, and both ATES and BTES suffer from a long initial process for geological investigation. Additionally, BTES requires a long transient period to reach typical performance. CAES and PHS are generally large scale installations and may take up to 2 and 8 years to build, respectively
(Dis)charge capacity	W–GW	Technology specific. Typically scales are MW – GW for PHS, MW for CAES, W-GW for batteries depending on application, kW-MW for PTES, TTES, ATES, BTES.
Storage cost per volume	(€/m^3)	Technology dependent. See Table A
Storage cost per kW (dis) charge	(€/kW)	Technology dependent. See Table A

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Table B (*continued*)

Parameter	Unit	Example
CAPEX	€	The CAPEX metrics covers the storage volume cost, pre-development costs, and construction & infrastructure costs (cost of land, expertise, borehole drilling, permitting, finance, materials, labour, interest rate over build period). Therefore, CAPEX costs depend on local regulations and practices and are site-specific
OPEX	€	The OPEX (fixed & variable) metrics covers the cost of operation & maintenance, such as insurance, connection costs, carbon costs, decommissioning fund costs, renewable heat subsidies, heat revenues, fuel prices (including fossil fuels, gate fees for waste incineration & price of heat from various sources), EfW, industry, waste water treatment plants, and buildings. OPEX varies with regulations and practices at various scales.
(Dis)charge cycles	–	Larger the number, higher the revenue options. A STES may operate at shorter timeframes than inter-seasonally, and may operate at multiple timeframes, depending on the design.
Wholesale market electricity price	€/kWh	The wholesale market price for electricity varies significantly with time and place depending on local generation technologies, subsidies, markets, regulations, and geo-political circumstances. Control strategies for STES may be designed which take advantage of the price variability and charge at times of low-cost, and discharge at times of high-cost. However, the price of electricity has little impact the storage volume cost, power capacity cost or energy capital cost.
Wholesale market price	€/kWh	Currently tied to gas and electricity wholesale markets.
Renewable heat subsidies	€/kWh	Vary by country.
Price of renewable & waste heat sources	€/kWh	Varies per country, region, source & fraction of that source in the system. This likely influences the control strategy, deployment, benefit and added value of STES
Carbon price	€/tCO$_2$	
Energy demand of end-users	kWh–GWh	Varies with climate, time of year, type of building & sector, building occupancy & energy performance, and accuracy of energy performance data – influences OPEX
Applications	–	Domestic hot water (DHW); space heating and cooling; Industrial, Commercial or Domestic. Influences OPEX.

Typical economic boundary conditions for STES: key factors influencing the economics of STES.
Source: The authors.

The economic ‘boundary conditions’ can be a useful framing for highlighting some of the key parameters that influence the economic or technical performance of a technology. Boundary conditions provide an idealised framing of the key factors most commonly used in analysis, rather than all the factors that influence the economic or technical performance of a specific technology in real-world contexts or in specific use cases. The values for these parameters will therefore vary significantly for different STES types. Data monitoring of real-world economic and technological performance of STES is limited, and most STES projects only monitor minimal techno-economic metrics. Accordingly, we have identified the key economic ‘boundary conditions’ for STES: the key factors which influence STES economics and form the basis of most economic analysis of STES, Table D, and the technical ‘boundary conditions’ of STES, Table E.

Note that the range of parameters that influence the economics & technological performance of STES are large and site, technology, project and system-specific. The choice and values of parameters included in economic assessments varies and typically use theoretical assumptions and simplified rather than real-world and site-specific data. This contributes to the high uncertainties in the economics of STES. Another contribution to this is most analysis not including all the relevant parameters that influence the project techno-economic performance. Aspects related to the optimal integration with the end-use buildings [100] and sustainable use and management of the subsurface are notable examples.

Accordingly, Tables D and E present parameters typically included in economic and technological assessments of STES, providing an overview of typical techno-economic boundary conditions for STES, and highlights that these factors render only a high-level and partial image of STES economic and technical performance. Alternative approaches including more extensive and interdisciplinary parameters to techno-economic accounting - including wider social, socio-economic and environmental parameters - are emerging to resolve this. We present and discuss these different approaches in a forthcoming paper.

Table C
The key technical ‘boundary conditions’ of STES: key factors influencing the technical requirements & performance of STES.

Parameter	Unit	Example
Volume of pumped groundwater	m^3	Relevant to ATES but not all STES, such as those that obtain and store heat in & from mediums other than water (BTES, PTES). The first 5 parameters of this table comprise the monitoring data of 73 Dutch LT-ATES systems from 2016 to 2018 that Fleuchaus et al. [100] used to analyse the technological performance of Dutch ATES. This study shows lower pumped volumes can improve the techno-economics of ATES by lowering (pumping) costs, lowering thermal interference & increasing storage temperatures & efficiencies. Optimising this requires smart and dynamic management [101].
Abstracted thermal energy for heating and cooling	MWh	Overall system performance & economic performance of STES increase with this parameter. This factor is closely regulated and limited by geohydrology, but provides potential for higher abstraction levels. In the Netherlands, although accounting for 85 % of world's ATES, only 27 % of the abstracted groundwater is for ATES, regulation allows this to double & it is expected to increase [100].
Operating temperature	°C	The operating temperature of the heat network or STES limits applications & efficiency of storage & heat network.
Extraction temperatures heating and cooling	°C	Generally, the higher the temperature of extracted heat, the higher the operational efficiency and energy densities, but the higher the thermal losses and therefore the lower the storage efficiency. In practice, extraction temperatures of STES are generally required to match the operating temperature of the heat/coolth network they are connected to.
Injection temperatures for heating and cooling	°C	The difference between extraction and injection temperatures can be used to calculate another key technical metric: thermal imbalance (ΔT). A small imbalance (<5 %) means that the net ground(water) temperature is minimally affected by the STES being studied. Fleuchaus et al. [100] finds an average imbalance of 2.3 % in the Netherlands. Larger imbalances reduce the COP & can be unsustainable if not actively counterbalanced, and typically result from poor data monitoring and STES management [100].
Min. and max. injection temperature for heating and cooling	°C	Generally, the larger the difference between injection and storage temperature, the higher the charging power and efficiency. In practice, the injection temperature are imposed by the temperature of the heat/coolth source, and are limited by the technical specifications of the materials making up the injection pipes
Thermal Interference	°C	Not often monitored but high interference can reduce the efficiency of the project & others using the resource. Cooling the warm well from thermal interference or loss can cause problems in heating mode and also the other way around. This is most relevant for ATES & minewater heat.

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Table C (*continued*)

Parameter	Unit	Example
Groundwater flow	m^3/s	Inversely proportional to storage efficiency and therefore techno-economic performance: Higher the flow, higher the thermal losses & thermal imbalance, lower the storage efficiencies. High flow rates found to cause storage η as low as 33 % for an ATES in Sweden [102].
Storage capacity	MWh	Storage volume has greatest impact on COP: the higher the volume, the higher the COP [11].
Coefficient of performance of heating & cooling	–	Two key factors affecting STES efficiency is the COP of the heat pumps, and the fraction of renewables. COP of heat pump varies with storage volume and temperature [11]. COP of STES can be many times higher than standard GWHP due to relatively lower & constant cooling temperatures & higher heating temperatures in STES [11].
Solar or renewables fraction (SF)	%	Higher the fraction of renewables, the higher the COP of a heat pump & system efficiency [11].
Applications	–	Domestic hot water (DHW); space heating; cooling; Industrial, Commercial, Domestic, Horticultural. Competing applications for the resource may affect techno-economic profiles & performance. Groundwater, for instance, is finite & approximately 27 % of abstracted groundwater in the Netherlands is used for ATES applications, 54 % for drinking water, 9 % industry and 15 % [100]. The share of ATES is expected to increase.

The key technical ‘boundary conditions’ of STES: key factors influencing the technical requirements & performance of STES.
Source: The authors & cited.

Table D
Techno-economics for a world-leading STES model & example: Vojens, Danish PTES.

Project name	Vojens
Model	Solar thermal PTES, large-scale STES
System integration	Medium-scale heat network with PTES providing balancing & inter-seasonal storage for 70,000 m^2 of solar collectors, 3 gas engines, 10 MW electric boiler & absorption heat pump. The heat network operates between 40 and 90 °C for 2000 customers. This forms the technical boundary conditions of the system. Seasonal flux of solar pairs well with STES: summer surplus stored for winter demand. The economic boundary conditions include wholesale market electricity and gas price, renewable heat subsidies, land costs & Capex.
Status	Commercial
Build time	2014–2015
Year Installed	2015
Operational start date	2016
Life time	25–30 years
Cost	€5.01 million
CAPEX	Medium
OPEX	Low
Storage volume	200,000 m^3
Storage volume cost	30–24 €/m^3 *decreasing since operation*
Temperature range	40–90 °C range of the heat network
PTES Storage capacity	12,180 MWh
PTES (Dis)charge capacity	38,500 kW
Heat lost via (dis)charges	14 % Annual heat loss related to (dis)charges
Measured heat loss	– (MWh/year)
Storage efficiency	>90 %
Geological requirements	Size of pit is relevant for storage sizing, so ideally matches the size required. Vojens is world's largest PTES, and in a disused sand pit. Existing and available pit beneficial, stable ground, preferably no groundwater or at a depth it does not interfere with the PTES. Ideally dry soils as these insulate better than moist or saturated soils. If groundwater, ideally has no significant groundwater flow across the site to minimise heat loss. Compactable soil for use in insulation.
Regulatory considerations	Relatively smooth regulatory process as site is often post-industrial, abandoned & not environmentally significant, unlike aquifers. Vojens PTES is an old sand pit. Using such sites provides the space requirements for PTES that is a key requirement for above-ground energy storage, & limits ES options in urbanized areas and cities: the lack of space in these contexts is often the main reason why PTES & other forms of large storage above ground is not deployed. In Denmark the space requirement is also overcome by siting PTES in urban parks. Regulations promote shift from oil-based heat networks to 100 % RE. Ground-sourced heat pumps (GSHP) may face restrictions in high-density areas due to land restrictions.
Additional techno-economic considerations	Use of existing geological structure (pit) reduced CAPEX. Storage medium (sand, soil, earth) is abundant & very cheap. Use of surface & subsurface material for additional insulation reduces OPEX. Thermal properties of the soil & subsurface will influence thermal losses, & so system efficiencies & costs, but all underground TES or partially underground TES will have lower heat losses than above-ground TTES. PTES are not yet state-of-the-art. The cover technology for instance, for PTES is not mature, & often has to be replaced during its lifetime. e.g. Dronninglund PTES was upgraded in 2022 with a newer, improved lid due to failure of the original lid. Cost analysis rarely considers the costs of replacements & upgrades. Lifetime without replacements of 20 years is not yet proven. Due to high risk and cost pressure, low-cost solutions have been preferred. Technical better solutions are economically very challenging due to requiring large scale & state-of-the-art components, construction & operation. Comparison – PTES cheaper than TTES but on average more expensive than ATES or BTES [103]. PTES & BTES can be easily upgraded & expanded. e.g. Dronninglund PTES was upgraded in 2022, e.g. a newer, improved lid.
Environmental considerations	Sustainable storage – medium is more abundant & eco-friendly (e.g. water, salt, earth) than other ES. Sustainable generation than incumbents: the energy required for manufacture as a fraction of lifetime energy generation is 2.3 % for wind, 3.8 % for PV [104]. 12.6 % of world's end-use energy consumption is in mining, transporting & refining fossil fuels & uranium [105].
Heat source(s)	Solar with backup gas & electric boilers. See ‘system integration’ row.
STES roles	The PTES increases the utilisation of solar, balancing high seasonal variability of solar inter-seasonally - enabling solar thermal as the main heat source & reducing reliance on non-renewable sources.
End users	2000 customers
Business model	Community owned partnership with local council

Key techno-economic parameters & data for real-world case studies of different types of STES: Vojens PTES, the most cost-effective & largest PTES to date.
Sources: [4,18,26,50,55,68,85,86,88,106–110].

Table E
Techno-economics of STES for a world-leading model & example: Dutch ATES.

Project name	Various	Battery storage (Li-ion)
Model	Near-surface ATES, large-scale STES	
System integration	The primary Dutch ATES model is a low temperature ATES connected to a low temperature (30–55 °C) heat network, often supplemented by solar thermal collectors. 99 % of the 3000 Dutch ATES are these LT-ATES, storing thermal energy at relatively low temperatures (10–25 °C), alternating between cooling and heating according to demand & assisted by a heat pump. All types of ATES in the Netherlands must achieve a Subsurface Heat Balance (SHB) between stored 'cold' and 'warm' energy. The Hague ATES systems extract thermal energy at 7–13 °C, using heat pumps to raise the temperature for end-use, & lower the temperature for reinjection. The permitted temperature reinjection change, ΔT, is 6 °C. The heat is supplied via centralised networks that operate between 10 and 25 °C for 500,000 customers, with decentralised heat pumps to raise the end-use temperature. This forms the technical boundary conditions of the system. For HT-ATES, the heat network sets different boundary conditions, such as 55–90 °C operating temperature & maximum flow capacities. The economic boundary conditions include wholesale market electricity and gas price, renewable heat subsidies, & CAPEX. Most ATES in Europe are low temperature systems (<30 °C).	
Status	Commercial	Commercial
Build time	2–4 years	Months
Year installed	Harderwijk – 1992; Eindhoven University 2021	
Operational start date	Harderwijk – 1992; Eindhoven University 2021	
Life time (years)	30	
Cost	€13.45 million for Eindhoven University's 20 MW ATES	
CAPEX	Medium	Low
OPEX	Low (typically 2–6 % of CAPEX)	Low
Storage volume	213,1000 m^3 (Heuvelgalerie MT-ATES 1992) Dutch ATES are mostly relatively small projects 300–1000 kW storage capacity, sufficient for 50–200 houses or 1 ha of greenhouses. Storage volume data is unavailable for most Dutch ATES.	
Storage cost	€/m^3 cost data is unavailable for most Dutch ATES.	
Temperature range	7–13 °C	
Permitted water temperature injection - reinjection ΔT	6 °C	
Storage capacity	1650 MWh (Haarlem MT-ATES) 7650 MWh (Harderwijk MT-ATES) 20 MWh (Eindhoven university) 3 MWh (resident office park, Hague)	
(Dis)charge capacity (MWh/a)		
Cost per kW (dis)charge (EUR)		144.6
Storage efficiency (heat recovery efficiency)	65–95 % real-world norm Year 1 efficiencies 68 %, Year 10 efficiencies 87 % for 19 Hague ATES systems.	80–99 %
Lifetime	20–30 years Utrecht University HT-ATES (1991), Heuvelgalerie MT-ATES (1992) and Dolfinarium (1997) MT-ATES systems have been operational for over 25 years, the former at 32 years.	15 years
CO_2 emission reduction per year	13,300 tonnes/year for Eindhoven University, 11,000 tonnes/year for TU Delft and 12,000 tonnes/year for the city of Delft (modelled), at €3–5 million CAPEX & 376,000–424,000 €/year OPEX depending on geology of site, & serving 27,000 people [111]. Dutch ATES CO_2 accounting indicates mean CO_2 reduction per ATES-system is between 45 and 80 tonne CO_2/year [79].	
Geological requirements	The Netherlands' widespread thick sedimentary aquifers provides good geology for ATES, with the country's over 2000 ATES systems being in relatively shallow sandy aquifers (20–150 m). Other supporting conditions are: stable ground, natural aquifer layer, confining low-permeability layers, no or low groundwater flow & hydraulic conductivity to minimise thermal interference & loss, non-corrosive water chemistry, low particulates concentrations to avoid well clogging. Thermal interference limits size of large-scale ATES, & the number of ATES in an aquifer. Ambient groundwater temperature is 10–16 °C in the Netherlands but is site-specific, can vary >4 °C and should hence be determined for each ATES system individually [112].	
Regulatory considerations	Legal frameworks are a key barrier to ATES & a key influence on their techno-economics [88]. Water extraction from aquifers is limited in most countries. In the Netherlands, the maximum permitted capacity of individual ATES systems is 5,000,000 m^3/year. Dutch ATES use on average, across all ATES systems, is only 56 % of their permitted volume [113], showing regulations are not restrictive & operation can be sustainable. High regulations on water extraction & water temperature reinjection add uncertainty & risk. Regulations limit reinjection in aquifers to 20–25 °C in many countries. Clear regulatory framework reduces this uncertainty. UTES – higher regulatory & space limitations above ground in most urban areas limits above-ground heat decarbonisation options, but favours UTES. Underground STES have low above-ground footprints, much lower than most above-ground large-scale ES, such as battery or TTES or PTES. This is a significant benefit where land or buildings are at a premium, are protected, have higher regulations or lacks space for large-scale ES, such as in many cities & high-density urban areas. In these contexts, large-scale ES will be very effective: co-located with high volumes & density of aggregated heat &	Relatively simple, swift process. Fires from overheating may require tighter regulation or standards.

(continued on next page)

Table E (*continued*)

Project name	Various	Battery storage (Li-ion)
	cooling demand. This space & regulatory consideration is also an urban planning and techno-economic consideration. Highlights the interdisciplinary (socio-technical) nature of factors affecting the techno-economics & deployment of STES.	
Additional techno-economic considerations	*Aquifer depth* - increases drilling costs. Aquifer depth increases water temperature, increasing heat pump efficiencies & therefore OPEX. *Aquifer size* – larger size, larger (dis)charge capacity & potential revenues. *Aquifer flow rate* – increased velocities reduces ATES efficiencies & increases negative interference for other ATES projects. Design modifications can limit these impacts. *ATES interactions* – heat interference from ATES projects can lower the efficiencies of ATES in the same aquifer. The techno-economics is a trade-off between optimal subsurface use for total energy savings & individual ATES efficiency. *Longevity* - lack of evaluation of impact of ATES on groundwater system jeopardizes long term usability of the aquifer. Use - Dutch experience shows that actual pumped water volumes are on average 40 % lower than the design values or permitted capacity, affecting revenues. Economics of ATES mainly sensitive to storage temperatures, depth and price of heat & cooling from incumbents, such as price of gas & electricity. Technical performance of ATES affected by scale & O&M quality. Beernink et al. [112] analysed 40 % of Utrecht's ATES systems, 57 ATES systems, finding that recovery efficiency is positively correlated to stored volume. Efficiency of large-scale ATES systems can be improved by better well placement & optimising pumped volumes [101]. Efficiency of all ATES sensitive to design. Cost pressures often cause less efficient designs: such as less prevention of well clogging to save on well costs [49]. Comparison – ATES & BTES lowest-cost STES [103], although ATES can have higher Opex than BTES, PTES or TTES [26]. PTES & BTES can be easily upgraded & expanded. ATES not easily upgraded but can be optimised considerably. Shallow BTES & PTES makes cost of upgrades lower.	High power & energy density. Energy density of Li-ion BES 200 Wh/kg Short-term storage <4 hours. Rapid response. Well established market for rapid response, short provision (seconds to hours) services. Can be easily expanded but not upgraded. Can provide a range of grid services: peak shaving, frequency response, voltage support, black start.
Environmental considerations	Longer lifetime & low material requirements of ATES, BTES, PTES & TTES reduces their embedded carbon costs compared to battery storage.	
Heat Source(s)	Primarily groundwater heat plus heat from solar thermal collectors. E.g. in Haarlem (2002), Steenbergen (2016) and Monster (2017). Earlier projects used CHP as part of the heat network system, Harderwijk (1998). In a heat network of 750 houses, the Hague also uses seawater with heat pumps & exchangers as its central energy unit [114].	
STES role	The ATES increases the utilisation of RE & waste heat & balances the system.	See above
End users	500,000 inhabitants in the Hague. Horticulture another key end-user of Dutch ATES.	
Business model	Eindhoven University paid by their ATES in 6–10 years but had a $1.8 million grant.	

Key techno-economic parameters & data for real-world case studies of different Dutch ATES, considered among the most cost-effective ATES to date. Lack of data availability for a single project in the Netherlands results in this table amalgamating data from multiple Dutch projects and sources, with Bakr et al.'s [92] analysis of 19 ATES in the Hague, Beernink et al.'s [112] analysis of 57 ATES systems in the province of Utrecht, and Fleuchaus et al.'s [100] analysis of 73 ATES forming key sources. These studies highlight lack of published data a key barrier to techno-economic analysis STES in the Netherlands.

Li-ion Battery Electrical Energy Storage (BESS), is provided for comparison as the most commercialized type of BESS, at both small-scale and large-scale [115]. Values presented for BESS are from Koohi-Fayegh and Rosen [99] and Khaki & Das [115].

Sources: [4,26,43,45,49,50,85–87,91,92,100,106,108,109,111,112,114–117].

Appendix B. Case study interviewees

Country	Code	Description
Netherlands	#NL1	Senior hydrogeologist specialising in STES in the Netherlands
	#NL2	Senior researcher and academic specialising in underground STES
	#NL3	Senior representative of underground energy industry association
	#NL4	Project and business manager specialising in A-STES in the Netherlands
	#NL5	Senior hydrogeologist with experience studying the impacts of STES
	#NL6	Associate Professor in Environmental Engineering at Dutch University
	#NL7	Technical advisor on groundwater for Dutch Province
Denmark	#DK1	Operation Manager at Danish district scheme with STES.
	#DK2	Civil Engineer involved with many STES and solar heat network projects in Denmark
	#DK3	Analyst at Danish Climate Council
	#DK4	Analyst/Energy Planner at the Copenhagen Municipality
	#DK5	Director of Danish district heating company

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