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Identification of key factors for the sustainable integration of high-temperature aquifer thermal energy storage systems in district heating networks

Niklas Scholliers [a,*], Max Ohagen [b,c], Claire Bossennec [c], Ingo Sass [b,c], Vanessa Zeller [a], Liselotte Schebek [a]

[a] Material Flow Management and Resource Economy, Institute IWAR, Technical University of Darmstadt, Germany
[b] Geothermal Science and Technology, Institute of Applied Geosciences, Technical University of Darmstadt, Germany
[c] Section 4.8 Geoenergy, Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences, Germany

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ABSTRACT

High-temperature aquifer thermal energy storage systems for storage and utilization of excess heat are a promising element for decarbonization strategies of district heating systems. Based on a combination of literature review and expert consultation, this study aims to identify potential environmental and economic key factors determining a sustainable integration of high-temperature aquifer thermal energy storage systems into district heating networks. For this objective, we use several methods in five steps to narrow down the potentially high number of influencing factors. We identify hard boundary constraints for project development, the most relevant life cycle phases and related internal factors. Moreover, we identify influencing external factors and methodological factors that impact environmental and economic outcomes from a systemic perspective. Our findings suggest that potential key factors mainly pertain to the construction and operation phases, which are significantly affected by drilling, heat production, and the electricity required for submersible pumps and heat pumps for injection and extraction of stored heat. Identifying these factors enhances the comprehension and transparency of decision support based on life cycle assessment and life cycle costing. The results further guides research and practical improvement actions towards the most pertinent factors.

1. Introduction

District heating networks (DHNs) are expected to play a crucial role in a green and cost-effective transformation of energy supply [1]. Despite advancements, the environmental impact of DHNs remains significant, as nearly 90% of the heat supplied globally is still produced using carbon-intensive fuels [1]. Therefore, concepts of 4th generation [2] and 5th generation [3] district heating networks are increasingly applied [4]. Having the advantage of low temperatures and the potential to integrate a wider range of heat-producing technologies, they result in improved energy efficiencies from a smart system understanding [5] and lower costs [6]. However, 3rd generation district heating networks are likely to persist in the medium to long term, as significant challenges hinder their transformation into fourth or fifth-generation networks [7, 8]. Consequently, cost-effective and smart solutions for transforming 3rd generation DHNs into sustainable networks [9] are needed. One option is using excess heat by implementing seasonal heat storage systems. Specifically, high-temperature aquifer thermal energy storage (HT-ATES) systems promise to be a sustainable and cost-effective energy technology solution in the energy systems context due to their ability to store large amounts of heat at a high-temperature level [10]. As this technology has yet to substantially penetrate energy markets [11], knowledge of successful integration and its corresponding effects on sustainability is still limited. It is essential to thoroughly understand the sustainability impacts of its role concerning energy efficiency, renewable energy integration, economics, and system design, before considering its further integration into DHNs.

Environment and economy are two key pillars for assessing sustainability in the energy context, with environmental impacts being evaluated through various impact assessment techniques. This study uses life cycle assessment (LCA) methods, as it is a method that quantifies environmental impacts over the whole life cycle of products [12]. Although this method might not fully address subsurface impacts, it is

* Corresponding author.
E-mail address: n.scholliers@iwar.tu-darmstadt.de (N. Scholliers).

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Abbreviations

ΔT	Temperature Difference
ATES	Aquifer Thermal Energy Storage
CLD	Causal Loop Diagram
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DHN	District Heating Network
GWP	Global Warming Potential
HT-ATES	High-Temperature Aquifer Thermal Energy Storage
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LT-ATES	Low-Temperature Aquifer Thermal Energy Storage

still considered a viable approach for comprehensively examining environmental impacts. The focus on the financial effects occurring throughout the entire lifespan of the technology, ensuring consistent system boundaries is referred to as life cycle costing (LCC) [13].

While obtaining LCA or LCC results is undoubtedly crucial for decision-making, it is equally important to comprehend how these outcomes are attained and which factors play the most significant role in achieving them. Also, understanding the interdependences of key factors is helpful to guide actions towards HT-ATES development.

According to Langkau et al. [14], factors can be classified as key factors if they possess a significant influence on outcomes. Hence, we define key factors as those with a significant impact on environmental or economic outcomes. However, the quantitative significance of these factors was not explored in detail, so the investigation primarily identifies **potential key factors**.

While some studies on HT-ATES focus on the technical integration into DHNs [15], numerical simulation of hydrogeological parameter variation [16], risk analysis [17], mono-well design within a single geothermal layer [18], and thermal losses and storage capacities [19], research on environmental-economic sustainability remains limited and receives little attention. Daniilidis et al. [20] propose a methodology for techno-economic assessment of an HT-ATES integration into a district heating system, including a calculation of levelized cost of heat and reductions of operational carbon dioxide (CO_2)-emissions. Zeghici et al. [21] evaluated the performance of a gas-driven microturbine and a heat pump unit coupled to an HT-ATES system in Bucharest and show savings in primary energy and CO_2 emissions compared to an older district heating system. Wesselink et al. [22] propose a framework to evaluate the market potential of HT-ATES in DHNs. By applying this framework to a specific case that combines a geothermal heat plant in Groningen, they identify the lifetime of HT-ATES and heat demand as the most significant factors that influence the levelized cost of energy.

While previous literature has examined certain sustainability aspects around HT-ATES sustainability, a comprehensive understanding of the factors affecting environmental and economic impacts and their interdependences remains incomplete. So far, the only referenced LCA study on HT-ATES, conducted by Werner [23], focuses on two very specific cases without sufficient emphasis on general influencing factors or economic factors.

The aim of this study is to examine the factors that affect the environmental and economic impacts of incorporating HT-ATES into DHNs from a life cycle point of view. By identifying the interdependences of key factors, a more systemic understanding is achieved, which supports the better interpretation of results and serves as a foundation for future research to focus on the most important factors. This study's approach involves adopting a general perspective and strives to minimize the multiple factors influencing the results for further quantitative exploration. This leads to addressing the question: "What are the potential internal, external, and methodological key factors for the environmental and economic impacts of HT-ATES integration into district heating networks?"

The comprehensive methodology used to answer this question is described in chapter 2, using a combination of methods including literature review, expert interviews, PESTLE-analysis [24] (standing for P – Political, E – Economic, S – Social, T – Technological, L – Legal, and E – Environmental) and a causal loop diagram (CLD). Chapter 3 lists and discusses all identified potential key factors, while chapter 4 summarizes the main conclusions and outcomes of this study.

2. Methods

Potential key factors were identified through a stepwise approach. General hard boundary constraints of HT-ATES integration into DHNs were identified (I) by conducting semi-structured expert interviews and a discussion workshop. A literature review of recent studies was then conducted (II) to determine the most contributing phases of LCA and LCC. Subsequently, these studies were analyzed (III) to identify potential internal key factors within the relevant phases. Then, external factors were identified (IV) through a PESTLE analysis and potential key factors were derived using a CLD. The final phase (V) involved the identification of potential methodological key factors.

2.1. Identification of hard boundary constraints

We define hard boundary constraints (I) as essential factors with requirements that must be fulfilled for the successful integration of HT-ATES. These factors are binary constants - either fulfilled or not, without intermediate state. Failure to satisfy any one of these factors will prevent the successful integration of HT-ATES in DHN.

To identify these factors, semi-structured expert interviews were conducted following Bryman [25], involving representatives from DHN operators and geological experts. Semi-structured interviews combine pre-planned questions with broader, open-ended inquiries [25] and allow follow-up questions, which were not initially included in the interview schedule. Three pre-planned questions (Q1-3) were asked for hard boundary constraints, one further question (Q4) for potential external key factors (IV).

- Q1: In your role as a DHN operator/geological expert, what factors hinder the integration of HT-ATES in district heating networks?
- Q2: If you think of other stakeholders, what other factors might hinder integration?
- Q3: How would you categorize these factors?
- Q4: Which external factors within the PESTLE fields might not hinder but influence a successful integration?

As follow-up and comprehension questions concerning various factors were anticipated during the interviews, this technique was deemed appropriate for the exploratory interviews. Identified boundary constraints were consolidated and categorized during a discussion workshop comprising five geoscientists, four specialists in district heating/energy systems from two energy suppliers, and one LCA expert and, whenever possible, backed up by literature. Factors that were not considered appropriate as hard boundary constraints were reviewed as external factors.

2.2. Identification of relevant LCA phases

To identify relevant LCA phases (II), the life cycle of HT-ATES was divided into phases, often found in LCA-analysis: construction, operation and end-of-life added by the development phase, relevant in LCC. A literature review was then conducted to pinpoint the most relevant phases.

The initial stage, **Construction**, is the first considered phase in most LCA studies. For all aquifer thermal energy storage (ATES) systems, this phase comprises a subsurface and a surface component, focusing on drilling, building construction, machinery installation, and the connection to the district heating system [26]. During the **Operation** phase, environmental and economic impacts arise due to operation and maintenance, for example electricity consumption. The **End-of-Life** phase encompasses demolition and waste disposal. The **Development** phase includes all research activities and information gathering before constructing an ATES. While typically used in economic research, this stage is often overlooked in LCA methodology due to its minimal effect on the environment.

The literature review followed the snowballing method [27], which enabled effective research of both published and grey literature. The initial papers of Werner [23] for ATES LCAs and Schüppler et al. [26] for ATES cost analysis were used for backward snowballing. Furthermore, forward snowballing via Google Scholar was used to identify literature citing the investigated paper. References were assessed based on their contribution to the four life cycle phases, rated in three classes. "x" represents a high contribution, "o" a low contribution, and "-" indicates no consideration. We defined a 15% contribution threshold, acting as a guidance due to varying factors like different technologies, system boundaries, and evaluation techniques.

2.3. Identification of potential internal key factors

Potential internal key factors (III) were identified based on their potential contribution to environmental and economic impacts within identified significant life cycle phases. The same literature as in (II) has been used for this purpose. Factors might play an underrated role in LCA studies, but in case of high uncertainty or value-variance, their contribution is potentially much higher, which is often analyzed in sensitivity analysis [26]. Langkau et al. [14] define inventory parameters of the life cycle inventory (LCI) model as “the essential parameters of the inventory [, which] are the quantified elementary and intermediate flows, e.g. material and energy inputs, emissions and products.” Parameters influencing these flows, such as the efficiency of the submersible pump, or alternative choices, such as different materials are also classified as inventory parameters. The expressions internal factor and inventory parameter are used synonymously and are valid for environmental and economic factors. Both mostly overlap since monetary values and environmental impacts can be assigned to most LCI parameters [28]. Some factors, however, are only related to economic impacts, such as staff costs.

2.4. Identification of potential external key factors

External factors are defined by Langkau et al. [14] as factors influencing the internal factors directly or indirectly but not being part of the LCI. For the identification of potential external key factors (IV) and their interdependences, we followed their approach with a PESTLE analysis in combination with a CLD.

External factors in comparison to hard boundary constraints can take on several values without hindering a successful integration. Hydrogeological properties, for example, can influence the success of HT-ATES projects, but they do not necessarily hinder it. External factors and hard boundary constraints may overlap, if one factor has a threshold as well as a range of viable values.

The PESTLE analysis [24] as a widely used method in the field of energy [29–31], and specifically recommended for scenario analysis in the LCA field [14], supports the brainstorming process of external factors by categorising them into the PESTLE fields. For the PESTLE analysis, factors were retrieved through the semi-structured expert interviews (Q4) and consolidated in the discussion workshop. For the use of the CLD, the approaches of Langkau et al. [14] and Vries [32] were followed to investigate interdependences among external factors and interdependences between external factors and relevant LCA phases. When constructing a CLD, the main goal is to depict relevant factors and their interdependences using arrows. A positive arrow from A to B signifies that when A increases, B increases, and vice versa for decreases. Conversely, a negative arrow indicates an inverse relationship. External key factors include factors with extensive connections to other external factors and those directly linked to internal key factors [14]. To maintain simplicity, the focus was solely on the influence of LCA and LCC phases rather than on internal factors. Factors identified as potential key factors were backed up by literature, whenever possible.

2.5. Identification of potential methodological key factors

In a further step, potential methodological key factors (V) were identified, as the standards for LCA by the International Organization for Standardization (ISO), ISO 14040 [33] and ISO 14044 [34], provide only a methodological framework, and no faithful standard for LCC exists to date [35]. Therefore, methodological variation is possible and even required when different research questions are analyzed. A methodological factor can refer, e.g., to different choices of the system model, system boundaries, the applied allocation procedure, or the chosen end-of-life model. Again, the literature was reviewed and temporal issues in LCA extracted from Lueddeckens et al. [36] were discussed.

3. Results and discussion

Following results reflect our findings in hard boundary constraints, relevant life cycle phases, potential internal and external key factors as well as potential methodological key factors.

3.1. Hard boundary constraints

Hard boundary constraints have been identified in the following fields: *General Legal Constraints*, *Site-specific Constraints* and *Company-specific Constraints*. Site-specific constraints are further divided into *Above Ground*, *Geological/Geohydrological/Petrophysical Reservoir Properties*, and *Technical Aspects*. The identified constraints play a significant role in ensuring the technical viability, environmental safety, and economic feasibility of subsurface heating projects and should be carefully considered individually.

3.1.1. General legal constraints (international/national/regional)

General legal constraints can hinder the development of HT-ATES projects. They are not site-specific but valid on an international, national, or greater regional level. A relevant example is the *Legal Allowance to heat Groundwater*, which is required to potentially heat groundwater. The granting of permission is typically contingent upon meeting several prerequisites. In Germany, these requirements fall under the scopes of the German ”Bergrecht” and “Wasserrecht”, specifying, for example, technical and safety standards, establishing a monitoring system, and conducting an environmental impact study.

3.1.2. Site-specific constraints: Above ground

Above-ground constraints are often related to legal or physical areas. *Avoiding Protected Areas* is crucial to confirm that the drilling location does not fall within a nature reserve or a drinking water protection area, as these zones often face stricter environmental regulations. Drilling in such areas may require extra permits and rigorous environmental assessments. Opting for sites outside these protected zones simplifies the legal process and reduces environmental concerns. Securing a *Drilling Permit from the Mining Authority* is vital. This permit ensures compliance with mining and environmental laws, involving detailed project plans, environmental assessments, and safety protocols. The mining authority assesses potential impacts on the environment and the community before granting permission, ensuring legal compliance and averting future legal issues. Assessing the *Physical Space Availability for the Drilling*

Site is critical. It must accommodate equipment, material storage, and staff while ensuring safe access for vehicles and machinery. Site selection should minimize disruption to local ecosystems and communities and consider proximity to roadways and utilities for efficient equipment transport and site management. Adequate *Surface Area for Operation* is equally essential. It must accommodate infrastructure like groundwater pumps, heat pumps, pipes, heat exchangers, valves, and potentially storage tanks. Design should allow for future expansion and maintenance access.

3.1.3. Site-specific constraints: Geological/geohydrological/petrophysical reservoir properties

When considering HT-ATES projects, several structural, geohydrological and petrophysical reservoir properties must be evaluated beforehand [11,17]. A *Concept Model and Subsurface Information* for understanding geological, hydrogeological, and geothermal characteristics is essential to predict aquifer behaviour, heat transfer rates, and the impacts of interventions, with accurate data being critical for system design and safety [37]. Determining the feasibility of project infrastructure and related *Available Space Underground* is crucial, involving the assessment of geological formations, their properties and risks related to geomechanical aspects for heat storage infrastructure placement. It may also include existing underground infrastructure, like building foundations or tube lines, which could impede drilling. *Separation from drinking water aquifers* [38–40] prevents contamination through heat, bacterial development or depletion of potable water sources. This requires ensuring that the project does not negatively impact drinking water aquifers, involving careful planning and monitoring, especially since long-term field studies on the ecological condition of groundwater are currently insufficient. *Permeability and Hydraulic Conductivity* [37,41,42] ensure reduced heat loss and minimal impact on surrounding areas through efficient water and heat movement in the aquifer. High values are desirable for effective heat storage but should coincide with slow-moving groundwater, as this allows for controlled heat transfer, which is essential for efficient system operation. Recommendations suggest values greater than 250–500 millidarcy for optimal performance. *Thermal and Petrophysical Reservoir Properties* [43–45], such as thermal conductivity, heat capacity, porosity and reservoir geometry influence heat loss processes and therefore the suitability of an aquifer for HT-ATES. Project-specific economic thresholds can be defined, although thresholds of these factors from a physical perspective still need to be defined. Having an adequate volume is crucial for large-scale heat storage, and an *Aquifer Thickness > 20 Meters* [42,46,47] offers a greater storage capacity, making them capable of storing the necessary heat for DHNs. *Confined Aquifers*, enclosed by impermeable layers, help maintain favourable pressure conditions for storage and reduce the risk of leakage to adjacent aquifers [48,49].

3.1.4. Site-specific constraints: Technical aspects

Technical site-specific constraints relate to the technical integration of HT-ATES in DHNs. Key for heat storage and reuse is a *Seasonal Heat Demand Variation and Excess Heat Availability* to assess surplus heat source accessibility from incineration plants, industry, or renewables. To optimize design, understanding seasonal heat demand fluctuations ensures efficient summer storage for increased winter demand. Of importance is a *Short Distance between HT-ATES and DHN*. Studies indicate an economically feasible maximum range between 15 km [50] and 87 km [51] for the proximity of low grade heat sources to 3rd generation DHNs. Closer proximity reduces infrastructure expenses and minimizes energy losses during heat transfer. Ensuring the hydraulic feasibility for *Net Hydraulic Placement* is essential [52]. To achieve this, it is necessary to assess various factors such as the availability of appropriate supply points, power flow, changes in heat gradients over time, consumer load demands, and whether the existing pipe dimensions at the site are sufficient to meet the demand.

3.1.5. Company-specific constraints

Companies face or define internal constraints for HT-ATES projects. The *Technology Readiness Level* holds significance in influencing a company's decision to invest in technologies due to the maturity level of the technology in question. It refers to the stage of development that a technology must reach before a company is willing to allocate resources to it. Companies may establish a distinct technology readiness level threshold to mitigate risks, favouring technologies that have undergone testing and demonstrated their effectiveness. The *Duration Limit of Project Phases* sets boundaries for the planning and execution phases of a project. In the German context, project phases are specified by the "Honorarordnung für Architekten und Ingenieure". Companies can set specific duration thresholds for specific phases, indicating the maximum duration a company is willing to dedicate to each project phase, spanning from initial planning to ultimate implementation. This threshold is a valuable tool for managing project timelines and allocating resources effectively. Establishing a baseline for *Storage Capacity* safeguards the feasibility and effectiveness of a project. It pertains to the minimum level of heat storage, that a company necessitates for a project to be deemed economically viable. This criterion ensures that the investment aligns with the company's requirements for energy storage capacity and the potential for a return on investment.

3.2. Relevant life cycle-phases

The selected literature sources to identify relevant life cycle phases for HT-ATES are presented in Table 1. Following the method outlined, the overview presents the considered and most contributing life cycle phases and further information on impact assessment methods used in environmental and economic studies.

As to our knowledge, there is only one (not peer-reviewed) LCA study on HT-ATES [23], we included LCA studies on low-temperature aquifer thermal energy storage (LT-ATES) systems [40,53–56], despite the slight technological difference. Considering that these studies include only factors relevant to environmental impacts and mostly focus on the technology itself, the search was extended to literature containing economic assessment [20,26,42,57–59] and studies containing simple greenhouse gas accounting [20,26,58,59]. To include more detailed factors on drilling, sources on geothermal planning costs [60] and drilling [61,62] were added.

For environmental studies, the operation phase is identified as highest contributor to environmental impacts. Four studies [23,40,53,55] consider the construction phase to be also relevant, partly depending on the underlying assessment method. Only one study [55] considers the end-of-life phase to be relevant, but the most contributing element in the end-of-life phase is the disposal of waste water from well maintenance, which could be seen as part of the operation phase. As expected, the development phase is not regarded at all in environmental studies. The construction and operation phases are considered potentially key life cycle phases for environmental results, with the strong advice that further examination should be given to the end-of-life and development phases. All investigated economic studies consider the construction phase to be of high importance. Additionally, where considered, the operation phase is also regarded as a life cycle phase with high-cost impacts. Only three studies [26,57,60] consider the development phase, but come to the conclusion that it is of less relevance. None of the reviewed studies considers the end-of-life phase, which could be subject of further research. The findings indicate that both the construction and operation phases are most relevant for economic and environmental impacts.

3.3. Potential internal key factors

Based on the reviewed literature (3.2), potential internal environmental (Table 2) and economic key factors (Table 3) were identified. Challenges mirrored those in pinpointing key LCA phases, particularly in

Table 1
Assessed and most contributing LCA phases in literature.

Study	Subject	Development	Construction	Operation	End-of-Life	Comment
Studies on environmental impacts						
Werner [23]	HT-ATES	–	o	x	–	Impact assessment method: Global Warming Potential (GWP).
		–	x	x	–	Impact assessment method: Other Eco-Indicator99 – midpoint categories than GWP.
Stemmle et al. [40]	LT-ATES	–	x	x	o	Impact assessment method: IMPACT 2002+ V2.10, GWP and end-point-categories.
Ni et al. [53]	LT-ATES	–	x	x	o	Impact assessment method: Several midpoint categories. Biological medium production contributes more than 15% but is irrelevant for HT-ATES. We consider material acquisition and functional equipment manufacturing as part of the construction phase.
Tomasetta [56]	LT-ATES/Ground Water Heat Pump	–	o	x	o	Impact assessment method: Eco-Indicator99, hierarchist perspective/average weighting.
Moulopoulos [55]	LT-ATES	–	x	x	x	Impact assessment method: ReCiPe.
Studies on economic impacts						
Schüppler et al. [26]	LT-ATES	o	x	x	–	We consider "pre-investigation" in the development phase and "replacement" as capital expenditures in the construction phase.
Daniilidis et al. [20]	HT-ATES	–	x	x	–	No allocation to capital expenditures and operation expenditures is given in absolute cost numbers. The assumption is that both are above 15%.
Holstenkamp et al. [42]	HT-ATES	–	x	–	–	No absolute numbers, but stating that drilling makes up a major part of overall costs.
Todorov et al. [57]	LT-ATES	o	x	x	–	–
Vanhoudt et al. [59]	LT-ATES	–	x	x	–	–
Micale et al. [60]	Geothermal Projects	o	x	x	–	Cost distribution for geothermal power plants.
Capuano [61]	Geothermal Well Drilling	–	x	–	–	Stating that appr. 50% of geothermal development process costs are due to drilling and completing the wells.
Lukawski et al. [62]	Geothermal Well Drilling	–	x	–	–	Stating that drilling expenditures for low-grade enhanced geothermal-systems can account for more than 60–75% of the total project cost.

Contribution of life cycle phase to environmental/economic impacts.
x: high (at least 15% contribution in one of the assessment categories).
o: low (lower than 15% contribution to any of the assessment categories).
-: not considered.

Table 2
Potential internal environmental key factors.

Category	Process	Process-specific factors	Cross-process factors
Construction			
Subsurface construction[a,b,c,d,e]	Well material[a,b,c,d,e]	Metal, polyethylene, polyvinylchloride, bentonite	Number of wells, borehole length
	Drilling[3]	Electricity	
	Disposal of construction waste[3]	Transport, electricity, drilling waste treatment	
Functional equipment[a,c,e]	Heat pump[c,e]	Specific lifetime	-
	Heat exchanger[c]	Refrigerant, specific lifetime	
	Submersible pump[a]	Specific lifetime	
Operation			
Electricity for running the ATES[a,b,c,d,e]	Submersible pumps[a,b,e]	Flow rate	Operating hours
	Heat pump[a,b,c,e]	COP, ΔT	
Maintenance[e]	Wastewater of well treatment[e]	Number of flushes, amount of water, type of deposit	-
(Heat production)[a]	Technology specific heat production		-

[a] [23].
[b] [40].
[c] [53].
[d] [56].
[e] [55].

defining system boundaries, considering different processes and factors, allocating sub-processes, and selecting assumptions. Factors not considered in underlying studies or with little impact compared to other factors remain unconsidered in the results.

3.3.1. Potential internal environmental key factors

During the **construction phase**, LCA studies indicate that subsurface construction has the most significant impact on the environment. According to Ni et al. [53], the production of the biological medium for bioremediation has the largest impact when considering it within the construction phase, but this only applies to this very specific case of in situ bioremediation and is therefore not further considered. The material used to construct the wells plays a significant role. According to Werner [23], HT-ATES systems typically use metal pipes made of stainless steel, which have a higher global environmental impact compared to polyethylene [40] or polyvinylchloride [55,56] used in LT-ATES systems. Ni et al. [53] highlight the importance of electricity consumption during well drilling, while also indicating that the disposal of construction waste can play a smaller but still significant role, as noted by Tomasetta [56]. Backfill material and its extraction and processing are mentioned by Moulopoulos [55] to be of greater importance. The internal factors mentioned depend on the design of the ATES, specifically the number

Table 3
Potential internal economic key factors.

Category	Process	Process-specific factors	Cross-process factors
Construction			
Subsurface construction[a,b,c,d,e,f,g]	Connection materials[a,d,e]	Horizontal piping, well connections, ducts, shut off valves	-
	Well material[a,g,h]	Clay seal, cementing	Number of wells, borehole length, drilling technology, rate of penetration
	Drilling: Equipment rental and services[g,h]	Contract drilling rig (day rate), directional drilling services, planning engineering and project management	
	Drilling: Materials, consumables and related services[g,h]	Casing, tubing, and services, number of bits used, fuel, freight and hauling	
Functional equipment[a,d,e]	Controlling and monitoring[a,e]	Electronic switchboard; pump control system, electricity connection	-
	Heat pump[a,d]	Specific lifetime	
	Heat exchanger[a,d,e]	Specific lifetime	
	Submersible pump[d,e]	Specific lifetime	
Operation			
Electricity for running the ATES[a,b,d,e]	Submersible pumps[a]		Operation mode (cut-off temperature, discharge capacity, charge-store-discharge-rest strategy, imbalance ratio)
	Heat pump[a,b]	COP	
Maintenance[a,c,f]	Well treatment[c]	Scaling, general corrosion, microbial corrosion	-
Staff[f]	Wages and services		-
(Heat production)[a,b]	Technology specific heat production		-

[a] [26].
[b] [20].
[c] [42].
[d] [57].
[e] [59].
[f] [60].
[g] [61].
[h] [62].

and length of wells. Functional equipment, such as heat pumps, heat exchangers, and submersible pumps, are also crucial during the construction phase [23,53,55].

During the **operation phase**, the most crucial factor for running the ATES is the electricity supply [23,40,53,55,56]. This includes the electricity required for the heat pump and submersible pumps. If a heat pump is necessary, this process is most important. Three studies [23,40,53] have identified the coefficient of performance (COP) of the heat pump as the most crucial factor. This depends on both the internal efficiency and the temperature difference (ΔT) between ATES and the DHN. The submersible pumps are mainly affected by their flow rate. One factor that affects both the heat pump and the submersible pump is the operating time. During the operation phase, wastewater treatment may be necessary because of flushing the wells [55]. It is important to consider whether the wastewater is treated in a sewage system or deposited as surface water, as this can affect the outcomes. Heat production is another potential key factor but is discussed in chapter 3.5.

3.3.2. Potential internal economic key factors

The construction of subsurface infrastructure is critical for both economic and environmental impacts, although the processes and factors involved differ. Materials used for connections, such as horizontal piping and technical equipment, are mentioned in the literature [26,57,59], as well as materials used for wells [26,61,62]. In contrast to environmental impacts, the primary focus regarding pipes is not on their pipe material composition, but rather on aspects like the clay seal and cementing. Additionally, the drilling process can be categorized into two distinct groups: 'equipment rental and services' and 'materials, consumables, and related services' [61,62]. The contracted drilling rig contributes the most to the first category, followed by accompanying services. The second category mostly consists of casing, tubing, and services, as well as consumables and the number of bits used, completed by freight and hauling. The majority of elements impacting the well material and drilling are influenced by the number of wells, the length of the boreholes, and the drilling technology used. These factors affect the penetration rate and consequently determine the duration for which the contract drilling rig is required. Functional equipment costs are determined by equipment for controlling and monitoring, heat pump, heat exchanger and submersible pumps [26,57,59].

During the operation phase, electricity for running the ATES, especially for the submersible pump and heat pump is the most crucial economic factor [20,26,57,59]. The COP of the heat pump has a significant impact on the electricity consumption during this phase. The selected economic studies also identify operation mode factors as key parameters. The studies often mention factors such as the cut-off temperature influencing discharge capacity, and the seasonal charge-store-discharge-rest strategy. For further consideration, these factors most likely influence environmental impacts equally, however, they are mostly mentioned by economic studies. Another mentioned category in the operation phase is maintenance [26,42,60], which involves well treatment affected by hydrochemical and hydrobiological water conditions that influence scaling, corrosion, and microbial corrosion [42]. Additionally, staff costs are incurred during this phase [60]. As for environmental impacts, heat production may play an important role, depending on the system boundaries.

Comparison of internal factors impacting environmental and economic aspects reveals significant overlap. In the construction phase, subsurface construction particularly drilling and well materials are crucial with distinct characteristics. Construction waste disposal stronger influences environmental impacts, while economic impacts hinge more on well-connection materials. Reducing subsurface construction in system design can mitigate construction-phase impacts, but trade-offs must consider potential heightened effects during operation. Functional equipment, such as heat pumps, heat exchangers, and submersible pumps, holds great importance, along with controlling and monitoring equipment contributing to economic impacts. In the operation phase, electricity is pivotal for both environmental and economic aspects, influenced by heat pump COP and operation mode. Well maintenance, including wastewater treatment, significantly affects environmental and economic impacts, alongside staff costs. Heat production may carry substantial environmental and economic impacts, treated as a methodological factor in chapter 3.5.

3.4. Potential external key factors

From the PESTLE-analysis, external factors were identified in six categories. Interdependences between those factors and the LCA phases were drawn in the CLD. The potential key factors were identified through either having at least four interdependences with other factors or through their connection to at least one of the two relevant LCA phases *Construction* and *Operation* (Fig. 1).

Potential **political** key factors include *"Green" Policies*, which improve a political climate in which funds for research projects, or subsidies can be established to improve knowledge on technical integration, subsurface, and geological risks. *Open Data Policies* [37,63] improve the openly available information on technical integration, subsurface, and geological risks and *Political* Support *Actions* such as roadmaps [64] and guidelines can help to improve the social acceptance of subsurface projects [16].

Potential **economic** key factors, such as *Financial Support*, for example research funds and subsidies, cannot reduce overall costs occurring during the lifecycle of HT-ATES, but help public and private corporations to finance projects and make them feasible [60]. *Opportunity Costs* of other heat-generating technologies within the DHN compete with marginal heat costs from HT-ATES systems. The rank within a DHN merit order, therefore, constitutes if and if so, how much heat is deployed from the HT-ATES.

The identified potential **social** key factor is *Social Pressure to Act on Climate Change*, which can lead to more "Green" Policies and a public acceptance of geothermal energy. The opposite, Climate Sceptic Attitudes lead to less "Green" Policies.

Potential **technological** key factors encompass *Heat Demand of the DHN*, which influences the required temperature level of the DHN. This factor is sensible to insulation of housing and connection points of the DHN. The *Complexity of Technical DHN Integration* influences bound capacities within the development and construction phases referring to modifications required for seamless operation. It also includes the adequate integration of the potential heat pump into the power grid to avoid power shortages or interruptions. The *Available Excess Heat* can be one delimiting factor of the storable heat amount within the aquifer, originating from waste incineration plants [65–67], renewable energies [17], waste heat [68] or others. The *Knowledge on Technical Integration* and the *Information on the Subsurface* reduce bound personal capacities in the development phase and are necessary for optimal construction and operation of the HT-ATES. The later factor contains information on composition and structure (types of rock, soil, presence of aquifers), on hydrogeological properties, groundwater flow and chemical composition of groundwater (see potential environmental key factors below). The *Knowledge of Geological Risks* is crucial in thermal energy projects, its assessment contributing up to 11% of the total cost [60]. Risks include groundwater contamination, especially if the ATES system interacts with different water layers, induced seismicity due to changes in pressure and temperature because of the ATES (rather low risk), land subsidence due to improper water extraction and injection management and chemical reactions like scaling or dissolution of minerals.

The only identified potential **legal** key factor is the *ΔT-Permission to Heat the Aquifer* [69], which leads to greater potential heat storage capacities and influences the operating mode for HT-ATES, for example due to lower cut-off temperatures.

Potential **environmental** key factors can be divided into direct and indirect factors. Direct factors contain the *Undisturbed Aquifer Temperature* [70–73], which influences the time needed for the ATES to reach

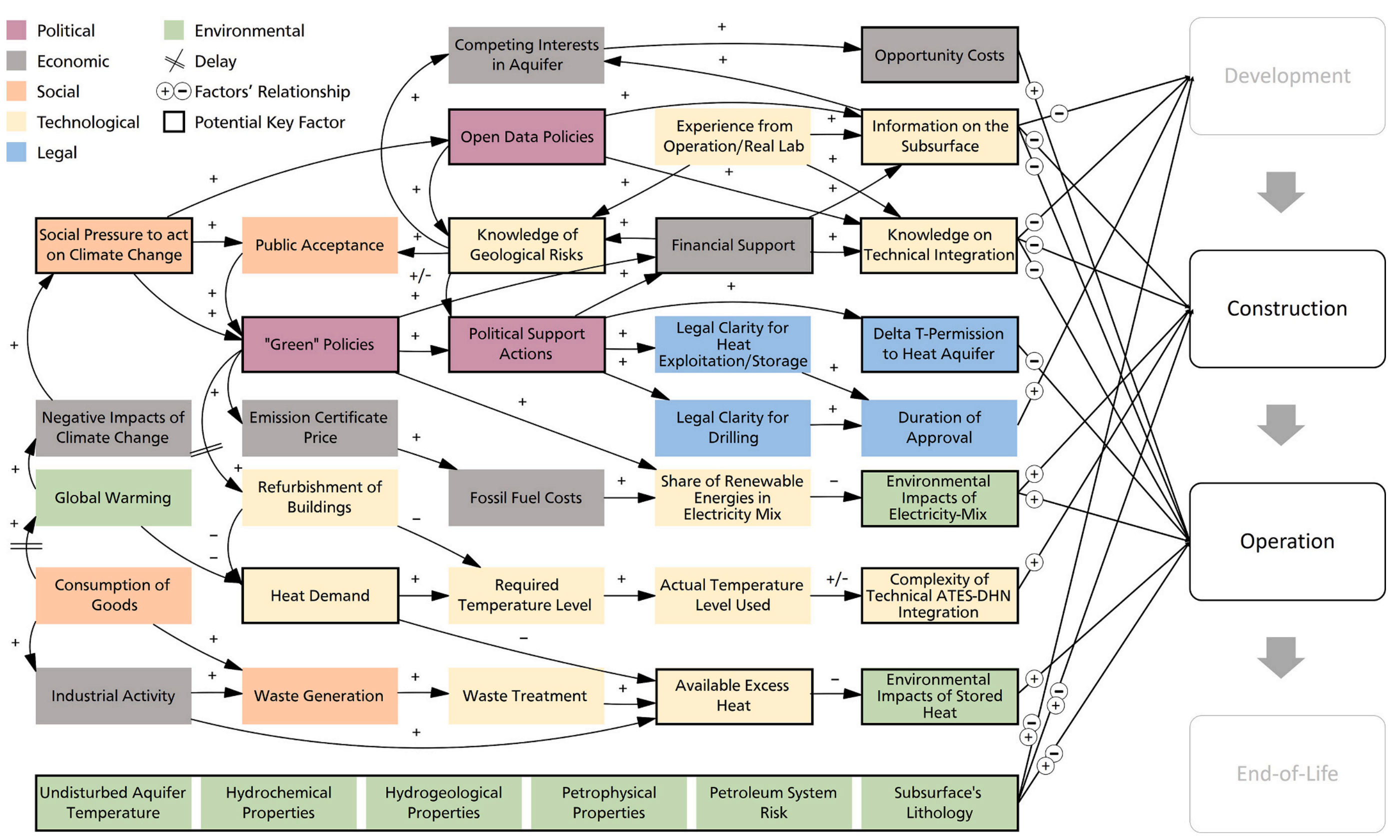

Fig. 1. Causal loop diagram with external factors and potential external key factors. Key factors having four or more interdependences to other factors or direct connections to the relevant LCA phases construction and operation.

its full potential capacity, energy needed for extraction and therefore the system's efficiency. *Hydrochemical Properties* [74], such as the mineral content of the water affects the potential for scaling, corrosion, clogging and other chemical reactions when the water's temperature changes. High salinity influences the material choice as well as maintenance intervals. *Hydrogeological Properties* [75], such as permeability, porosity, and transmissivity of the aquifer influence how efficiently the heat can be stored and transmitted. It affects groundwater flow as well as thermal conductivity. The *Petrophysical Properties* [43–45] described in (3.1.3) affect the thermal efficiency of HT-ATES. Low thermal conductivities in combination with high porosities and heat capacities prove to be advantageous and in turn influence the design, construction and configuration of well pumps for optimal geometries of the heat plume. *Petroleum system risk* affects system design, construction elements, and maintenance. Targeted aquifers may also contain oil or gas, which means that reservoir fluids may contain contaminants such as organic acids, fluoride, arsenic, salinity, and nitrate [76,77]. The *Subsurface' Lithology* plays a role in aquifer presence and thickness and determines the suitable depth and location for ATES installation. Additionally, consolidation state affect clogging risk and filter selection.

Indirect factors enclose the *Environmental Impacts of Stored Heat*, which depends on the way heat for storage is being produced. Environmental impacts occurring in upstream processes can be allocated to the ATES. The *Environmental Impacts of Electricity Mix* consumed for example by the heat pump and the submersible pump can be allocated to the heat provided by the ATES, therefore influencing the environmental impacts.

3.5. Potential methodological key factors

Potential methodological key factors have been analyzed according to the LCA stages *Goal and Scope*, *Life Cycle Inventory* and *Impact Assessment*. Within the **Goal and Scope** stage, analyzed papers show differences in their *System Boundaries*, reflecting different research questions resulting in variations in results. As highlighted in 3.2, different life cycle phases were considered, sometimes neglecting the development phase or end-of-life phase. Given that HT-ATES represents a storage technology, heat generation (operation phase) should be considered [23]. If heat generation is included within the system boundaries and therefore as an internal factor, environmental as well as economic results are fundamentally influenced [20,23,26]. LCA can be regarded as a decision-making tool and is often used as such in a comparative setting in which environmental or economic impacts are compared to a *Reference System* (e.g. Refs. [23,40,53]), based on the same functional unit. Impacts can vary significantly depending on the reference system used [55]. For HT-ATES, it is important to carefully select the appropriate reference technology. As a storage technology, one may question whether it is appropriate to compare it to a heat-producing technology that lacks the ability to store energy in any form. Alternatively, it could be compared only to reference technologies with storage capabilities. The *Technological Time Scope* [78], which is usually related to the product or service life cycle varies between studies, typically ranging from 15 [23,55] to 35 [40] years, and has a significant impact on the contribution of different LCA phases. LCA phases typically become more influential, when they last longer compared to other phases.

During the **Life Cycle Inventory**, different *Databases and System Models* [79] provide choices for modelling of foreground and background models [55]. Additionally, dataset availability can play a role in the modelling phase, e.g. when specific datasets for materials are not available. *Electricity and Heat Mix Scenarios* can serve as a valuable tool to assess future impacts. In the coming decades, district heating systems will undergo major changes with higher shares of renewables, fuel shifts, and sector coupling, affecting the prediction of future impacts [40]. Considering the lifetime of HT-ATES to be several decades, assumptions for energy scenarios can lead to widely varying results. The *Temporal Resolution of the Inventory*, "describes the time granulometry when temporal differentiation is carried out" [80] and can have a significant impact on LCA-results [81], while *Time Differentiation* refers to, "the action of distributing the information on a time scale related to the models' components" [80]. As demonstrated by Stemmle et al. [40], the time dependency of the LCI is vital for the electricity mix and associated greenhouse gas emissions, impacting both current and future scenarios. This likely also affects DHNs, where HT-ATES' heat source and associated costs and environmental impacts can rapidly change. The *Inventory Modelling Period* [78] refers to the time range impacts are accounted for. As significant emissions are not expected to occur after the HT-ATES lifetime, the inventory modelling period is considered to be of less importance.

During **Impact Assessment**, *Methods for Impact Assessment* in LCA must be carefully chosen. Literature shows varying environmental impact assessment methods, including midpoint, endpoint, or single-score indicators, depending on the research question. Economic impacts are typically measured monetarily, with different convertible currencies, being less influenced by this factor. Weighting archetypes (hierarchist, individualist, egalitarian) as in the Eco-indicator99 method provide further methodological choices [55]. To date, there is no scientific consensus regarding the allocation of *Impacts from Waste Incineration or Excess Heat* from industry and multiple approaches coexist [82]. The current draft amendment of the building energy law in Germany [83] considers unavoidable waste heat as emission-free but is under widespread discussion. As demonstrated by Werner [23], greenhouse gases resulting from heat generation via waste treatment can significantly impact environmental impacts of HT-ATES. Moreover, cost allocation could be a crucial factor, dependening on whether waste is viewed as a valuable resource with a market price or simply as refuse, for which utilities incur disposal fees. The *Impact Modelling Period* [78], pertains to the time horizon evaluated by the impact assessment method. Its choice is critical for assessing the environmental impacts of HT-ATES because characterization factors vary for different timeframes. Many studies use a 100-year time horizon (GWP_{100}), but often lack justification, especially when dealing with methane emissions. This is crucial, since characterisation values for methane are 81.2 for 20 years and 27.9 for 100 years [84]. *Discounting* is a method of assigning a value to time and is commonly used in economic analysis. It is also used in LCA [85], but discussed controversially [36,86]. While it may be reasonable to use static discount rates based on market interests for short-term economic decisions, it becomes less clear for longer time horizons, because then any impact arising after a couple decades becomes diminishing small [87]. Studies suggest declining interest rates for intergenerational decisions spanning over 30 years [13,88], which HT-ATES lifetimes may exceed. *Time-dependent characterization* refers to the use of time dependent characterisation factors in life cycle impact assessment [36]. It addresses inconsistencies between the product time horizon and the assessed time horizon for impact assessment. The presumably most mature model [89] for assessing impacts of greenhouse gases time-dependently demonstrates significant differences in results of biofuels by considering dynamic characterisation factors. *Dynamic Weighting* relates to time dependent weighting of LCA results [36] and can address time-sensitive weighting methods, such as distance-to-target [90], or time-dependent changes in the distribution of age in society [87]. This factor can be considered, if LCA studies of HT-ATES are weighted from a policy perspective. *Time-dependent Normalization* is not a common practice in literature, but is sometimes recommended [36] for evaluating near-time and long-term toxicity impacts [91], for acknowledging changes in the known amount of resources, or when considering national and international emission reduction targets [92]. Discounting can also be seen as a form of time-dependent normalization [93]. Predictions of relevance for HT-ATES remain unclear due to the scarcity of literature on this topic.

4. Conclusion

This research aimed to identify potential internal, external and methodological key factors that influence the environmental and economic results of integrating HT-ATES in DHNs. Additionally, hard boundary constraints for successful integration were identified, which were found to be mostly site-specific, related to surface conditions and to geological and geohydrological reservoir properties. Further identified constraints are the legal permit to heat groundwater and company specific constraints.

Out of the four life cycle phases of development, construction, operation and end-of-life, a literature review identified construction and operation as the two most researched and most significant phases in terms of environmental and economic impacts. Potential internal key factors within these phases include subsurface construction, functional equipment, and electricity to run the system, with the electricity requirements of heat pumps and associated COP and submersible pumps being critical. The way in which heat is produced can fundamentally alter the results when considered within the system boundaries. To improve sustainability, these factors are critical and can be addressed in the design and operation of the HT-ATES.

A PESTLE analysis with a corresponding causal loop diagram identified potential external key factors that directly influence the construction and operation of HT-ATES. Most factors are related to the technical complexity of HT-ATES, including information and knowledge about the energy system. Indirect environmental factors characterising subsurface conditions, the legal ΔT-limit to heat the aquifer, and opportunity costs, further influence results. Improving these factors can directly improve the sustainability of HT-ATES, or if improvement is not possible, assessing them helps in decision making of different HT-ATES locations. Other external factors influence the integration of HT-ATES indirectly through interdependences with other factors. In particular political factors and financial support as well as social pressure to act on climate change, heat demand and available excess heat can be addressed from a systemic point of view to improve sustainability.

Potential methodological key factors were identified in the goal and scope, life cycle inventory and impact assessment phases of LCA studies. General methodological key factors involve the choice of databases, system models, and impact assessment methods. For HT-ATES, special attention should be given to the choice of system boundaries, the reference system, the technological time scale, energy mix scenarios and accounting methods of environmental impacts of waste heat. The technology is also sensitive to temporal factors due to the decades of operation, but the actual influence of temporal factors needs further research.

Given the limited number of environmental and economic studies of HT-ATES, our approach provides a general method for identifying the potentially most significant factors for further research, without the need for detailed quantitative analysis of each factor. The methodology has been developed for HT-ATES, but due to its general form, it can easily be applied to the integration of other energy (storage) technologies into energy systems where the literature on environmental or economic impacts is scarce. However, quantification of the identified factors remains an area for further investigation and requires comprehensive LCA and LCC studies.

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CRediT authorship contribution statement

Niklas Scholliers: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization. **Max Ohagen:** Writing – review & editing, Writing – original draft, Validation, Resources, Investigation. **Claire Bossennec:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation. **Ingo Sass:** Supervision, Project administration, Funding acquisition. **Vanessa Zeller:** Writing – review & editing, Supervision. **Liselotte Schebek:** Supervision, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL-Write in order to improve the text editorially. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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

No data was used for the research described in the article.

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