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Life Cycle Assessment of an Aquifer Thermal Energy Storage System: Influence of design parameters and comparison with conventional systems

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ABSTRACT

This paper presents a Life Cycle Assessment (LCA) of a low-power capacity Aquifer Thermal Energy Storage (ATES) system supplying a building on Bordeaux INP's university campus, powered by the French low-carbon electricity mix. It compares environmental impacts with alternative thermal energy supply solutions, analyzing various scenarios including design choices, construction methods, equipment lifespan, and failures.

Results show that the operational phase contributes 60% to the total environmental impact, mainly from electricity consumption by the heat pump and pumping wells. The ATES operational phase has a climate change impact of 37 gCO_{2eq} kWh_{th}^{-1}, lower than reported in existing literature, but borehole construction, particularly chromium steel production for the casing, poses environmental burdens. The comparative assessment of the different scenarios underlines the pivotal influence of energy delivery optimization, borehole casing material choice, and heat pump performance coefficient on LCA outcomes.

Comparative analyses demonstrate that ATES outperforms conventional natural gas or biomass heating and vapor compressor chillers for cooling, but slightly trails air or ground-source heat pumps. Despite high construction phase impacts, mitigation occurs relatively quickly, except for human health concerns.

The study underscores the potential of low-power ATES systems with low-carbon electricity to replace fossil fuel or biomass-based heating, reducing environmental footprints. The choice between ATES and other heat pumps depends on the electricity mix, performance factors, and delivered energy.

1. Introduction

Human activities generate Greenhouse Gas (GHG) emissions in the atmosphere, which affects many extreme weather and climate events in all regions of the globe (IPCC, 2023). Energy use in buildings is one of the main sectors contributing to GHG emissions. The heating of buildings accounts for 20% of GHG emissions worldwide (IEA, 2019). Although heat demand is expected to decline by 30% over the 21st century, cooling demand is expected to increase by 70% (Isaac and van Vuuren, 2008). To meet the European Commission's target of reducing greenhouse gas emissions by 55% by 2030 (EU-Concil, 2021), it is crucial to reduce energy consumption for thermal comfort in buildings and accelerate the transition from fossil to renewable sources.

The geothermal energy sector shows promise in mitigating the environmental footprint associated with the energy used for thermal comfort in buildings. It comprises different types of technologies (open-loop systems or closed-loop systems), exploiting the ground from very shallow (<10 m) to very deep (>5 km) depths. Shallow systems coupled with heat pumps (HP) and using free cooling offer better environmental performance than deeper systems (Pratiwi and Trutnevyte, 2021). For example, Ground Source Heat Pump systems (GSHP) can reduce GHG emissions from 30 to 90% compared to conventional energy systems (Saner et al., 2010; Bayer et al., 2012; Blum et al., 2010). Among shallow geothermal systems coupled with HP, Aquifer Thermal Energy Storage (ATES) is suitable for providing heat and cold to large buildings or structures with high thermal demand such as hospitals, universities, airports, office buildings, etc. Fleuchaus et al. (2018). In temperate climates, ATES bridges the seasonal gap between thermal energy demand and supply. This open-loop system uses a minimum of two wells to temporally store and extract sensible heat and cold in the subsurface through injection and withdrawal of groundwater (Fleuchaus et al., 2018). A heat exchanger allows transferring the energy from the groundwater to the building and *vice versa* (Fig. 1). In winter, a HP

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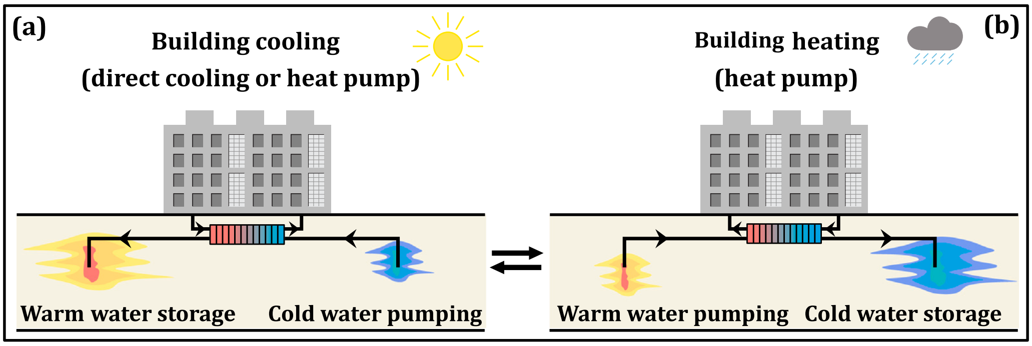

Fig. 1. Operation of an ATES system.

is used to reach suitable temperatures to heat the building, while in summer the system can offer free cooling to maintain thermal comfort. The HP can also be used in summer during very hot days when the cooling load cannot be reached with free cooling.

ATES systems can achieve GHG reductions up to 75% compared to conventional energy solutions based on fossil fuels (Fleuchaus et al., 2018; Stemmle et al., 2021). The environmental impacts of ATES projects are often calculated only based on GHG savings during the operation phase of large buildings (Schüppler et al., 2019; Vanhoudt et al., 2011; Hoes et al., 2006; Fleuchaus et al., 2018). Thus, the development and widespread use of more comprehensive environmental studies are necessary. These investigations should encompass not only the assessment of GHG during operational phases but also conduct a comprehensive examination of broader environmental impacts on human health, ecosystems, and resources availability throughout the entire life cycle of the system.

In this context, Life Cycle Assessment (LCA) is a standardized method (ISO, 2006a,b) used to evaluate the environmental impacts (such as climate change, terrestrial acidification, particulate matter formation, etc.) of a system throughout all stages and processes (material extraction, production and assembly, transport, operation, and end-of-life). LCAs evaluating the overall environmental impacts and damages of ATES compared to conventional energy systems are scarce. To our knowledge, the literature presents only four LCAs of ATES system (Moulopoulos, 2014; Tomasetta et al., 2015; Ni et al., 2020; Stemmle et al., 2021). These studies relate GHG emissions close to 100 gCO_{2eq} per kWh of thermal energy provided to the building. These results emphasize high GHG reduction compared to conventional thermal energy supply based on natural gas generating about 250 gCO_{2eq} kWh_{th}^{-1} (Stemmle et al., 2021; ADEME, 2022). These LCA results mainly focus on GHG emissions of high power capacity ATES in countries presenting electric mix with high emission factors (China, Netherlands, and Germany), but (Stemmle et al., 2021) show the substantial GHG reduction potentially achieved with the future "*free fossil fuel*" German electrical mix planned for 2050 for a high power capacity ATES.

However, within the context of a low-capacity ATES powered by low-carbon electricity, there remains a lack of studies that assess and quantify the additional impacts of ATES systems, including impacts on resources availability, human health, and ecosystems, in comparison to conventional thermal power sources or alternative renewable technologies.

This paper presents multiple LCAs conducted on the newly established ATES system, operational since early 2022, for the building of the ENSEGID (École Nationale Supérieure en Environnement Géoressources et Ingénierie du développement Durable), a department of Bordeaux INP, located on the university campus in Bordeaux (France) (Fig. 2a). The annual thermal demand of the building is 132 MWh_{th} for heating and 78 MWh_{th} for cooling. It is notably low compared to the capacity of the majority of ATES-powered buildings worldwide (Fleuchaus et al., 2018, 2019). Initially, this ATES system has been designed to cater to 65% of the floor area (3600 m^2), with plans for subsequent years to extend its coverage to the entire building (5500 m^2). The HP and the downhole well pumps (DWP) are powered by the French electricity mix, primarily derived from nuclear power, making it less carbon-intensive in comparison to the electricity mixes used in other ATES LCA studies (Stemmle et al., 2021; Moulopoulos, 2014; Ni et al., 2020). The primary objective is to assess the environmental relevance of the ATES solution, considering not only greenhouse gas emissions but also all categories of environmental impacts and damages. Within the context of low thermal demand and the use of a low carbon-intensive electricity mix, various scenarios involving well construction, equipment replacement and maintenance, as well as building thermal demand and COP value, are examined.

The study also conducts a comparative LCA of the ATES system at ENSEGID, juxtaposed with four alternative scenarios featuring fossil fuel, biomass energy, Air Source Heat Pump (ASHP), and Ground Source Heat Pump (GSHP).

The present work follows the four phases of Life Cycle Assessment (LCA) delineated by international standards (ISO 14040; ISO 14044): (i) The goal and scope, and (ii) the life cycle inventory (LCI) are described in the *Materials and Methods* section. Subsequently, (iii) the life cycle impact assessment (LCIA) results and their (iv) interpretation are presented in the *Results and Discussion* section, facilitating a discourse on the findings in relation to existing literature.

2. Material and methods

2.1. Study site

ENSEGID is a French graduate school training over 130 students per year located on the campus of Bordeaux INP, France. The staff comprises 60 members, divided between research/teaching activities and administrative/technical tasks. The total floor area of the building is 5500 m^2.

The local geology corresponds to the top of a large multi-layered sedimentary system (Larroque et al., 2013; Labat et al., 2021; Godinaud et al., 2023), offering good opportunities for geothermal exploitation. The ATES targets the upper part of the confined oligocene aquifer, lying in heterogeneous limestones. The system comprises one "hot" well (GF1) and one "cold" well (GF2) (Fig. 2a). The wells are 70 m depth (Fig. 2b), made with steel and chromium steel casing, and separated by a distance of 145 m. The technical room (Fig. 2c) comprises the HP and the heat exchanger (HE) and is located close to GF1. Additionally, four piezometers (pz51, pz52, pz101, and pz102) were drilled to a depth of 70 m. These piezometers serve a dual function: monitoring the extension of the thermal plume in the aquifer and supporting academic research.

The system has been in operation since February 2022. During the short period of operation of ENSEGID-ATES (only 1.5 years), some problems occurred regarding DWP flowrate regulation and heat pump operation. There are still some adjustments and decisions to take regarding the regulation of the system. Consequently, the first months of

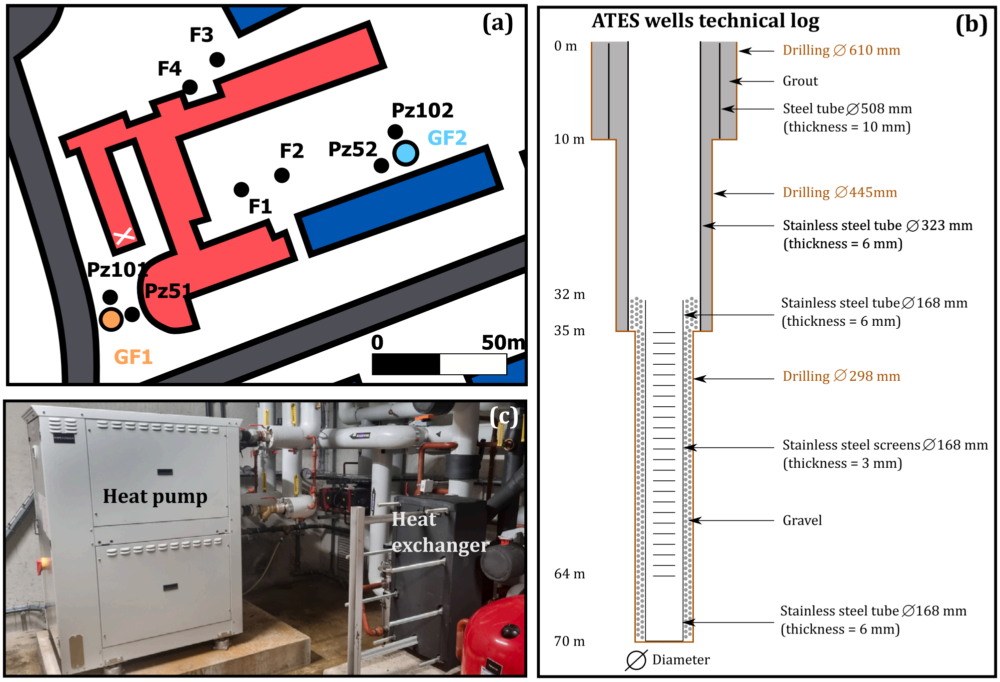

Fig. 2. ATES site at ENSEGID: (a) A map of the site depicting ENSEGID with the red building, while the technical room is indicated by a white cross, (b) the technical log of an individual well, and (c) the machine room. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Thermal load and electrical consumption of ATES obtained from the company in charge of pre-investigation studies. The COP = 5 during winter was the one used during the pre-investigation study.

	Heating with heat pump (COP = 5)	Free cooling
Annual thermal demand	132 MWh_{th}	78 MWh_{th}
Annual heat pump consumption	26.4 MWh_{el}	–
Annual DWP consumption	20 MWh_{el}	10 MWh_{el}
Electricity consumption for 30 years	1392 MWh_{el}	300 MWh_{el}

operation cannot be representative of the global and future operational modes. For this reason, the thermal demand of the building and the electrical consumption of the equipment used in the LCA are based on the pre-investigation/feasibility study (Table 1). Thus all the scenarios consider a thermal demand of 132 MWh_{th} of heat and 78 MWh_{th} of cooling per year.

2.2. Goal and scope

This study aims to investigate the environmental impacts of the new ATES of the ENSEGID building. To scrutinize the influence of design or material choice, potential equipment failure, and optimization of the amount of delivery energy on the environmental impact, multiple ATES configurations are assessed. A reference scenario based on the real ATES configuration at ENSEGID has been initially defined:

- **Sc ATES**$_{ref}$: The reference scenario considers an ATES lifetime of 30 years, aligning with the minimum 30-year geothermal exploitation permits issued in France. It is based on the data collection during ATES construction and the actual ENSEGID thermal demand (Table 1). The borehole casing is made of chromium steel tubes. The replacement of the equipment (HP, HE, DWP) is not considered, and mandatory borehole maintenance is planned after 10 years and 20 years of operation. The COP of the HP is 5 and the cooling mode is 100% geocooling,

From which 6 alternative scenarios have been derived for comparison:

- **Sc ATES**$_{replacement}$: This scenario evaluates the impact of equipment lifetime and/or failure by considering equipment replacement once during the ATES lifetime, along with borehole maintenance every 5 years to prevent clogging issues.
- **Sc ATES**$_{leak}$: This scenario considers a 6% annual leakage of the refrigerant fluid from the HP during operation. This is a typical value reported in the literature (Saner et al., 2010; Greening and Azapagic, 2012). The effect of a potential leakage was not assessed or detailed in other ATES LCAs studies (Stemmle et al., 2021; Moulopoulos, 2014; Ni et al., 2020; Tomasetta et al., 2015),
- **Sc ATES**$_{optim}$: This scenario examines the influence of optimizing the amount of thermal energy delivered to the building. It involves utilizing the ATES to provide thermal energy for the entire building (and not only 65%) considering an increase in the volume of extracted/injected water. This adjustment leads to increased electricity consumption for both the HP and the DWP, assumed to be proportional to the increased covered floor area (from 3600 m^2 to 5500 m^2: +52.8%). The installed equipment is supposed to be designed to ensure the increase in thermal demand.
- **Sc ATES**$_{PVC}$: This scenario evaluates the influence of borehole casing composition by substituting steel casing with PVC, a material commonly used in the Netherlands, a leading country in ATES technology (Fleuchaus et al., 2018).
- **Sc ATES**$_{COP4}$ and **Sc ATES**$_{COP6}$: These scenarios evaluate the effect of a modified heat pump COP during winter, with values set at 4 (Sc ATES$_{COP4}$) and 6 (Sc ATES$_{COP6}$), representing the typical range of ATES COP HP (Fleuchaus et al., 2019; Moulopoulos, 2014; Vanhoudt et al., 2011; Luo and Ma, 2022). In **Sc ATES**$_{COP4}$ it generates an increase of 198 MWh (+11.7%) of electricity consumption during the 30 years of operation and in **Sc ATES**$_{COP6}$ it generates a decrease of 132 MWh (−7.8%).

The second step of this study consists of comparing the environmental impacts of the ATES with other thermal energy systems that could be installed at ENSEGID. The following scenarios are considered :

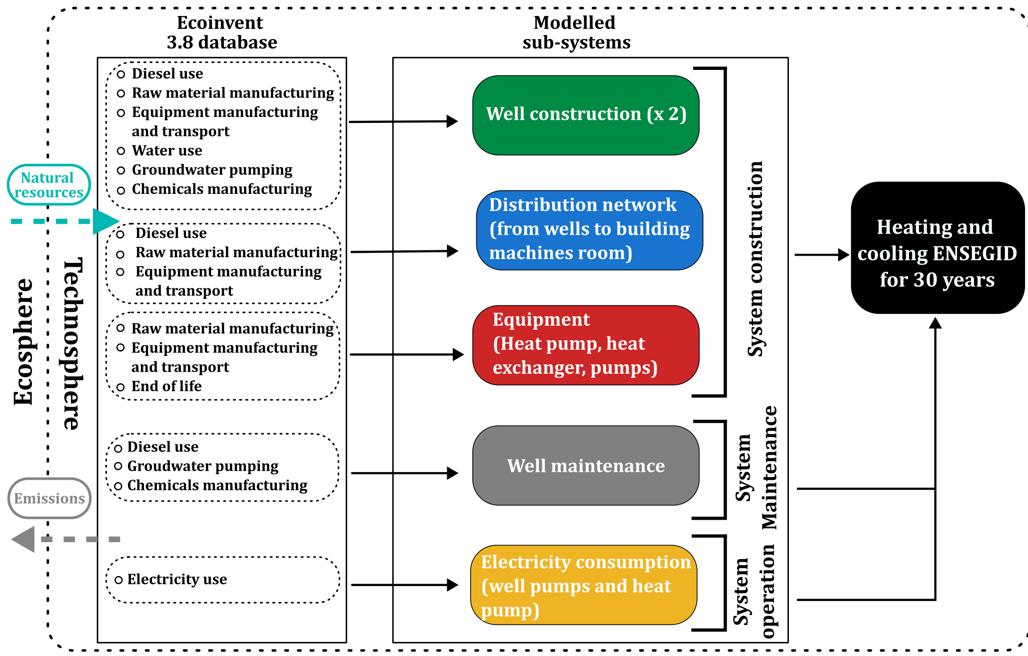

Fig. 3. System boundaries for **Sc ATES**.

- **Sc ASHP**: heat and cold are provided by a reversible air source heat pump (ASHP)
- **Sc GSHP**: heat and cold are provided by a borehole heat exchanger (BHE) coupled with a HP
- **Sc Biomass**: a biomass furnace provides heat and a vapor compression chiller provides cold,
- **Sc Gas**: a central gas boiler provides heat and a vapor compression chiller provides cold,

To compare all the scenarios, the functional unit is defined as follows: "to provide 1 kWh_{th} to ENSEGID" where kWh_{th} represents the production of 1 kWh of thermal energy delivered to the building. Therefore, all the results are expressed in the form of *impact/*kWh_{th}. Following the estimated thermal load of the building, the heating load represents 63% of the total thermal load and the cooling load 37%. In all scenarios, the system boundaries encompass construction and operation (Fig. 3). The LCA is performed considering 30 years of operation (i.e., for 6.3×10^6 kWh of thermal energy provided to the building in the **Sc ATES**$_{ref}$ and 9.7×10^6 kWh of thermal energy in the **Sc ATES**$_{optim}$).

The scope of the LCA excludes the energy distribution network within the building (as it is considered unchanged regardless of the scenario or thermal solution envisaged Stemmle et al., 2021) and the construction of the four piezometers (as their presence or absence do not interfere with the thermal energy supply)

The ecoinvent 3.8 database (Wernet et al., 2016) retrieves the resources and flow emissions related to the processes in the background system. For each scenario, environmental impacts at the midpoint level and damages at the endpoint level are determined using ReCiPe 2016 (H) LCIA method (Huijbregts et al., 2017). The contribution of each midpoint impact in the three damage categories is also assessed (Fig. 4) with RCiPe 2016 (H). As the carbon footprint of a system is a major driver for decisions, a focus is made on the midpoint "climate change". The impacts and damages are computed with OpenLCA 2.0 (Ciroth, 2007).

2.3. Life cycle inventory Sc ATES$_{ref}$

The LCI of the Sc ATES$_{ref}$ is divided into 5 main life-cyle stages : (1) wells construction, (2) water distribution network (from wells to machines room) construction, (3) equipment construction related to ATES (i.e. the HE, HP, and DWP), (4) operation of the system and (5) maintenance. It does not include the end-of-life of the wells, as it represents a negligible impact (Stemmle et al., 2021; Ni et al., 2020). This section summarizes the main process of the 5 defined stages. The complete compilation of the Sc ATES$_{ref}$ LCI and the derived scenario are available in Appendix A

2.3.1. Well construction

This stage includes all the processes necessary to manufacture well material (steel and chromium steel pipe, well-head, gravel, bentonite, concrete, cement), to drilling works (diesel and water consumption), to develop the well (well pumping, hydrochloric acid injection). All data and quantities were collected during construction from the company in charge of the construction of the well, and the technical log of the well is depicted in Fig. 2b. The construction of one ATES well required 3250 liters of diesel.

2.3.2. Distribution network construction

The water distribution network from the wells to the machine room is made of high-density polyethylene pipes (HDPE). A building machine was used for 1 day to excavate the trenches. Electrical wires were also buried in the ground to provide electricity to the well pumps.

2.3.3. Equipment

The equipment includes the HE, its insulation panels, the HP, and the DWPs. The installed HP at ENSEGID has a capacity of 115 kW and weighs 520 kg. The ecoinvent database provides a 30 kW HP weighing 400 kg. Consequently, 1.3 units of this HP were chosen in ecoinvent to adjust the weight to that of ENSEGID's. As no process is available in ecoinvent 3.8 to model a heat exchanger, it was represented using the most appropriate product (i.e. stainless steel) as suggested in the studies of Stemmle et al. (2021) and Roy and Pant (2020). The weight of the heat exchanger installed at ENSEGID is 400 kg.

2.3.4. Operation

The operation stage corresponds to the electricity consumption of the HP and the DWP (Table 1). During summer, the system is supposed to only operate in *geocooling* mode, i.e. the HP is turned off.

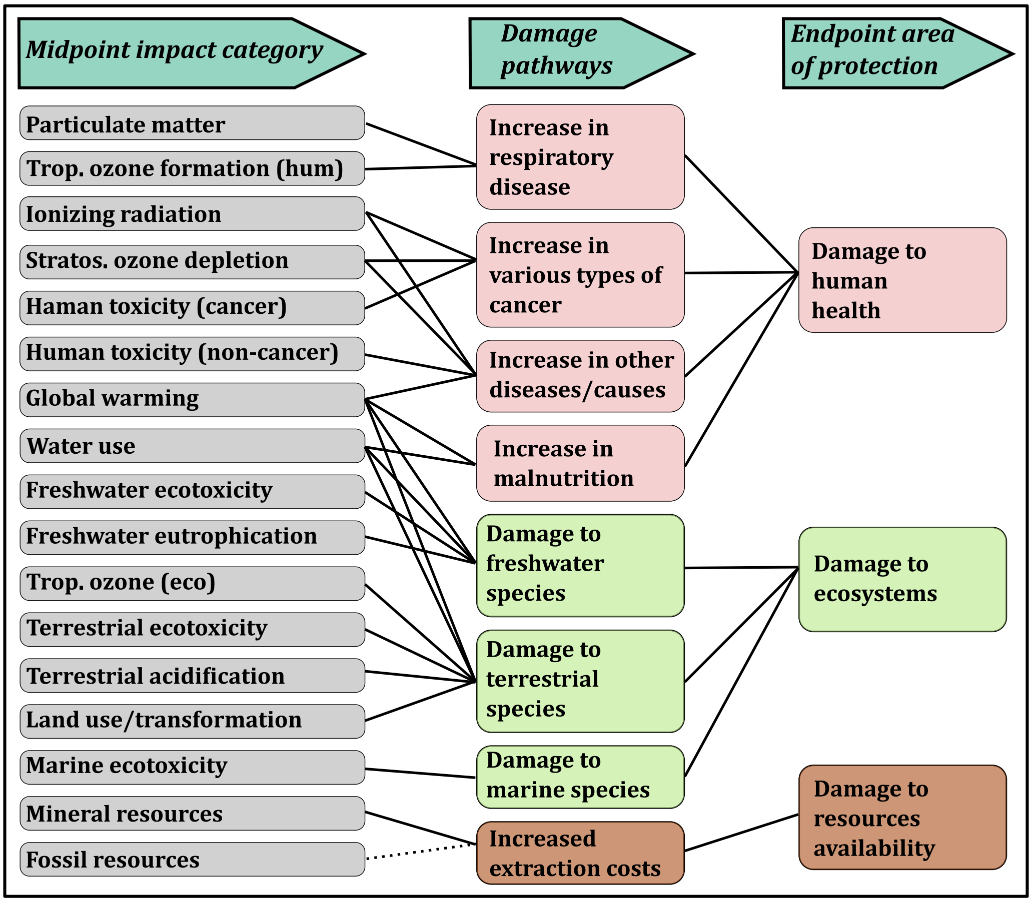

Fig. 4. Relation between midpoint and endpoint damage categories.
Source: From Huijbregts et al. (2017).

2.3.5. Maintenance

In France, groundwater well maintenance is mandatory every 10 years. The maintenance stage is modeled considering 8 h of machine operation per well to remove the pump, clean the well, and regenerate with hydrochloric acid and well pumping to check productivity.

2.4. LCI of the other thermal solutions

2.4.1. LCI Sc ASHP

In the Sc ASHP, the heat and cold demand is provided by an ASHP system. A HP equivalent to the Sc $ATES_{ref}$ is selected in Ecoinvent. The annual performance factor (APF) representing the ratio of heating and cooling on all electricity consumed (compressor, crankcase heating resistance, standby) is set at 3 based on the results from Kinab et al. (2010).

2.4.2. LCI Sc GSHP

In the Sc GSHP, the heat and cold demand is provided by a GSHP system extracting energy from the ground through a borehole heat exchanger (BHE). The BHE is made of several boreholes equipped with vertical U pipes carrying a fluid from the ground to a HP. For a thermal demand similar to ENSEGID, the required length of the pipes is calculated following the ASHRAE methodology (Kavanaugh and Rafferty, 1997). It results in 12 boreholes of 118 m depth. The materials and processes required for the BHE construction are scaled on Saner et al. (2010). Based on Biglarian and Abdollahi (2022), the seasonal performance factor (SPF) representing the seasonal ratio of heating and cooling on all electricity consumed of the GSHP is set at 2.8 for the summer season and 3.2 for winter. The compilation of the processes considered in Sc GSHP LCI is available in Appendix B

2.4.3. LCI Sc biomass

In the Sc Biomass, the cold demand is a conventional vapor compression chiller. The heat demand is provided by a biomass furnace using pellets. The efficiency is set at 92%. The compilation of the processes considered in Sc Biomass LCI is available in Appendix B. The COP and the efficiency are standard values reported by constructors.

2.4.4. LCI Sc gas

In Sc Gas, the cold demand is provided with a conventional vapor compression chiller, and the heating is provided with natural gas. The LCI considers the installation of one gas boiler (modeled as an oil boiler in ecoinvent, see Appendix B) and one conventional vapor compressor chiller. It is modeled as an HP in ecoinvent. The compressor chiller is powered by electricity and its COP = 4. The boiler efficiency is 95%. The compilation of the processes considered in Sc Gas LCI is available in Appendix B. The COP and the efficiency are standard values reported by constructors.

3. Results and discussion

3.1. Sc $ATES_{ref}$

3.1.1. Processes contribution share assessment

Fig. 5 shows the contribution of the Sc $ATES_{ref}$ subsystems to the midpoint climate change impact and the endpoint damages on ecosystems, human health and resources availability.

The operation stage driven by electricity use is the major environmental hotspot (Fig. 5) with a contribution of 63% in the ecosystems, resources availability and climate change categories. It represents 48% of the damages to human health. The main contributor of the operation

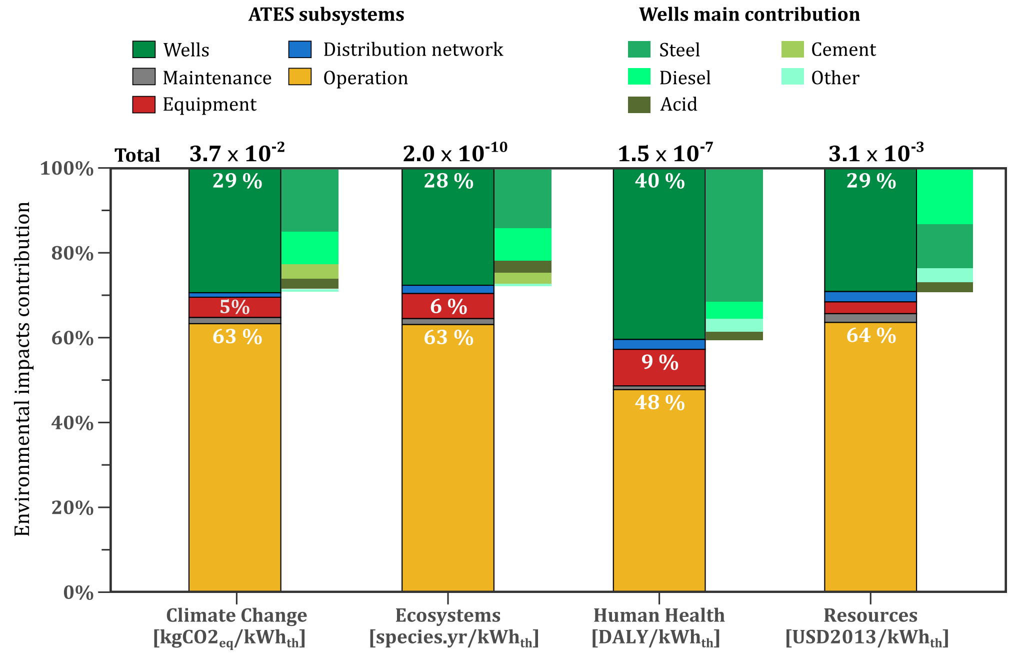

Fig. 5. LCA results for the Sc ATES$_{ref}$. Each bar plot represents the contribution of each subsystem in an impact or damage category. The main drivers involved during borehole completion are also detailed. For each category, the total impact per kWh$_{th}$ is available at the top of the bar.

stage is electricity production through the combustion of gas, hard coal, and oil, despite the relatively low contribution of these fossil fuels to the French electricity mix retrieved from ecoinvent 3.8 (<2%).

The geothermal borehole construction is the second main contributor, representing between 28 and 40% in the four categories. The production of the steel and chromium steel pipes required for the construction of the boreholes is responsible for the major part of the impacts (Fig. 5). The diesel combustion in the drilling machine has also a notable contribution, and the two other main contributors during the construction of the well arise from the acid and cement production. The manufacturing of other equipment (HP, HE, GDP), is the third contributor to the impacts. Finally, the impacts associated with the maintenance and the distribution network construction are negligible.

3.1.2. Midpoints contribution analysis

The ReCiPe methodology allows for assessing the contribution of each midpoint in the final endpoint damages (Fig. 6). For ecosystems, it emphasizes that "climate change" is responsible for 51% of the damages. Terrestrial acidification (mainly caused by coal and oil combustion required for electricity production, and by diesel and steel required for wells construction) has the second-highest contribution of 17%.

Four midpoints mainly cause damage to human health: particulate matter formation (mainly caused by electricity generation from fossil fuel and steel and diesel required for wells), climate change, human carcinogenic (mainly caused by steel pipes for borehole construction) and non-carcinogenic toxicity (mainly caused by interior equipment construction and electricity generation from nuclear power).

The damage to resources availability is mainly driven by fossil resources scarcity, although the major energy used comes from nuclear power. In the ReCiPe 2016 uranium is considered as a mineral. At the endpoint level, fossil fuels and minerals are aggregated within the resources availability endpoint category using the surplus cost methodology (Huijbregts et al., 2017) that usually results in higher damage for fossil fuel (such as natural gas) than minerals (such as uranium).

3.2. Comparison between the different ATES scenarios

The LCA results of the other ATES scenarios reveal notable differences compared to the Sc ATES$_{ref}$ (Fig. 7). Sc ATES$_{leak}$, Sc ATES$_{COP4}$ and Sc ATES$_{repl}$ lead to an increase in environmental impacts, while Sc ATES$_{PVC}$, Sc ATES$_{optim}$ and Sc ATES$_{COP6}$ reduce the environmental impact of the ATES at mid and endpoint levels.

3.2.1. Sc ATES$_{leak}$

This scenario generates a 15% and 7% increase in climate change and ozone depletion, respectively (Fig. 7b), due to the leakage of hydrofluorocarbon-based refrigerant. This leads to an increase of 7% in ecosystem damages and 3% in human health damages, mainly driven by climate change.

Overall, this scenario underscores the relevance of preventing HP leakage through scheduled maintenance practices and prioritizing the selection of HP systems that operate with refrigerants possessing low global warming potential. It is pertinent to note that the refrigerant employed by the heat pump installed at ENSEGID constitutes an HFC gas characterized by a notably high global warming potential (GWP) exceeding 1500 kgCO$_{2eq}$, thereby significantly contributing to climate change. This concern is further underscored by the forthcoming prohibition set by the EU Commission, slated for 2030, which aims to restrict the usage of refrigerants with a GWP surpassing 400. Consequently, this necessitates urgent attention towards transitioning to environmentally sustainable alternatives in heating and cooling.

3.2.2. Sc ATES$_{repl}$

Considering the replacement of the equipment (HP, HE and DWP) and an increased number of borehole maintenance, Sc ATES$_{repl}$ generates the highest increase in ecotoxicity and human toxicity midpoint impacts, due to the higher demand for steel and copper required for manufacturing the new equipment. This scenario leads to the highest increase in human health (+10%) and ecosystems (+8%) damages (Fig. 7a). Over the assumed minimum 30-year operational span examined for an ATES system, it seems advisable to carefully consider the replacement of the DWPs and HE components potentially attributable to issues such as clogging (Gjengedal et al., 2020). The HP lifespan can vary depending on maintenance, usage, maintenance, or installation

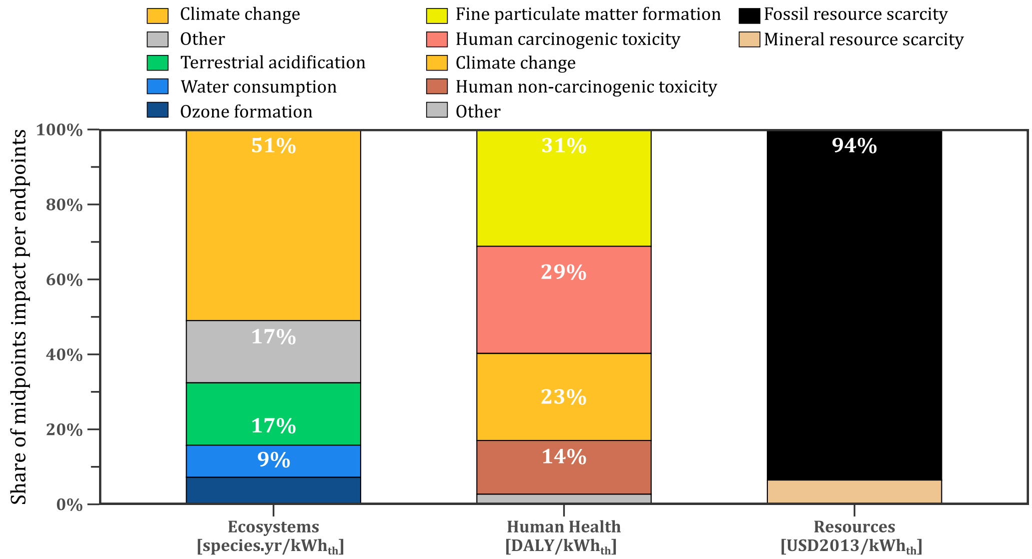

Fig. 6. Midpoint contribution per endpoint category. "Other" concatenates all the midpoints representing less than 5% of the impact in a given endpoint.

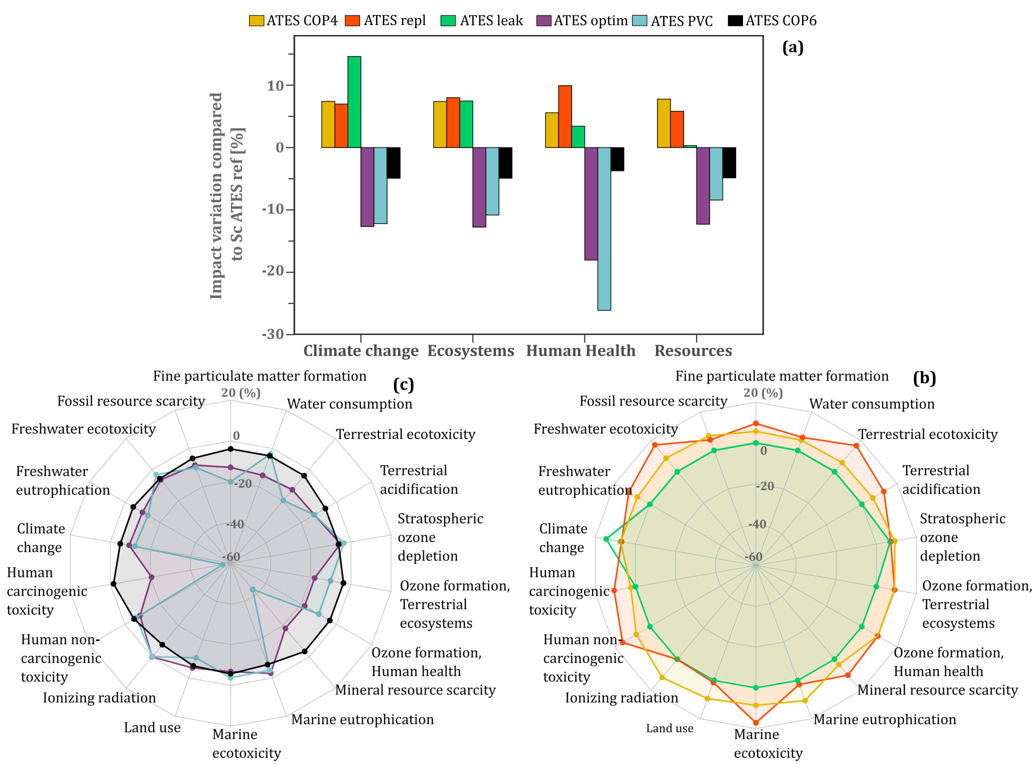

Fig. 7. LCA results from the various ATES scenarios compared to **Sc ATES**$_{ref}$: (a) Difference (in %) between the other scenario at endpoint damages category and climate change, and difference (in %) between (b) the scenarios increasing the impact at midpoint level and (c) the scenarios decreasing the impact at midpoint level.

quality. Therefore, it is advisable to anticipate the need for at least one replacement within a 30-year lifespan.

Taking into account such considerations prevents underestimations of the environmental impact of the system, especially in the context of an ATES with a low capacity as studied here.

3.2.3. Sc ATES$_{COP4-6}$

The increase of electricity consumption (+11.7%) during the operation in Sc ATES$_{COP4}$ leads to an increase in all midpoint (Fig. 7b) impacts from 2% (human carcinogenic toxicity) to 11% (ionizing radiation), leading to an increase of 7% in ecosystem damages, 6% in human health damages, and 8% in resources availability. On the opposite, the decrease of electricity consumption (−7.8%) during the operation in Sc ATES$_{COP6}$ leads to a decrease in all midpoint impacts (Fig. 7c) from −1.5% (human carcinogenic toxicity) to −7% (ionizing radiation), leading to a decrease of −7% in ecosystem damages, −6% in human health damages, and −5% in resources availability.

These two scenarios illustrate the importance of achieving the highest possible COP, even in the context of a low power capacity ATES where electricity has a low carbon intensity. It is also worth mentioning that in the studied scenarios, the thermal demand of the building was considered unchanged during the 30 years. Nevertheless, with climate change, the thermal demand for cooling will certainly increase while heating demand will decrease. The operation of ATES systems will be affected, resulting in more heat storage and less cold storage. It will certainly influence the amount of heat and cold available in the aquifer and the performance of ATES in the future (Godinaud, 2023), which may result in different environmental damages estimated with LCA.

3.2.4. Sc $ATES_{PVC}$

The replacement of chromium steel casing with PVC reduces the impact in all midpoint categories. The reduction in human health damage (−27%) is mainly explained by the decrease at the midpoint level of human carcinogenic toxicity (−56%) and fine particulate formation (−20%) (Fig. 7c). This is due to reduced steelmaking by-products and waste (slag, dust, and sludges). Using PVC instead of steel tubes also reduces the mineral resource scarcity impact (−43%). PVC casing for ATES boreholes is a common practice in the Netherlands, but the choice of the casing composition could be influenced by the geological nature of the aquifer. For instance, PVC casing in hard limestone formations, such as those exploited at ENSEGID, may be potentially more prone to breakage during installation or maintenance than steel casings, which are much more resistant.

3.2.5. Sc $ATES_{optim}$

This scenario emphasizes the benefits of optimizing the use of available boreholes by increasing the thermal energy delivery to the building. Compared to the Sc $ATES_{ref}$ at the endpoint level, it denotes a decrease of 9% in resources availability and ecosystems damages and 13% in human health damages. These results should encourage planning strategies to maximize the use of the installed boreholes by providing as much energy as possible to the building or connecting several buildings to the same ATES system. This scenario considers that the increase in thermal energy delivery is achieved through an increase in the pumping flow rate from the borehole and thus an increase in electricity consumption. Nevertheless, it is crucial to note that the aquifer's properties limit the amount of extracted water from each borehole. A comprehensive evaluation of these characteristics is essential to plan the number of required boreholes and before considering ATES as a promising thermal solution. For an ATES with a high capacity and a limited number of boreholes, the contribution of the operation to the LCA score will also grow. Nevertheless, the overall impact per kWh_{th} will be lower. To overpass the limits fixed by the aquifer properties, a solution to provide more energy to the building would be to increase the temperature difference between withdrawal and injected water temperatures (Stemmle et al., 2021). This strategy does not increase the electricity consumption and enables achieving a greater quantity of thermal energy per unit flow rate, consequently resulting in a reduced environmental footprint.

3.2.6. Best and worst-case scenarios

By combining the scenarios that decrease impacts, and those that increase impacts, we can define both best- and worst-case scenarios (Fig. 8).

It shows the range of potential impacts of low power capacity ATES in France, considering different design parameters. For example, climate change impacts range from $27gCO2_{eq}$ (a 25.6% decrease compared to the baseline) to $47gCO2_{eq}$ (a 29% increase compared to the baseline).

3.3. Relevance of a low ATES capacity compared to other thermal solutions

3.3.1. Comparison of total environmental impacts

The comparative results first reveal that Sc $ATES_{ref}$ generate slightly more damages to ecosystems and resources availability than Sc ASHP, and Sc GSHP (Fig. 9), but the results of these three HP-based solutions are in the same range for these two endpoints.

For these 3 solutions, climate change is responsible for about half of the damage to ecosystems, and fossil resource scarcity mainly dominates the resource availability damage. Nevertheless, Sc $ATES_{ref}$ affects human health more than the two other heat pump-based solutions. This is primarily attributed to the high carcinogenic toxicity associated with the chromium steel tube production for the borehole casing, while Sc GSHP construction only relies on polyethylene tubes and Sc ASHP does not require borehole construction. It is worth noting that Sc $ATES_{best}$ represented by the bottom of the red bar (Fig. 9) reveals similar or slightly less damages than Sc ASHP and Sc GSHP.

Overall, the environmental impacts and damages of Sc ASHP and Sc GSHP are similar and are mainly affected by HP electricity consumption. Consequently, the APF value as well as the electricity mix generate a high variability in the results (Fig. 10).

For example, an ASHP with an APF of 2.0 has a higher carbon footprint compared to ATES, regardless of the ATES scenario under consideration or the electricity mix considered. In the context of the Sc $ATES_{ref}$, ASHP demonstrates superior performance when the APF exceeds 2.5, considering the utilization of the French electricity mix. However, for a more carbon-intensive electricity mix, as the German one, the APF of ASHP must surpass 3.5 to be better than Sc $ATES_{ref}$ (Fig. 10). The findings indicate that in buildings with low thermal demands, the implementation of an ATES system is notably more advantageous than ASHP, especially in regions characterized by a carbon-intensive electricity mix. These results would be very similar when comparing ATES and GSHP. Still, in the context of Sc GSHP, it is noteworthy that the implementation of BHE requires a larger spatial footprint compared to ATES boreholes. This may pose challenges in deployment, particularly for structures with elevated thermal energy requirements.

Regarding the two last alternative solutions, Sc Biomass exhibits the most damage to ecosystems, with a relative increase of +73% compared to Sc $ATES_{ref}$. It is primarily attributed to the substantial impact of land use change resulting from forestry activities aimed at wood pellet production (Fig. 9). It contributes to 70% of the damage to ecosystems that rely on wood pellet combustion producing a great amount of fine particulate emission. These emissions represent the major part of Sc Biomass damages to human health which is 28% higher than the damage of Sc $ATES_{ref}$.

Sc Gas relies on natural gas combustion for heating, generating high GHG emissions. It results in substantial damage to ecosystems due to climate change (+67% compared to Sc $ATES_{ref}$). This scenario is the most impacting regarding damage to human health primarily due to climate change. Natural gas extraction also contributes to the highest damage to resources availability, which is approximately 6 times higher than the other scenarios.

These two latest scenarios (Sc Gas and Biomass) integrate a classical vapor compression chiller for cooling purposes. As the French electricity mix is a low carbon intensive one, the impact of the cooling is lower compared to the heating. Cooling energy is mainly based on devices using electricity to transfer heat from the cooled space to an external medium (Braungardt et al., 2018). Thus, apart from geothermal exploitation or the use of available cold medium (snow storage, or sea/lake water), cooling systems can be considered renewable depending on the nature of the electricity mix. Adsorption and absorption cooling systems require heat but are negligible in cooling energy generation compared to vapor compressor chillers. The technology of solar cooling systems using an absorption chiller is a promising technology to reduce the environmental impact of cooling technology (Beccali et al., 2012; Herrando et al., 2022) but was not assessed here.

3.4. Environmental impacts evolution along the life cycle

Although the ATES presents less (Sc Gas and Biomass) or very close (Sc ASHP and GSHP) environmental impacts along its life cycle compared with the other solutions, it is worth noting that its construction phase (including wells, distribution network, and equipment) generates

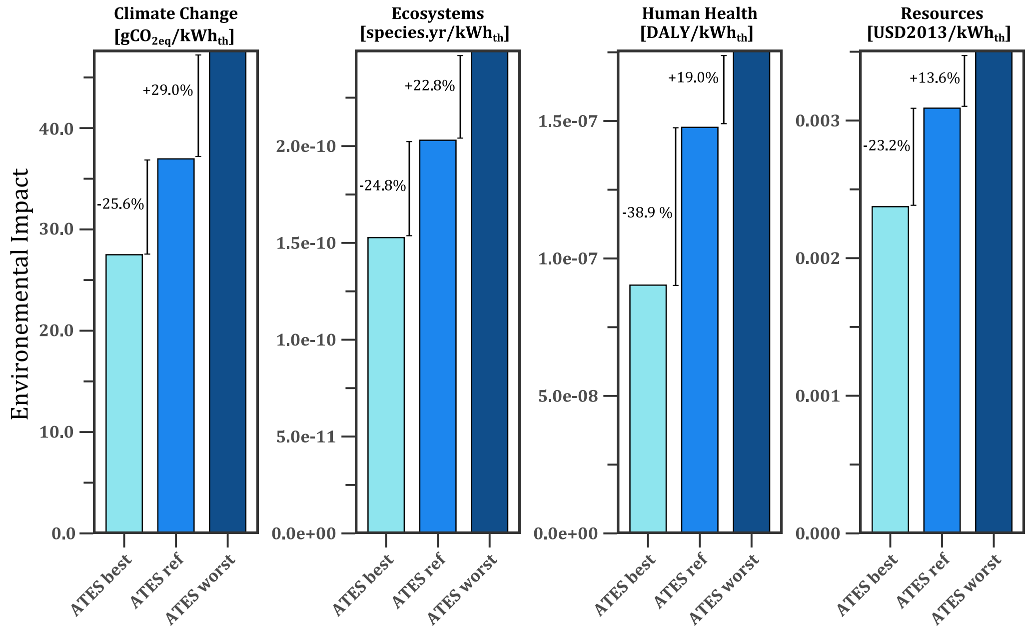

Fig. 8. Comparison of the LCA results between Sc ATES$_{ref}$ and the Sc ATES$_{best}$ and Sc ATES$_{worst}$ scenario.

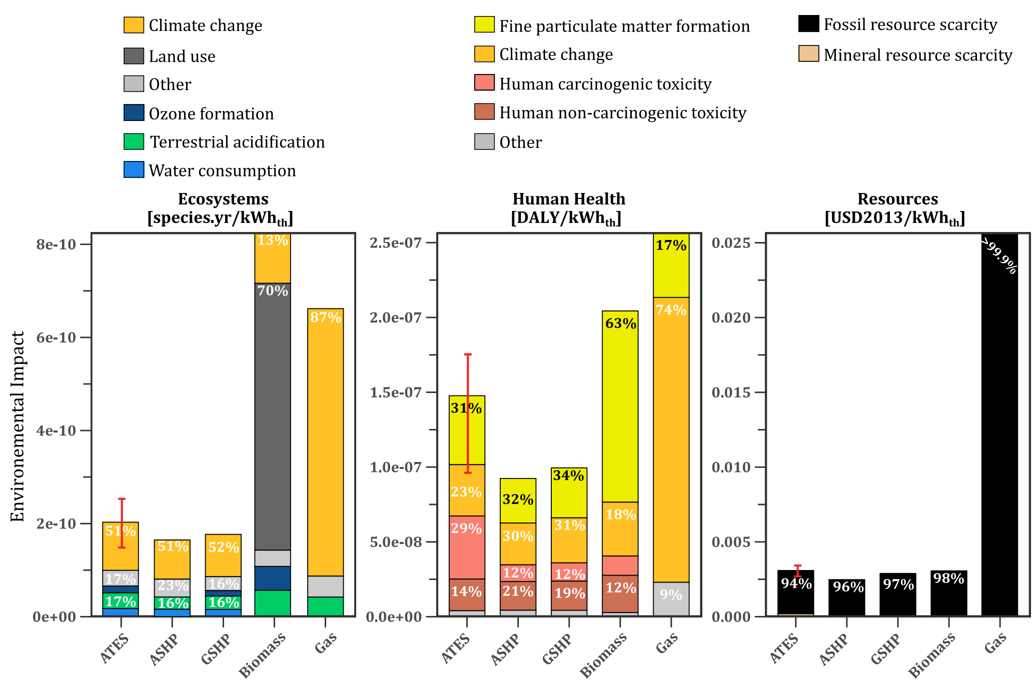

Fig. 9. LCA results for Sc ATES, Sc Biomass, Sc Gas, Sc ASHP and Sc GSHP. "Other" concatenates all the midpoints representing less than 5% of the impact in a given endpoint. The red bar on Sc ATES represents the maximum and minimum damage of Sc ATES$_{worst}$ and Sc ATES$_{best}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

more impacts and damages (Fig. 11). It is therefore relevant to compare the impacts and damages of the different scenarios over 30 years.

ATES exhibits a lower impact compared to Sc Gas within a short span of 2 years of operation across all categories, except for human health, where 10 years are required to compensate for the initial impact. Both Sc ATES and Sc Biomass demonstrate similar trends regarding climate change and resources availability. Sc ATES takes 15 years to counterbalance its initial impact on human health in comparison to Sc Biomass. However, Sc Biomass quickly surpasses Sc ATES in terms of impact on ecosystems, primarily attributed to land use change.

Compared to Sc GSHP and Sc ASHP, the ATES generates less impact per year thanks to its lower electricity consumption. In climate change, resources availability, and ecosystems this lower consumption allows to counterbalance the other solutions during the 30 years. For human health damages, chromium steel casing production generates such initial damage that the operation phase cannot counterbalance the damage during the life cycle.

3.5. Comparison between Sc ATES$_{ref}$ and ATES LCA from the literature

Among the other ATES LCA available in the literature, Tomasetta et al. (2015) only focus on heating mode during ATES operation,

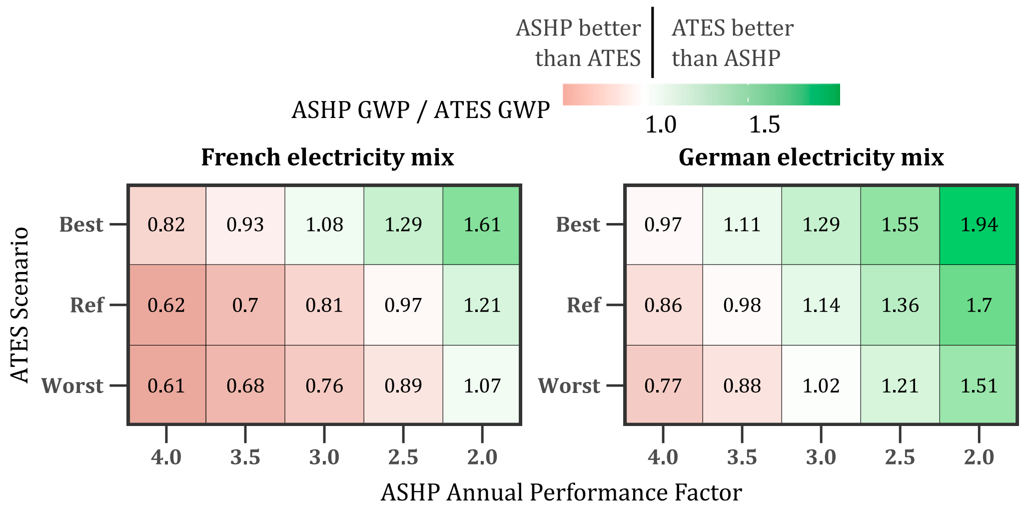

Fig. 10. Ratio between the climate change impact of ATES and ASHP depending on the scenarios and the ASHP annual performance factor. The first column panel represents the context of the French electricity mix and the second the German. The comparison with GSHP is not presented here as it will result in very similar results and trends.

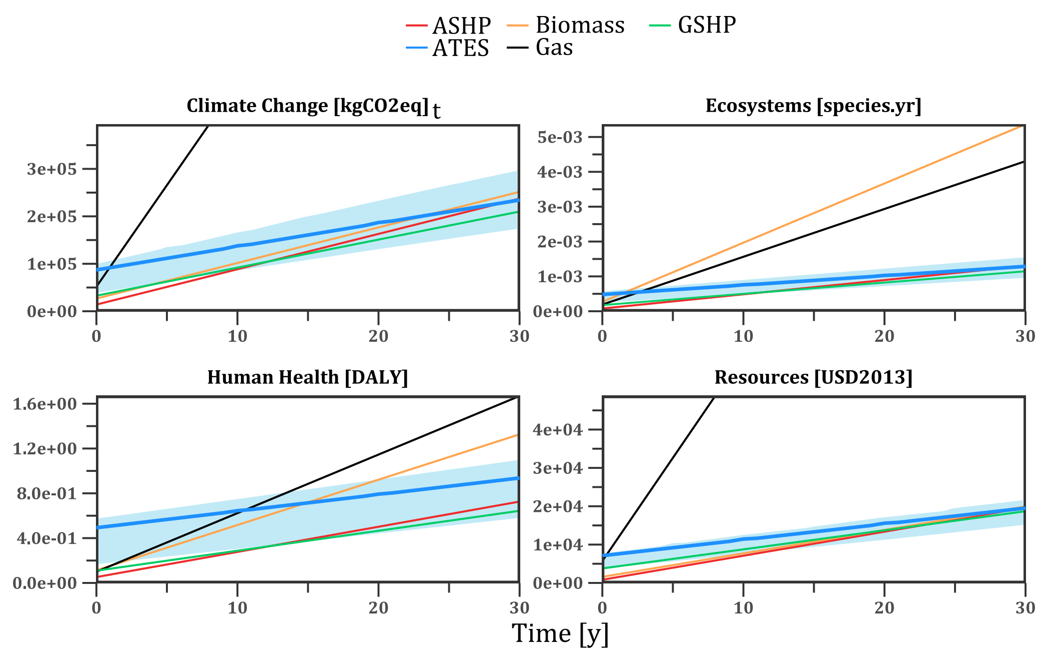

Fig. 11. Comparison of environmental impacts and damages evolution of the studied systems over 30 years. The initial impact corresponds to the construction of the systems. For Climate change and Resources the Y axis is cut for clarity. The blue shades represent the limits of the ATES best and worst scenarios.

which can be assimilated to a groundwater source heat pump as no heat storage occurred. Ni et al. (2020) realize two LCAs to compare a hypothetical ATES system used for in-situ bioremediation with a conventional energy system and conventional in-situ bioremediation technology. Even if the described ATES applications are uncommon and are not representative of the typical and standard ATES operation, they also indicate that the operational stage contributes the most to environmental damages.

The studies by Stemmle et al. (2021) and Moulopoulos (2014) describe ATES operating similarly to ENSEGID. Their LCA results also demonstrate a strong correlation between the environmental impacts and the nature of primary sources used to generate the electricity used by the HP and the DWP. However, the relative contribution of the operation is higher than the one estimated in Sc $ATES_{ref}$. Stemmle et al. (2021) show that the operation is responsible for 83%, 76%, and 98% of the damage to human health, ecosystems, and climate change. Moulopoulos (2014) assesses midpoint impact categories, and shows that the operation stage is responsible for more than 80% of the impact in 12 categories. The higher thermal demand of the two studied buildings (× 30 for Stemmle and × 2 for Moulopoulos, Table 2), and consequently the greater electricity consumption of these two ATES, explain the greater contribution of the operation in the LCA score. Moreover, the electricity mixes used in these two studies (German and Dutch) are mostly based on fossil fuels (lignite, coal, and gas) which generate more GHG emissions (Table 2) and particulate matter formation than the French electricity mix which is mainly based on nuclear power. Despite the lack of optimization in borehole exploitation at the ENSEGID site, the estimated climate change impact stands at 37 gCO_{2eq} kWh_{th}^{-1} (27 gCO_{2eq} kWh_{th}^{-1} for Sc $ATES_{best}$ and 47 gCO_{2eq} kWh_{th}^{-1} for Sc $ATES_{worst}$), which is respectively 2.6 and 6.2 times lower than the ATES systems studied in Stemmle et al. (2021) and Moulopoulos (2014). In their investigation utilizing Sobol indices, Stemmle et al. (2021) demonstrate that in a high-power capacity ATES system powered by a carbon-intensive electricity mix, the COP of the HP introduces

Table 2
Comparison of the ATES designed and GHG emission results of the **Sc ATES** and the results described in the literature.

Study	Operation mode	Annual demand (MWh)	Heated area	Results for GHG (gCO_{2eq} kWh_{th}^{-1})	Assessment method
ENSEGID ATES, France	Heat and cold production	210	3600 m^2	ATES ref : 37 ATES best : 27 ATES best : 47	Recipe 2016 (H) - Midpoint
Moulopoulos (2014), Netherlands	Heat and cold production (peak load with gas boiler)	443	6000 m^2	Ref sc : 230 Without water treatment process and gas : 117	Recipe 2008 (H) - Midpoint
Stemmle et al. (2021), Germany	Heat and cold production	6160	60 000 m^2	96	Impact 2002+

significant variability in GHG emissions. In contrast, our study reveals that when considering a low-power capacity ATES system powered by a low-carbon electricity mix, the influence of COP diminishes but remains noteworthy. The composition of the well casing and the optimization of energy extraction from the well emerge as the more influential factors.

Nonetheless, a particular focus of the study conducted in Moulopoulos (2014) lies in the examination of a wastewater treatment process involving the extraction of 25 000 m^3 of water from the aquifer for maintenance purposes, a process that notably impacts the climate change midpoint assessment. The research treats the extracted aquifer water as domestic wastewater and employs the ReCiPe 2008 methodology, which was relatively underutilized for such applications at the time of the study. This process alone contributes to half of the overall climate change impact. Additionally, the study accounts for the use of a gas boiler to cover peak loads during winter. It is a common practice to use a second source of energy to meet thermal needs in extreme weather conditions or to secure the supply of thermal energy in the event of failure or maintenance of the geothermal system (Rostampour et al., 2019) but this was not considered at ENSEGID. Upon excluding these two processes from the estimated GHG emissions, the GHG emissions estimated by Moulopoulos decrease from 230 to 117 gCO_{2eq} kWh_{th}^{-1}, still representing a 3.2-fold increase compared to the GHG emissions of the Sc $ATES_{ref}$.

4. Conclusion

This study detailed the LCA of the ATES of ENSEGID, a low-capacity ATES powered by the low-carbon electricity mix in France. Several scenarios have been considered to assess the effects of design and construction choices as well as equipment lifetime and failure. Other thermal energy supply solutions have also been considered for comparison.

The LCA achieved on ENSEGID-ATES shows that the operation stage corresponding to the electricity use by the HP and the DWP is the most impacting process on the environment (an average of 60%). It results in a climate change impact of 37 gCO_{2eq} kWh_{th}^{-1}. Nevertheless, this GHG emission and the relative contribution of the operation stage at ENSEGID are lower than the results presented in other LCA from the literature. These results can be explained by the low carbon-intensive electricity from the French electricity mix and the low thermal demand of ENSEGID's building, which requires less electricity production. Consequently, at the ENSEGID site, the environmental impact contribution has shifted to the construction of the geothermal well mainly due to the chromium steel production required for the borehole casing. The study demonstrates that the impact of the borehole construction could be decreased by switching steel casing to PVC casing and by pumping as much energy as possible from the geothermal wells by increasing the volume of pumped water. This study also highlights the impact of equipment replacement and potential HP leakage in the context of an ATES using a low-carbon electricity mix. It suggests the importance of considering these assumptions regarding those types of equipment when performing an LCA on ATES, as the electrical mix is expected to move towards a less carbon-intensity solution.

In the context of the ENSEGID thermal demand, the study demonstrates that the ATES solution has a better environmental performance than a solution based on natural gas or biomass for heating and a vapor compressor chiller for cooling. Nevertheless, the damages are slightly higher with the ATES than with the two solutions considering ASHP or GSHP. The major role of the electricity mix and the HP COP in the LCA results emphasized in the literature review is also confirmed through the comparison of the French and German electricity mixes, and different values of COP for ATES and APF for ASHP solutions. Overall, the potential of a low-power capacity ATES to reduce the environmental impact of buildings is more relevant in countries characterized by a carbon-intensive electricity mix. Compared to the other scenarios, Sc ATES presents a higher impact at the construction stage. Nevertheless, this impact is mitigated in a short time except for human health.

This study underscores the potential of an ATES system with a low-carbon electricity mix to outperform fossil fuel or biomass heating solutions, reducing environmental impact. Generalizing studies integrating LCA and economic assessments, especially for geothermal technology and other heat pump-based solutions, is crucial. Despite challenges in fluctuating electricity prices, a 30-year cost analysis for ATES is essential. Comparing LCA results with economic analyses for various thermal power solutions and communicating findings to stakeholders can lead to a balanced and sustainable solution for the building sector.

CRediT authorship contribution statement

Jérémy Godinaud: Conceptualization, Data curation, Formal analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review & editing. **Philippe Loubet:** Software, Writing – review & editing, Conceptualization, Methodology. **Sandrine Gombert-Courvoisier:** Supervision, Writing – review & editing. **Alexandre Pryet:** Project administration, Supervision, Validation. **Alain Dupuy:** Supervision. **François Larroque:** Project administration, Supervision, Validation.

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

Data will be made available on request.

Appendix A. Sc ATES LCI

In this appendix the **Sc $ATES_{ref}$** is detailed. For the other ATES scenarios, the changing processes are only mentioned

A.1. Sc $ATES_{ref}$

See Tables A.3–A.7.

Table A.3
LCI of one geothermal well.

Geothermal well drilling			
Component	LCI process/flow	Amount per well	Data collection
Bentonite	Market for bentonite — bentonite — APOS,U - GLO	2000 kg	Drilling company
Grout	Market for concrete, normal — concrete, normal — APOS,U - RoW	5500 kg	Drilling company
Chromium steel tube	Market for chromium steel pipe — chromium steel pipe — APOS,U - GLO	2256 kg	Drilling company
Steel tube	(1) market for drawing of pipe, steel — drawing of pipe, steel — APOS,U - GLO (2) market for reinforcing steel — reinforcing steel — APOS,U - GLO	1250 kg	Drilling company
Well-head	Market for steel, chromium steel 18/8 — steel, chromium steel 18/8 — APOS,U - GLO	500 kg	Stemmle et al. (2021)
Concrete screed	Market for concrete, normal — concrete, normal — APOS,U - RoW	0.2 m^3	Drilling company
Filter gravel	Market for gravel, round — gravel, round — APOS,U - RoW	9000 kg	Drilling company
Hydrochloric acid	Market for hydrochloric acid, without water, in 30% solution state — hydrochloric acid, without water, in 30% solution state — APOS,U - RoW	5000 kg	Drilling company
Diesel for drilling machines	Market for diesel, burned in building machine — diesel, burned in building machine — APOS,U - GLO	2550 L	Drilling company
Diesel for power generator	Market for machine operation, diesel, ≥74.57 kW, generators — machine operation, diesel, ≥74.57 kW, generators — APOS,U - GLO	700 L	Drilling company
Water for drilling	Tap water production, underground water with chemical treatment — tap water — APOS,U - Europe without Switzerland	100 t	Water management authority
Water evacuated from pumping test to the sewerage	Wastewater, unpolluted (flow)	−2730 m^3	Drilling company
Water returned to the environment after treatment	Water, well, FR (flow)	2730 m^3	Drilling company

Table A.4
LCI of distribution network construction.

Distribution network construction			
Component	LCI process	Amount	Data collection
Horizontal PE tube	Market for polyethylene pipe, DN 200, SDR 41 — polyethylene pipe, DN 200, SDR 41 — Cutoff, U - GLO	150 m	Estimation
Electrical wiring	Market for cable, three-conductor cable — cable, three-conductor cable — Cutoff, U - GLO	150 m	Estimation
Diesel for working machine	Market for diesel, burned in building machine — diesel, burned in building machine — Cutoff, U - GLO	35 L	Earth-moving company

Table A.5
LCI of equipment.

Equipment			
Component	LCI process	Amount	Data collection
Heat pump	Market for heat pump, 30 kW — heat pump, 30 kW — Cutoff, U - GLO	1.3 items	Estimation from technical note
Groundwater pump	Market for water pump, 22 kW — water pump, 22 kW — Cutoff, U - GLO	1 item	
Insulation heat exchanger	Market for polyurethane, rigid foam — polyurethane, rigid foam — Cutoff, U - RER	30 kg	Stemmle et al. (2021)
Heat exchanger	Market for steel, chromium steel 18/8 — steel, chromium steel 18/8 — Cutoff, U - GLO	400.0 kg	Estimation from technical note

Table A.6
LCI of maintenance.

For two maintenance			
Component	LCI process	Amount	Data collection
Hydrochloric acid	Market for hydrochloric acid, without water, in 30% solution state — hydrochloric acid, without water, in 30% solution state — Cutoff, U - RER	2000 kg	Estimation
Diesel for machine operation	Market for machine operation, diesel, ≥74.57 kW, generators — machine operation, diesel, ≥74.57 kW, generators — Cutoff, U - GLO	32 h (corresponding to 480 L)	Estimation
Water evacuated from pumping test to the sewerage	Wastewater, unpolluted (flow)	−500 m^3	Estimation
Water returned to the environment after treatment	Water, well, FR (flow)	500 m^3	Estimation

Table A.7
LCI of operation.

Operation			
Component	LCI process	Amount	Data collection
Electricity consumption	Market for electricity, low voltage — electricity, low voltage — Cutoff, U - FR	1692 MWh	Estimation from company in charge of pre-investigation studies

Table A.8
LCI of operation (Sc $ATES_{leak}$).

Add to operation (Sc $ATES_{leak}$)			
Component	LCI process	Amount	Data collection
Refrigerant leakage	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a (output to the air in high density population)	21.7 kg	Based on literature (Saner et al., 2010; Greening and Azapagic, 2012)

Table A.9
LCI of operation (Sc $ATES_{leak}$).

Add to maintenance (Sc $ATES_{leak}$)			
Component	LCI process	Amount	Data collection
Refrigerant creation	Market for refrigerant R134a — refrigerant R134a — Cutoff, U - GLO	21.7 kg	Based on literature (Saner et al., 2010; Greening and Azapagic, 2012)

Table A.10
LCI of geothermal well (Sc $ATES_{PVC}$).

Add to geothermal well drilling (Sc $ATES_{PVC}$)			
Component	LCI process	Amount per well	Data collection
PVC tube	(1) market for polyvinylchloride, bulk polymerized — polyvinylchloride, bulk polymerized — APOS,U - GLO (2) market for extrusion, plastic pipes —extrusion, plastic pipes — APOS,U - GLO	366 kg	Drilling company

Table B.11
LCI of Sc Gas (The classic chiller is modeled with a heat pump process, and the gas boiler is equivalent to an oil boiler in OPEN LCA).

Sc Gas		
Component	LCI process	Amount
Chiller	Market for heat pump, 30 kW — heat pump, 30 kW — Cutoff, U - GLO	1.3 items
Gas boiler	Market for oil boiler, 100 kW — oil boiler, 100 kW — Cutoff, U - GLO	1 item
Electricity consumption	Market for electricity, low voltage — electricity, low voltage — Cutoff, U - FR	585.0 MWh
Gas consumption	Heat production, natural gas, at boiler atmospheric low-NOx non-modulating <100 kW — heat, central or small-scale, natural gas — Cutoff, U - Europe without Switzerland	4158.0 MWh

A.2. Sc $ATES_{leak}$

See Tables A.8–A.9.

A.3. Sc $ATES_{PVC}$

For this scenario, all the processes related to chromium steel casing were removed and replaced by the following processes (see Table A.10).

A.4. Sc $ATES_{COP4-6}$, Sc $ATES_{optim}$ and Sc $ATES_{repl}$

- For Sc $ATES_{COP4-6}$ the electricity consumption during the 30 years of operation is respectively 1890 MWh and 1560 MWh,
- For Sc $ATES_{optim}$ the electricity consumption during the 30 years of operation is 2585 MWh and the thermal demand of the building is increased at 9625 MWh
- For Sc $ATES_{repl}$, 5 maintenance are considered, two HP, two HE and four DWP

Appendix B. LCI of other thermal solution

See Tables B.11–B.13.

Sc ASHP

The LCI considers the process of HP construction and electricity consumption during 30 years of 2100 MWh

Table B.12
LCI of Sc Biomass (The classic chiller is modeled with a heat pump process).

Sc Biomass		
Component	LCI process	Amount
Chiller	Market for heat pump, 30 kW — heat pump, 30 kW — Cutoff, U - GLO	1.3 items
Furnace pellet	Furnace production, pellet, 50 kW — furnace, pellet, 50 kW — Cutoff, U - RoW	2 item
Electricity consumption	Market for electricity, low voltage — electricity, low voltage — Cutoff, U - FR	585.0 MWh
Heat from biomass consumption	Heat production, wood pellet, at furnace 25 kW, state-of-the-art 2014 — heat, central or small-scale, other than natural gas — Cutoff, U - CH	4276.0 MWh

Table B.13
LCI of Sc GSHP (The part of the table corresponding to 2 BHE construction was multiplied by 6 to obtain 12 BHE).

Sc GSHP		
For 2 BHE construction of 118 m depth		
Component	LCI process	Amount
Bentonite	Market for activated bentonite — activated bentonite — Cutoff, U - GLO	270 kg
Cement	Market for cement, unspecified — cement, unspecified — Cutoff, U - CH	42 kg
Diesel burnt in building machine	Market for diesel, burned in building machine — diesel, burned in building machine — Cutoff, U - GLO	17 583 MJ (corresponding to 484 L)
EDTA	Market for EDTA, ethylenediaminetetraacetic acid — EDTA, ethylenediaminetetraacetic acid — Cutoff, U - GLO	1.6 kg
Ethylene glycol	Market for ethylene glycol — ethylene glycol — Cutoff, U - GLO	155 kg
Polyethylene low density granulate	Market for polyethylene, low density, granulate — polyethylene, low density, granulate — Cutoff, U - GLO	264 kg
Potassium hydroxide	Market for potassium hydroxide — potassium hydroxide — Cutoff, U - GLO	1.6 kg
For equipment		
Heat pump	Market for heat pump, 30 kW — heat pump, 30 kW — Cutoff, U - GLO	1.3 items
Groundwater pump	Market for water pump, 22 kW — water pump, 22 kW — Cutoff, U - GLO	1 item
For operation		
Electricity consumption	Market for electricity, low voltage — electricity, low voltage — Cutoff, U - FR	2035 MWh

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