ACADÉMIE DES TECHNOLOGIES

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Communication to the Academy

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This working paper was prepared at the request of Yves Bamberger, Chairman of the Academy's Planning Committee. It is based on a review of the literature and some interviews, in particular with BRGM. It is a preliminary step to the creation of a dedicated project group of the Academy.

Inter-seasonal heat storage is the storage of excess, residual, renewable or recovered thermal energy for use in the following season. Seasonal cycle use is particularly suited to heating, cooling and refrigeration in the residential and tertiary sectors. While this approach makes it possible to reduce the share of fossil fuels in energy consumption, and while it has been implemented in several countries, it is very little developed in France.

This paper briefly presents the technologies for thermal energy storage, then describes the systems suitable for large-scale inter-seasonal storage in the residential and tertiary sectors and the barriers to their deployment in France.

Introduction

France's greenhouse gas emission reduction targets for the period 2015-2018, detailed in the National Low Carbon Strategy (SNBC), have not been met. Some of the most significant delays in this area are in the building sector, which in 2017 accounted for 22% of national CO_2 emissions - 13% for the residential sector and 9% for the tertiary sector [1]. The production and consumption of heat and cooling is the main target when aiming to ensure compliance with the sector's carbon budgets: in 2017, 75% of CO_2 emissions in the residential sector were attributed to heating and 12% to the production of domestic hot water [2]. In the tertiary sector, these uses are supplemented by the growing use of air conditioning [3].

In order to reduce the carbon footprint of the building sector, two approaches can be combined: demand reduction and decarbonisation of supply. The design of low-carbon thermal energy technologies is based either on the use of new energy sources, the transformation of which has low or no greenhouse gas emissions, or on a better use of existing sources. Seasonal Thermal Energy Storage (STES) technologies are part of the second approach: by storing the residual heat or cold from a building, the waste heat from industrial processes or data centres, the heat from renewable sources or cogeneration processes when there is a surplus; they can either bridge the gap between heat or cold production and demand, or improve the performance of technologies such as geothermal energy. For a given building, the use of thermal energy storage can reduce the emission factor of the heating system by several dozen or even hundreds of grams of CO_2 per kWh. In addition, certain techniques ensure the low-carbon production of heat as well as cold, thus meeting the two challenges of climate change: mitigation and adaptation.

In order to assess their potential for inter-seasonal use in the building sector, the technological principles of thermal energy storage are reviewed in the first chapter. Suitable technologies - aquifer, pit, borehole and underground cavern storage - are discussed in the following chapters. In conclusion, the paper suggests a number of avenues and questions that will allow an accurate assessment of the potential of these techniques in France and the formulation of recommendations to encourage their development.

Thermal energy Storage Technologies

The idea of storing the cold of winter for use during summer is an old one, as evidenced by the iceboxes in the castles of Versailles or Rambouillet in France, or the yakhtchal in Iran. On a large scale, these technologies began to be developed in the 1960s in the Shanghai region. The overuse of the region's geothermal resources to meet the cooling needs of the textile industries led to an increase in the temperature of the aquifers, i.e. a degradation of this geothermal resource. The injection of cold water into the aquifers in winter restored and preserved the resource, and up to 400 extraction and injection wells were operated in the region ***[4]***. However, due to the lack of studies on the chemical composition of the extracted water, the wells and heat exchangers became blocked after a few years of use. These installations were then abandoned. Around the world, following the first oil crisis, research into energy storage, particularly thermal energy, developed in the 1970s and 1980s, and was intensified from the 2000s onwards with the awareness of the need for an energy transition.

Thermal energy storage (TES) techniques are generally divided into three categories ***[5, 6]***:

– *Thermo-Chemical Storage* (TCS) is based either on a reversible chemical reaction, the endothermic direction of which corresponds to storage, or on a sorption/desorption process;
– Latent heat storage uses the exchange of energy that takes place at constant temperature during the change of state (usually solid-liquid) of a *Phase Change Material* (PCM);
– Storage by sensible heat, the most widespread, corresponds to the storage of thermal energy by increasing or decreasing the temperature of a medium. This medium can be water, possibly supplemented by chemical or mineral elements, rock, molten salts, etc. The most common example is the hot water tank, but the size, shape and location of tanks can vary considerably.

Figure 1.1 lists the different technologies corresponding to these three categories.

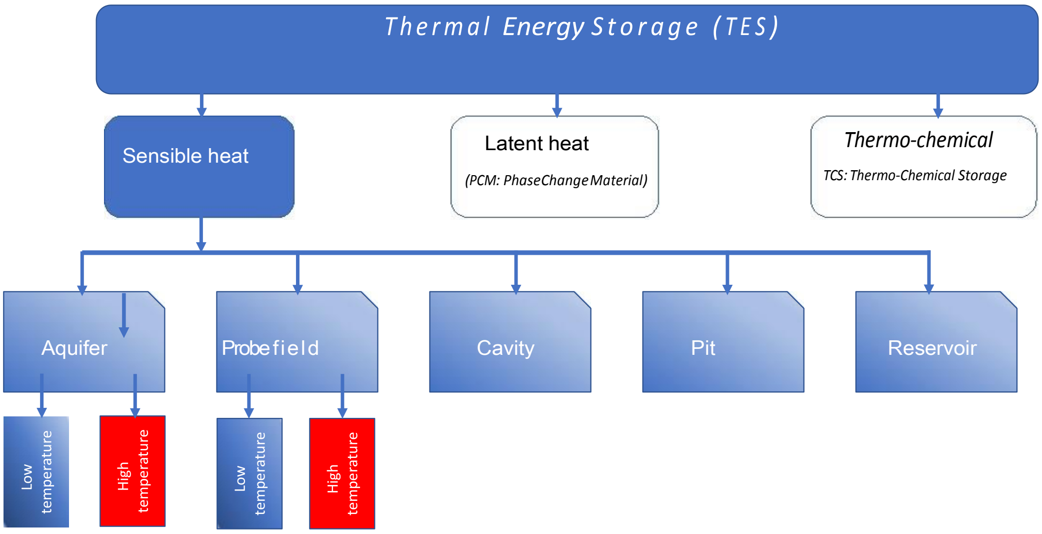

Fig. 1.1: Typology of thermal energy storage techniques

Thermochemical Storage (tcS)

There are two types of thermochemical storage. The first uses the enthalpy of reaction. A compound 'AB' (e.g. magnesium sulphate heptahydrate $MgSO_4$-7H20) is split into two products 'A' and 'B' (e.g. magnesium sulphate and water) by an input of thermal energy: the reaction occurs in the endothermic direction. The products are then stored separately. When they are again brought together, the two reactants 'A' and 'B' react to form the product 'AB', and thermal energy is released.

The second is based on sorption: a fluid, liquid or gas, called a sorbate, is absorbed or adsorbed by another medium, liquid or solid, called a sorbent. For example, this can be water and zeolite. Heat input results in desorption of the sorbate from the sorbent: and at its conclusion, the two media are stored separately. Heat output takes place when sorbate and sorbent are reunited: the sorption that occurs releases heat. This phenomenon is illustrated in Figure 2.

TCS technologies have very high storage densities, from 100 to 500 kWh/m^3, and are suitable for storage of the order of a few MWh. However, their *Technological Readiness Level* (TRL) is still low: TRLs vary between 3 and 5, with the exception of some sorption technologies for heat pumps, which are commercially available. In addition, component costs are high, and the investment cost for one kWh stored is between €10 and €100. Efficiency, defined as the ratio of energy recovered to energy stored, can in theory be very high, but this potential is not yet fully realised *[6]*.

At present, these cost characteristics make TCS unsuitable for inter-seasonal use in buildings. However, potential applications do exist and could be further developed if research continues to improve the materials *[5]*.

Latent Heat Storage (LHS)

Latent heat, or enthalpy of change of state, is the change in energy associated with a change of state (usually melting-solidification or vaporisation-liquification). Unlike sensible heat, this change is not associated with a change in temperature, since a change of state occurs at a quasi-fixed temperature. LHS is therefore well suited to applications where temperature variations are small. Many different materials are used (hydrated salts, paraffins, fatty acids, etc.) and cover a wide range of charging and discharging temperatures.

Storage densities are high, around 100 kWh/m3. Storage capacities range from 10 kWh to 10 MWh, and material costs vary significantly, from a few euros to several hundred euros per kWh, depending on the materials considered *[6]*. Most technologies are at the high end of this estimate. Storage efficiency is between 75% and 90% **[5]**.

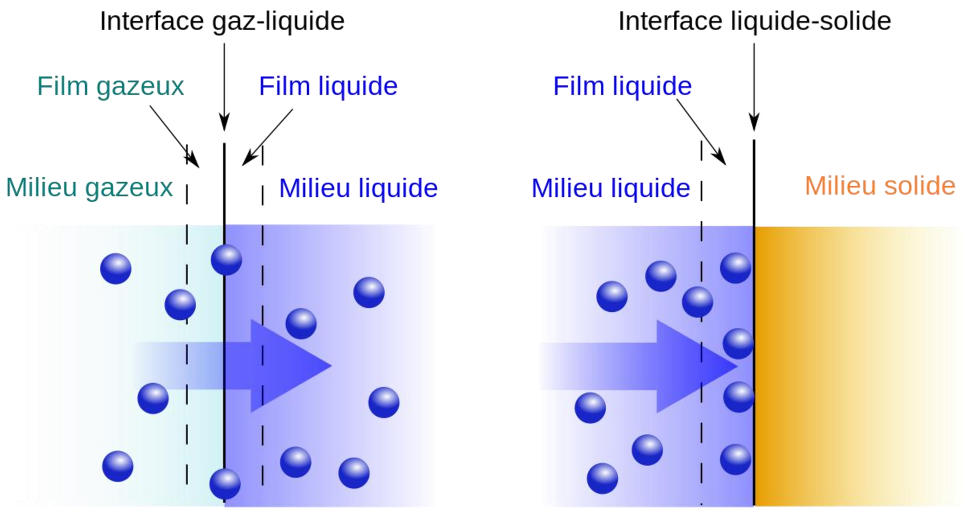

Fig. 1.2: Representation of the absorption and adsorption phenomena. Source: *[7]*

LHS covers all levels of technological maturity. It is reaching the stage of commercial development for certain industrial uses, as well as in daily or weekly cycles in the residential/tertiary sector, where its integration in building materials allows for the smoothing of temperatures in order to maintain a comfortable temperature.

Due to the high initial cost per stored kWh, only uses with high heat charging and discharging frequencies are of interest at present. Their potential for inter-seasonal storage in buildings has therefore not been demonstrated.

Aquifer (ateS)

Aquifer Thermal Energy Storage (ATES) is an open system, where water as a heat transfer fluid is taken from an aquifer, circulated through a heat exchanger, and then re-injected into the aquifer, usually through a geothermal doublet - the number of wells can vary. In the following season, the water flows in the opposite direction, creating a hot bubble and a cold bubble, as shown in Figure 1.3.

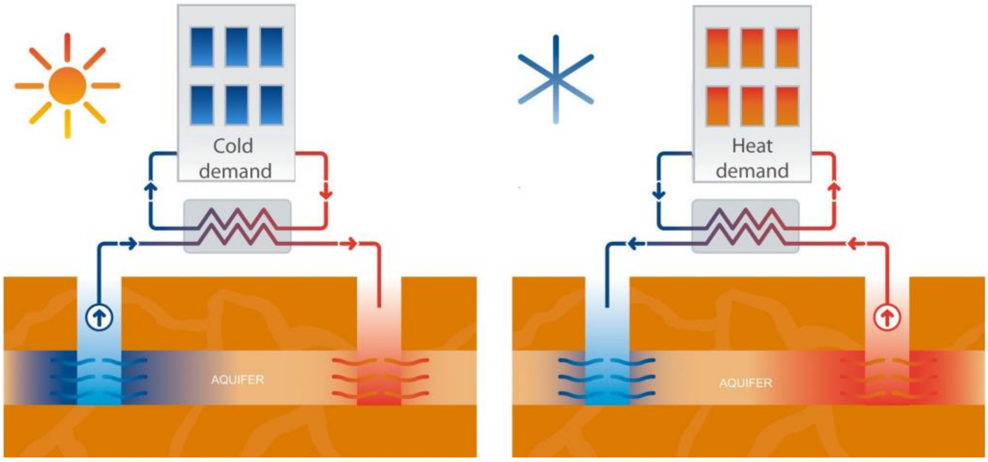

Fig. 1.3. Thermal energy storage in aquifers. Source: IF Technology

These bubbles are spaced far enough apart to prevent them from mixing due to the annual water flow in the aquifer.

Most systems operate with a maximum re-injection temperature of between 20 and 40ºC, due to regulatory and technical considerations: these are LT-ATES (Low-Temperature ATES), for which the aquifers used are located at depths ranging from 20 to 300 m. Systems operating at higher temperatures, called HT-ATES (High-Temperature ATES), use aquifers at much greater depths of around 1,000 m. While only a few HT-ATES implementations exist, LT-ATES have a high level of technological maturity and are reaching significant commercial development in several countries (TRL 9) ***[6]***. Volume and stored energy measurements are not relevant for these open systems, so the size is usually expressed in terms of power, which corresponds to the maximum extraction rate that can be achieved by the well. It varies from 0.1 to 20 MW, for capital expenditures ranging from 200,000 to 2,500,000 € [4]. The efficiency of ATES varies from 70 to 90%.

These operating and integration characteristics make aquifer thermal energy storage systems particularly well suited for inter-seasonal use in buildings (see p. 11 Concepts).

Borehole Field (BteS)

Like ATES systems, Borehole Thermal Energy Storage (BTES) is similar to conventional geothermal technologies: a heat transfer fluid circulates in a closed circuit in a borehole field to extract heat from the subsoil during winter or cold during summer. Reversing the direction of circulation in summer (respectively, in winter) allows thermal energy to be stored by heating (respectively, cooling) the subsoil, using the same boreholes, as illustrated in Figure 1.4.

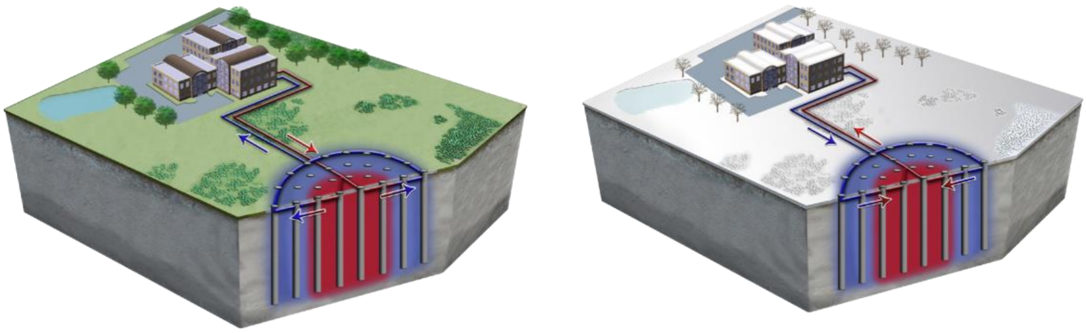

Fig. 1.4. Heat storage (left) and destorage in a borehole field. Source: Underground Energy

The distinction between a BTES system and a geothermal heat pump with vertical collection becomes unclear if the latter is designed for two-way circulation, which allows for thermal recharge of the subsoil during the summer months. Different criteria have been proposed to establish the difference, relating to the size of the installations, the efficiency of the storage, the origin of the heat or the injection temperature ***[8]***. Here, we refer to systems where the stored energy is waste heat from buildings or the environment as low-temperature BTES (LT-BTES) and those where an external source (such as solar panels) provides the stored thermal energy as high-temperature BTES (HT-BTES). In this document, considering that LT-BTES are more related to conventional geothermal energy, we deal only with HT-BTES. The LT-BTES fall under the regulatory framework of the geothermal energy called "of minimal importance" (decree nº2015-15), since they concern depths lower than 200 m and powers lower than 500 kW. This is not necessarily the case for LT-ATES, which can reach much higher powers (see p.25 Current market).

Depending on the type of soil and the size of the installation, the bore-hole probes can consist of pipes directly sunk into soft clay up to a depth of 40 m, or of actual boreholes up to 300 m deep. The estimated investment costs vary from 0.4 to 4 € per kWh of stored energy, but the average efficiency rarely exceeds 50%, due to the thermal conductivity of the drilled rocks, which are not isolated from their environment. However, the layout of the boreholes/probes (depth and distribution) allows us to estimate the useful storage volume, which varies between 10,000 and 100,000 m3, with a storage density of 15 to 30 kWh/m3 ***[9]***. Depending on the country, the maturity level varies from 6 to 8 ***[5]***.

These parameters make HT-BTES a suitable technology for inter-seasonal use in the residential/tertiary sector. In the following, the term BTES without further precision refers to HT-BTES technologies.

Cavity (cteS)

Cavern Thermal Energy Storage (CTES), sometimes called Mine Thermal Energy Storage (MTES), uses cavities that have lost their original purpose, such as abandoned mines or oil reservoirs. Once filled with water, these cavities constitute a resource similar to an aquifer. However, the lack of natural flow makes this resource less prone to temperature drift. Thermal energy storage is therefore more straightforward.
Figure 1.5 illustrates the operation of the CTES system at the Yvon Morandat well in Gardanne.

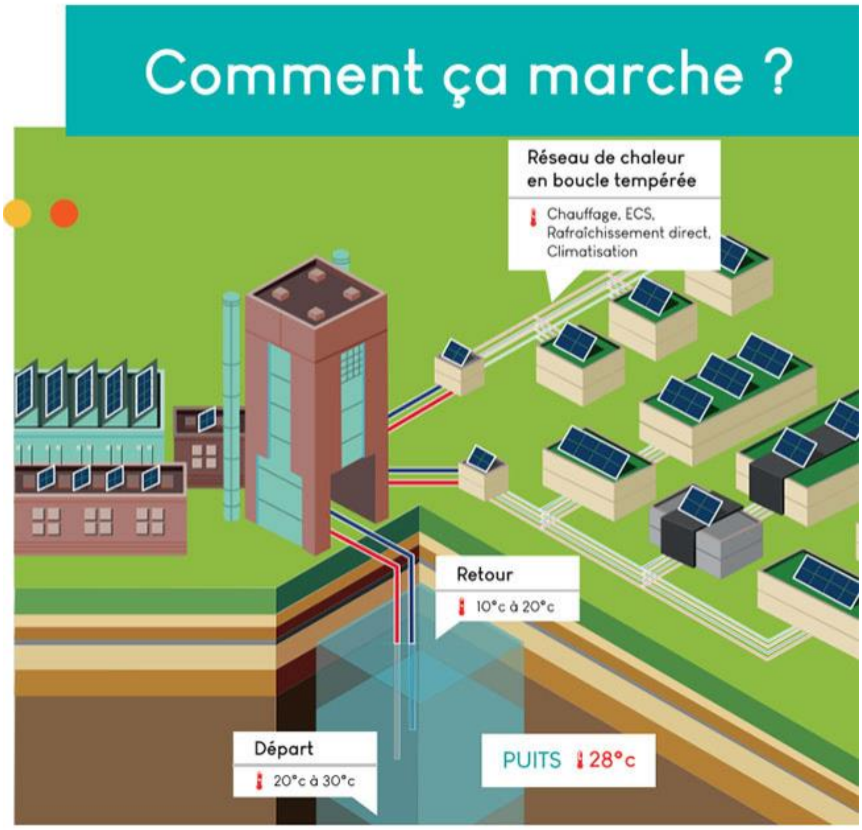

Fig. 1.5. Storage in flooded mine waters. Source: [10]

This type of system does not necessarily work with a geothermal doublet creating hot and cold bubbles at the same depth: thermal energy storage is sometimes aimed at maintaining the average annual temperature. However, thermal stratification can be used to extract and inject water at different temperatures in different periods.

The volumes of cavities considered vary from tens of thousands to millions of cubic metres. Because of the rare conditions that must be met, there are few CTES systems, and it is therefore difficult to give general key performance indicators.

However, the large volumes and the relatively low cost per kWh stored (when the reservoir exists beforehand) make them interesting for inter-seasonal use in the residential and commercial sector.

Pit (pteS)

Pit Thermal Energy Storage (PTES) requires the construction of a semi-buried storage tank. The excavated soil can be used to reinforce the walls of the pit.

The pit is then filled with water or a mixture of water and gravel, and covered with an insulating sheet that floats on the surface or a rigid insulating surface that can support a certain weight. This type of tank is mostly used for heat storage. A cross-section is shown in Figure 6.

Fig. 1.6. Cross-section of a pit storage tank (PTES). Source: PlanEnergi via ***[9].***

The storage density varies from 60 to 80 kWh/m3 ***[9]***. Storage volumes have increased considerably since the first experiments, and now reach several hundred thousand cubic meters. This has led to a reduction of the initial cost per stored kWh, now less than 1€ per kWh. The storage temperatures are between 70 and 90 ºC, and the efficiency can reach 80% if the materials used for the walls and roof are sufficiently insulating ***[5].***

These figures make PTESs the preferred systems for inter-seasonal storage in buildings, especially for small-scale heat networks. The technological maturity level reaches 9 in some countries ***[6].***

Tank (tteS)

The term "Tank Thermal Energy Storage" (TTES) covers a wide range of situations: domestic hot water tanks (generally used in daily cycles), oil or molten salt tanks in concentrated solar thermal power plants (for storage of a few hours), buffer tanks, etc. When it comes to inter-seasonal use, the preferred storage fluid is water, for the reasons of cost and frequency of cycles mentioned above.

The storage density is then similar to that of pit storage: 60 to 80 kWh/m3 ***[9]***. The volumes considered for this type of application vary between 1,000 and 10,000 m3. These tanks are usually dug into the ground or built on the surface and then covered with soil, which improves their insulation. The efficiency is similar to that of PTES systems, but the investment cost per stored kWh is higher: it is between 1 and 4 €/kWh ***[5]***. On the other hand, their integration in urban areas is easier since they occupy smaller surfaces.

Although the inter-seasonal use of this type of tank is documented [11], the volumes involved and the number of installations are small, and there are few experiments underway. The characteristics of this system compared to other sensible heat storage techniques (slightly higher cost, smaller volume, but almost no environmental requirements) make it more suitable for improving the performance of a small solar panel installation, for example in a single-family home, or for the creation of buffer tanks that are often essential in ATES, BTES, PTES and CTES. In the second case, the specific use of TTES is not inter-seasonal, the cycles considered being from a few hours to a few days. Tank storage is not considered in the rest of this document.

After a quick review of the different thermal energy storage technologies, summarised in Table 1.1, it can be seen that four of them, all based on sensible heat storage, are currently being used for large-scale storage of thermal energy on an inter-seasonal basis in the residential/tertiary sector: aquifer, borehole, pit and underground cavity storage.

This is due to the key characteristics of these technologies - large storage volumes and low investment costs - which make them suitable for low storage and de-storage rates and large amounts of stored energy of up to several GWh.

However, the deployment of each of these technologies is very different in different regions. This is only partly due to local conditions (urbanisation, climate, soil composition). The integration of these technologies and their current development in Europe are discussed in the following chapters.

Technology	Short name	Density (kWh/m3)	Initial cost	Size	Efficiency (%)	TRL
Thermo-chemical	TCS (Thermo-chemical storage)	100 - 500	10 -100€/kWh	2-4 MWh	90- 100	3- 5
Latent heat	PCM (Phase-Change material)	100	1-100€/kWh	10 kWh- 10 MWh	75– 90	5- 8
Aquifer	ATES (Aquifer thermal energy storage)	-	1000€/kW	0.1 -20 MW	-	5- 9
Probefield	BTES (Borehole thermal energy storage)	15 - 30	0.4 - 4€/kWh	0.1 -10 GWh	50	6- 8
Cavity	CTES (Cavern thermal energy storage)	60 - 80	-	100 000 -1000 000 m^3	-	5- 7
Pit	PTES (Pit thermal energy storage)	60 - 80	1€/kWh	1-10 GWh	50– 80	6- 8
Tank	TTES (Tank thermal energy storage)	60 - 80	1- 4€/kWh	10 kWh- 1 GWh	50– 90	6- 9

Table 1.1 Characteristics of thermal energy storage technologies. Sources: [5, 6]

Aquifer storage - ates

Low-temperature aquifer storage, which is quite similar to geothermal storage by groundwater heat extraction and return, is highly developed, with several thousand installations, mainly in the Netherlands. High-temperature storage is much more limited, but several pilot sites are being studied.

Concept

The main elements to describe the integration of a STES technology can be summarised in three categories:

- the origin of the stored heat or cold,
- the applications in the different branches of the building sector,
- the local constraints that condition its deployment.

A representation of these categories for ATES, inspired by [4], is given in Figures 2.1, 2.2 and 2.3.

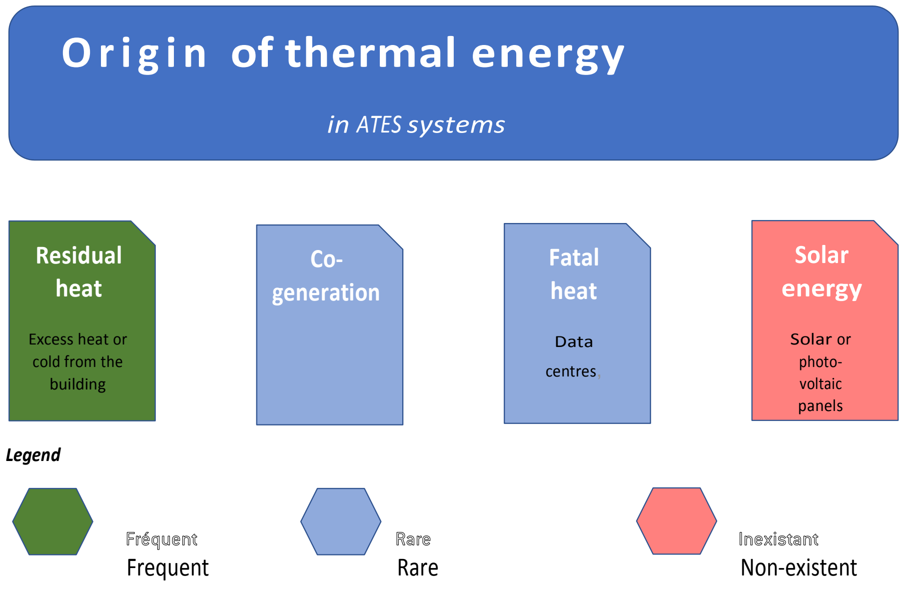

Fig. 2.1. Origin of thermal energy in ATES systems

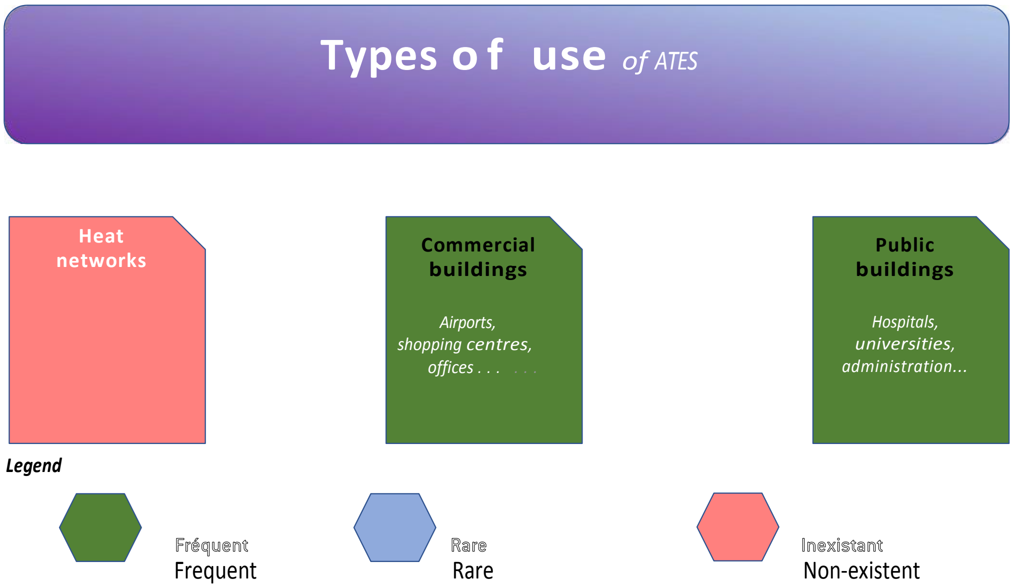

Fig. 2.2. Type of use of ATES

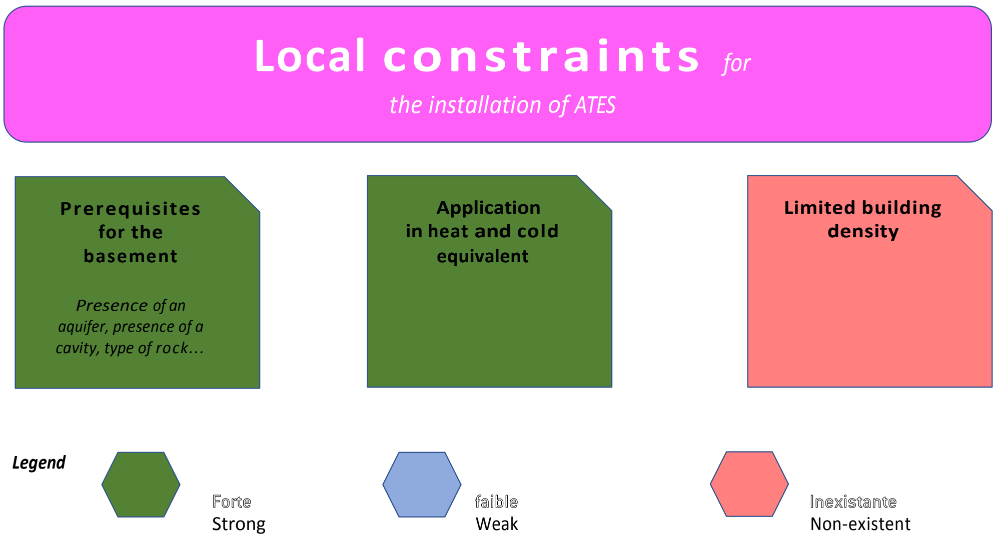

Fig. 2.3. Constraints for the installation of ATES systems

As mentioned in the previous chapter, most ATES are low temperature (LT-ATES). The maximum re-injection temperature, which determines the boundary between HT-ATES and LT-ATES, varies between authors: 20 ºC *[9]*, 25 ºC *[4]* or 40 ºC *[12]*. This difference in denomination is explained by a change in nature when the threshold is crossed: regulations are more restrictive, the required depths exceed 1,000 m, the installations are more complex because the pumps and exchangers are more subject to congestion, and the integration with surface networks is different.

More than 95% of the systems in operation today are LT-ATES. Their operation is quite simple since the thermal energy stored is the residual heat of the buildings: the circuit from the hot bubble to the cold bubble to heat the building in winter allows the cold bubble to be recharged with cooled water, and conversely in summer, the hot bubble is recharged with warm water, heated via the residual heat from the building. Systems aiming to store waste heat or heat from cogeneration are HT-ATES, which explains the frequency shown in Figure 2.1. Solar energy storage in aquifers has been studied a few times but never implemented [4].

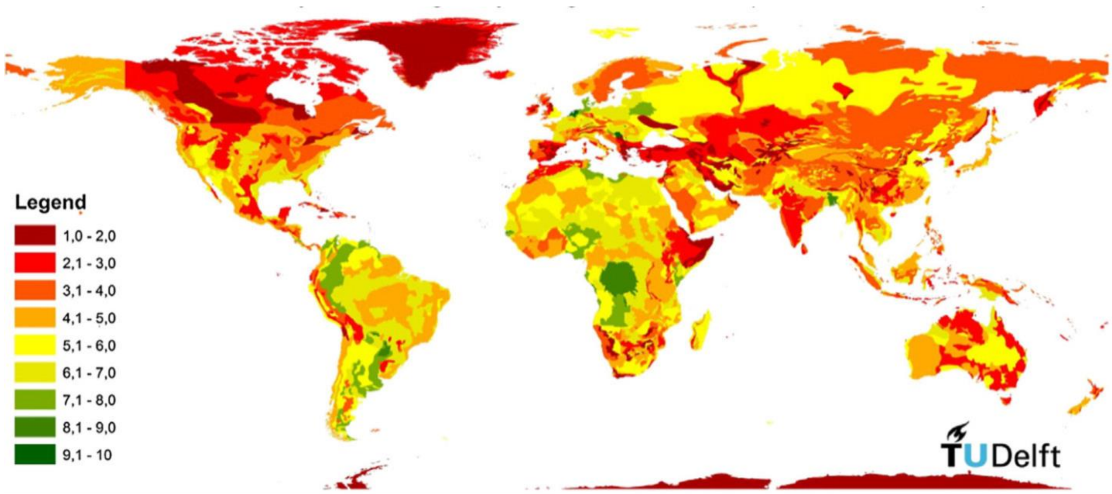

Fig. 2.4. Relevance of LT-ATES to climatic and hydrogeological conditions for the period 1976-2000 (10 = very relevant). Source: [13]

As shown in Figure 2.2, ATES are mainly used in commercial buildings (45%) on the one hand, and institutional buildings (25%) and hospitals (5%) on the other (source: IFTech via [9]). There is some minor use of ATES in heating networks, but pilot projects to encourage their development are being carried out.

The local conditions are crucial for the ATES (see Fig. 2.3). The presence of an aquifer is obviously a prerequisite, but it must also meet certain conditions: adequate temperature, low water flow velocity, chemical composition compatible with pumping and re-injection... In addition, climatic conditions are also essential, especially in the case of LT-ATES.

The potential for LT-ATES is shown in Figure 2.4. Such maps must incorporate many factors, and must also take into account climate change for the coming decades, which can have profound influence on the usefulness of LT-ATES systems in a given region. This makes their realisation complex.

Urban density is not *a priori* a determining criterion: the land occupation due to ATES is only related to pumping installations and heat exchangers and is therefore very low. An ATES can therefore be easily installed in a high density area. Only the massive use of ATES in a given area is a limiting factor, as it leads to conflicts of use for the aquifers considered. Indeed, because of the heat losses due to transport, it is preferable that the source of thermal energy, the storage reservoir and the place of use of this energy are located in close proximity. This is true for all STES technologies.

Current Market

Today there are about 3000 LT-ATES in operation, 85% of which are in the Netherlands *[4]*. Other countries with significant deployment are Sweden, Denmark and Belgium, and there are a few installations in about ten other countries (see Fig. 2.5).

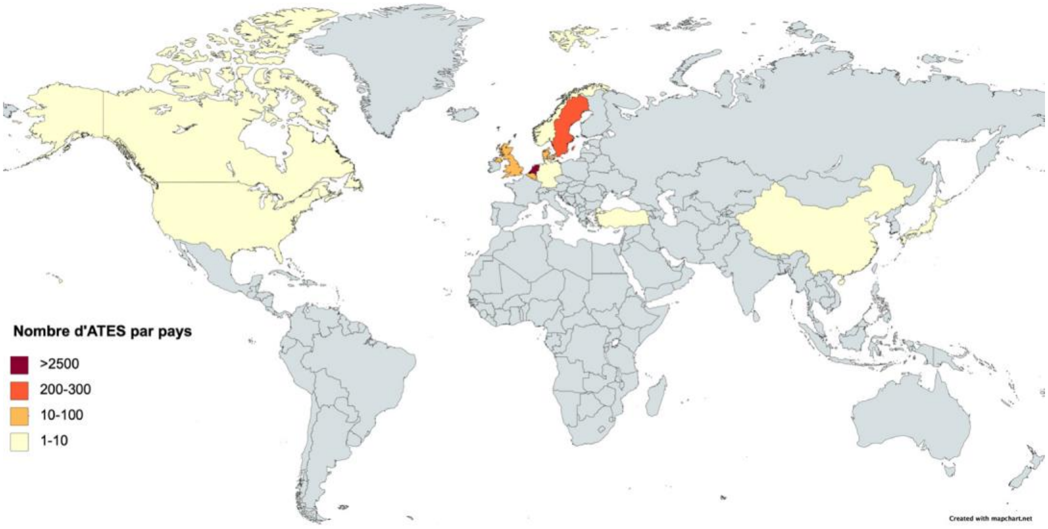

Fig. 2.5. ATES facilities worldwide. Source: Map modified from ***[4]***.

In the Netherlands, the market is well structured. The Dutch-ATES consortium includes partners with expertise in this technology: Over Morgen, Priva, Storengy (Engie group), Sun Energy, Deltares, TNO, as well as public partners (City of The Hague, RVO - Dutch Enterprise Agency).

The Dutch-based consulting and engineering company IF Technology and its parent company IF Tech International, design, implement, and monitor ATES systems in the Netherlands, but also in Belgium and the UK. The British company ICAX specialises in what it calls 'inter-seasonal heat transfer'.

Table 2.1 below gives four examples of LT–ATES for different types of equipment, all of which are currently in operation. The LT–ATES at the University of Eindhoven is one of the largest in the world in terms of power *[4]*.

Name, place, use	Year	CA-PEX (M€)	Power (MW)	Return time (year)	C02 avoided (t/year)	Energy supplied (GWh)	Refs
Hospital of Brasschaat (BE)	2000	0.7	0.35 (Hot) 1.2 (Cold)	8.4	427	3.4 (Hot) 2.7 (Cold)	[4] [14]
University of Eindhoven (NL)	2002	14.7	20 (Hot) 20 (Cold)	6-10	13300	25-33 (Hot) 25-30 (Cold)	[4] [15]
Stockholm Airport (SE)	2009	5	10 (Hot) 10 (Cold)	5	7700	20 (Total)	[4] [9]
Widex Headquarters Copenhague (DK)	2010	-	2.8 (Hot) 2.8 (Cold)	-	644	-	[4]
Riverlight Residence London (UK)	2013		9 (Hot) 1.8 (Cold)	-	-	1.4 (Total)	(4),(9] [16]

Table. 2.1. Examples of LT-ATES in operation

To calculate a payback time and a quantity of CO_2 avoided, a reference system for heating and cooling is defined: this is the existing system in the case of a renovation, or another possible system in the case of a new construction. The cumulative capital and operating costs are compared, and the payback time is the time after which the total for the ATES system becomes less than the total for the reference system. Such calculations typically result in a payback time of between 2 and 10 years. However, comprehensive studies that take into account possible changes in CO_2 costs and energy prices are few and far between.

Lifetime is a critical parameter for assessing the viability and cost-effectiveness of a LT-ATES system, but data are sparse on this topic because most ATES were built within the last 20 years. Depending on local characteristics and authors, estimates range from 25 to 50 years.

Most of the numerous HT-ATES pilot sites developed in the 1980s in France, Switzerland, and the United States (see ***[4]***) have been abandoned. However, there are some HT-ATES in operation today in Europe, such as:

– ATES Neubrandenburg in northern Germany. The heat from co-generation in a combined cycle power plant is stored in an aquifer at a depth of 1,200 m. Of the 12,000 MWh injected in the summer, 8,800 MWh are recovered in the winter. The water is extracted at about 80ºC (compared to 45ºC without injection) ***[17]***;
– the Reichstag Palace in Berlin, which operates with two bubbles for heat and two bubbles for cold (see Fig. 2.6). It is therefore both a LT-ATES, for the storage of residual cold at a depth of 30 m, and a HT-ATES, for the storage of heat produced on site by cogeneration at a depth of 300 m. This covers 60% of the building's cooling needs and 90% of its heating needs ***[18]***.

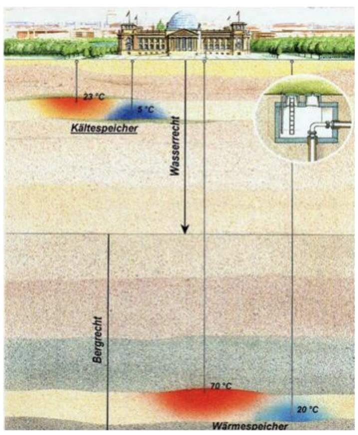

Fig. 2.6. Double ATES of the Reichstag. Source: https://www.geothermie.de/bibliothek/lexikon-der-geothermie/e/erdwaermespeicher-aquiferspeicher.html

Research and Development

Two European research consortia involving pilot sites with aquifer storage have been set up in recent years.

The first is the Europe-Wide Use of Sustainable Energy from Aquifers (E-Use(aq)) project of the Climate Knowledge and Innovation Community (Climate-KIC). It was launched in 2013 with the intention of demonstrating the feasibility of LT-ATES systems in different climate and regulatory contexts **[19]**. Industrial and academic partners from five countries (Italy, the Netherlands, Spain, Belgium, Denmark) are involved: the Universities of Bologna, Delft (TU Delft) and Wageningen, Deltares, Arcadis, KWR, ART-ER, Instituto de Tecnología Cerámica, ITECON, Naked Energy, Nomisma Energia, Ramboll and Bioclear Earth.

An in-depth study under Pathfinder funding identified barriers to the development of LT-ATES in different countries **[20]**. As these barriers vary according to local climatic conditions and market maturity, experimental sites were selected in the five countries. After several years of operation, evidence has been published **[21, 22]** and monitoring of the sites is ongoing. The sites, specifics and results are summarized in Table 2.2.

Name, place	Recorded barriers	Pro-posed solutions	CAPEX (euros)	Power (kW)	C02 avoided (t/year)
Nules, Spain	Lack of awareness, Regulatory difficulties	Closed–loop ATES	58 000	0 (Hot) 109 (Cold)	25
Bologna, Italy	Lack of awareness, skills integration	Integration into a heating network	460 000	160 (Hot) 140 (Cold)	17
Delft, The Netherlands	Imbalance in heat and cooling demand	Integration of solar thermal panels	62 000	70 (Hot) 30 (Cold)	25
Utrecht, The Netherlands	Aquifer water contamination	ATES with bioremediation	-	-	
Ham, Belgium	Imbalance in heat and cooling demand	Integration of solar thermal panels	116 000	650 (Hot) 1300 (Cold)	205
Copenhagen, Denmark	Aquifer water contamination	ATES with bioremediation	-	-	

Table. 2.2. E-Use(aq) pilot sites

The second is Heatstore, one of nine projects funded by the European Geothermica initiative. Launched in 2017, it is dedicated to high-temperature heat storage, all techniques combined (ATES, BTES, CTES, PTES) and involves many public and private partners. Eight existing geothermal or STES sites in the Netherlands, Denmark, Iceland and Portugal are the subject of case studies. Six pilot sites are under construction or experimentation, four of which concern aquifer storage. Their characteristics are summarized in Table 2.3 **[12]**.

name, place	Concept	partners
Bern, Switzerland	Storage of heat from cogeneration	Energie Wasser Bern, Universitat Politècnica de Catalunya, Fraunhofer IEG, ETH Zürich, Universität Bern
Geneva, Switzerland	Storage of waste heat from a MWIP	Services Industriels de Genève, University of Geneva, University of Neuchâtel, ETH Zürich, Universität Bern
Monster, Netherlands	Conversion of LT-ATES to HT-ATES for agricultural use	ECW Netwerk, TNO, KWR, IF Technology, NIOO

Table. 2.3. Heatstore pilot sites

In addition, the International Energy Agency's District Heating and Cooling (IEA-DHC) technology collaboration programme has been investigating the integration of large-scale inter-seasonal storage techniques into heat networks [9]. The participating countries are the United States, Canada, Denmark, Germany and the Netherlands. Aquifer storage is one of the two technologies selected (along with pit storage), and a detailed feasibility study for aquifer storage associated with the heat network at York University, Canada, was conducted in partnership with IF Tech International, CanmetENERGY, TESS - Thermal Energy Specialists and J.L. Richards *[23]*. This study was published to contribute to the awareness and dissemination of expertise regarding aquifer storage.

Finally, in the framework of the Geospeicher.bw collaboration between five German universities (Karlsruhe IT, Universities of Heidelberg, Stuttgart, Biberach, Offenburg), eight ATES demonstrators are being studied or implemented.

Hurdles in France

The obstacles to the development of ATES systems are different depending on whether the market is emerging, growing or mature *[4]*. France is in the first category and is therefore confronted with the usual difficulties of new markets: lack of confidence in the technology, lack of skills, lack of awareness, both among potential customers and among manufacturers and energy producers and suppliers. This translates into a lack of interest on the part of the players concerned, which prevents the search for solutions to the other obstacles mentioned below.

From an economic point of view, while the payback period is less than ten years for most installations, the initial investment cost may seem prohibitive. Business models that take into account investment and operational costs, but also the savings induced by energy storage and avoided CO_2, and that integrate all stakeholders, have not yet been demonstrated in France.

As far as regulations are concerned, the small LT-ATES meet the conditions for minimal geothermal energy on an open loop: depth less than 200 m, maximum thermal power less than 500 kW, withdrawal temperature less than 25ºC, withdrawal and reinjection of the same volume and in the same aquifer, pumped flow rate less than 80 m3/h.

The legal requirements are not very high (simple declaration), but the regulatory complexity can be a hindrance for small companies [24]. Many LT-ATES do not fall into this category, however, as they exceed the permitted capacity threshold. It is therefore difficult to determine whether these installations fall under the heading of "underground storage of heat energy" or "low-energy geothermal energy", both of which are governed by the Mining Code, or "exploitation of groundwater", which is regulated by the Environmental Code. Theabsence of an adequate legal framework is therefore a major obstacle.

From a technological point of view, the relative lack of hindsight on HT-ATES already built - most of which are less than twenty years old - may contribute to mistrust on the part of stakeholders. Moreover, while there seems to be a consensus on the harmlessness of LT-ATES on aquifer water, the effect of a HT-ATES on the quality of the aquifer where it is installed remains unknown [21].

In France, the hydrogeological and climatic conditions seem rather favourable (see Fig. 2.4). However, the lack of a database or maps concentrating all relevant information to assess the technical and economic feasibility of an ATES in a given location is an obstacle.

Finally, integration into an existing network may, in some cases, pose a problem. For example, the Geostocal project (Geostorage of heat: opportunities, optimisation and feasibility of storing waste heat in deep aquifers), financed by the French National Research Agency and co-sponsored by the French Geological and Mining Research Bureau (BRGM) between 2007 and 2010, studied the possibility of storing the waste heat from the Ivry-sur-Seine Domestic-waste incineration plant (DWIP) in the Dogger aquifer [25]. This aquifer is already used by several geothermal installations in the Ile-de-France region. In winter, the waste heat from the Ivry waste incineration plant is used by the heating network of the Parisian district heating company. In Summer, this waste heat is surplus to requirements, which is why Geostocal was launched. One of the reasons for abandoning the project was the large difference between the discharge temperature from the aquifer (95ºC) and the distribution temperature in the heating network (200ºC) [12].

Pit storage - ptes

Pit storage was initiated in Germany in the 1980s, but was developed industrially in Denmark in the 2010s. It is then systematically associated with a heating network and a solar heating plant (SHP), i.e. a low-temperature solar thermal panel plant.

Concept

As shown in Figure 3.1, pit storage has so far only been used to store solar energy in order to improve the coverage rate of solar panels. However, some installations incorporate the ability to additionally store electrical energy converted to thermal energy (Power to Heat) in order to effectively manage the intermittency of renewable sources such as wind turbines [5].

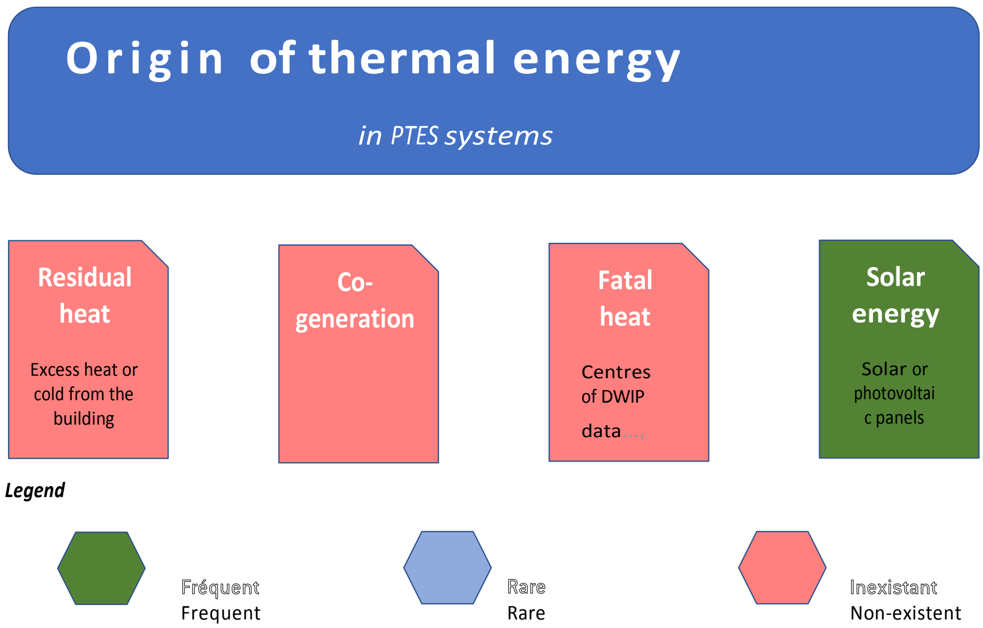

Fig. 3.1 Origin of thermal energy in PTES systems

Due to the high fixed cost of excavating the storage tank, and in contrast to the significant economies of scale that can be achieved, only the storage of energy from solar heating plants is interesting. This explains why it is only used for large-scale installations. On the other hand, PTES are mainly used for heat storage: the injection temperatures can reach 90 ºC. For this reason, as shown in Figure 3.2, buildings such as airports or hospitals, where equivalent cooling and heating needs coexist throughout the year, are not suitable for PTES. However, the thermal stratification inside the tanks, which can be more than 10 m deep, allows water to be drawn from them at a temperature varying from 20 to 90 ºC depending on the depth. They can therefore also be used as a cold source.

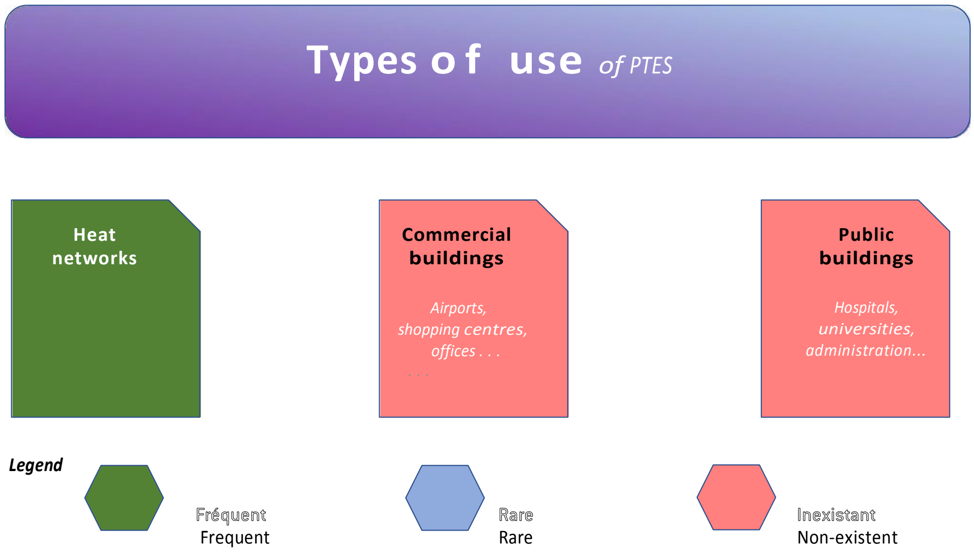

Fig. 3.2. Type of use of PTES systems

Regarding local constraints, PTES are suitable for areas where the need for heat is predominant. The nature of the subsoil is less constraining than for ATES technologies, but the composition of the soil must allow for low-cost excavation and reuse as reinforcement for the pit walls. Too much silt can be an obstacle in this regard ***[9]***. Finally, the urban density is a determining factor in assessing the feasibility of a PTES: the excavated areas are usually large (up to 21,000 m^2), and to this must be added the area of the solar heating plant (up to 70,000 m^2). Since PTES tanks are not designed to support a large weight (which would imply a much higher cost), only low-density populated urban areas are suitable for this use, such as peri-urban residential areas, because the surface area of the ground is large. These characteristics are summarized in Figure 3.3.

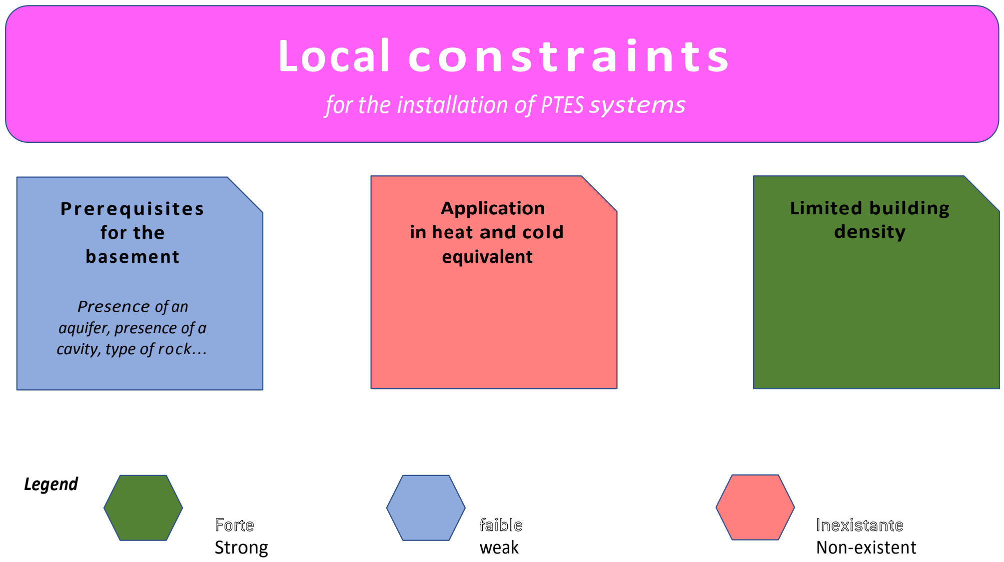

Fig. 3.3. Constraints for the installation of PTES systems

Current Market

There are about ten **pit** storage systems in Europe, which are located in Denmark and Germany. The German systems (in Stuttgart, Chemnitz, Augsburg, Steinfurt, Eggenstein) are quite old (built between 1984 and 2008) and small (volumes between 1,000 and 8,000 m3). They are combined with solar panels which are usually integrated into the buildings and have a surface area of about 1,000 square meters *[26]*. The independent research institute Solites - Research Institute for Solar and Sustainable Thermal Energy Systems - is the German reference for thermal energy storage in pits and tanks.

Location	Year	Solar panel area (m^2)	Volume of storage (m^3)	CAPEX (M€)	OPEX (€/year)	Stored energy (MWh)	Efficiency
Marstal	2012	33300	85000	3,34	33000	6 638	52%
Dronnin-glund	2013	37573	60000	2,28	30000	5 400	80%
Gram	2014	44836	125 000	4,32	-	12 125	50%
Vojens	2015	70000	210 000	5,01	-	121 280	-
Toftlund	2017	26000	85000	4,11	-	6 885	-

Table 3.1. 3.1 Key indicators of PTES systems in Denmark Source: *[9, 27]*

In Denmark, the storage tanks are larger. They are systematically associated with solar heating plants, which are among the largest in the world, and allow the houses associated with these plants to reach solar shares for heating between 40 and 60%. The actors most involved in these projects are PlanEnergi and Ramboll.

The key indicators for these installations are given in Table 3.1. The solar panel areas are given as a guide, all other data refer to storage tanks only. The first two projects in this list were initially implemented as demonstrators of the Sunstore project, funded by the European Union's Seventh Framework Programme, while the next three were commercially oriented [27].

The cost data are shown in Figure 3.4. The construction costs of the German and Danish PTES are shown in relation to their water equivalent volume. This quantity allows for a comparison of storage types with different compositions (in this case, water and water-gravel mix). It corresponds to the volume of water that would allow the same amount of energy to be stored as the medium used, and therefore depends on the thermal capacity of the medium. The Marstal PTES is shown twice, as the current site was built in two phases: Marstal-1 in 2003 and Marstal-2 in 2012. This figure, which also shows the costs of some BTESs (see Chapter 4), highlights the economies of scale mentioned earlier.

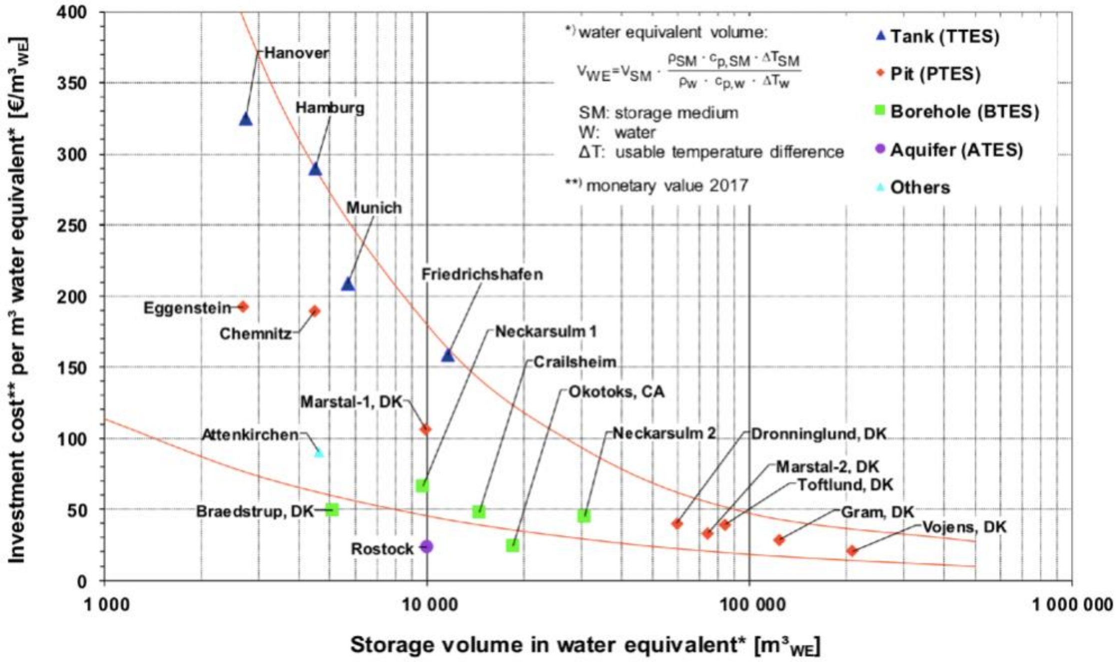

Fig. 3.4. Investment cost per volume (2017 value) for several STES - excluding taxes, excluding design, excluding connection. Source: Solites via [9]

Research and Development

The conditions to be met for a Danish-style PTES storage to be advantageous are well identified: the presence of a large solar heating plant connected to a heating network in an area of limited density. This makes it possible to significantly increase the solar fraction of the installation, and thus to amortize the cost of the solar panels, while benefiting from a low storage cost, due to economies of scale. The research and development activities specifically dedicated to PTES models are therefore limited.

However, PTES systems benefit from advances in research on materials used for the cover and walls (e.g. high density polyethylene): more durable, less expensive, more insulating and higher temperature resistant materials will improve the performance of this type of storage.

In addition, the operating facilities are monitored and optimized in the field, e.g. the trade-offs between the different sources of heat to be used or stored at a given time (solar panels vs. complementary sources, usually gas boilers), depending on the real-time price of gas and electricity from the networks and on the weather conditions.

The IEA-DHC programme (see p. 28 2.3. Research and development) has produced and made public a detailed case study that assesses the technical and economic feasibility of pit storage in combination with a heat network in Germany *[28]*. The report also presents an estimate of the investment costs for a PTES in Germany and Denmark, depending on its volume.

Finally, innovative uses of PTES storage are being studied or developed. In Denmark, in Høje-Taastrup, a 70,000 m3 pit is being built to store heat from a cogeneration plant. The plant operates as a supplement to intermittent sources of electricity: when the latter are not able to produce, the plant is switched on, and the heat produced is stored if it exceeds demand; conversely, heat is taken from the reservoir when the intermittent sources produce electricity *[29]*. However, this use is not inter-seasonal, as the optimal charge/discharge frequency is estimated to be 25 per year: this is similar to the reservoir storage.

Hurdles in France

The storage in PTES as it has been developed so far is mainly used to increase the coverage rate of solar heating plants connected to heating networks. The lack of such configurations in France is therefore the main obstacle to the development of PTES.

France is among the European countries where the percentage of thermal energy distributed by heat networks in the residential sector is the lowest: in 2016, this rate was 6.8%, compared to 14.1% for Germany, 40.5% for Sweden, and 58.5% for Denmark, which is in first place in Europe *[30]*.

From an economic point of view, the investment and maintenance costs in relation to the volume of the storage itself are relatively low, but if these costs are added to those of the construction of a solar heating plant and a heating network in an existing building, the operation is unlikely to be profitable. These systems are therefore mainly suitable for new housing estates, or possibly for feeding into an existing heating network. An additional cost factor is the amount of ground space they occupy, which makes them only suitable for low-density areas.

As far as the regulatory framework is concerned, there do not seem to be any significant obstacles to the development of PTES in France.

The technological barriers are low for these systems, whose commercial operation is the subject of several operations in Denmark. However, some data are not well known due to the lack of experience with these installations. For example, estimates of the lifetime of wall and roofing materials subjected to temperatures of 90 °C vary between 5 and 25 years *[9]*.

The local geographical conditions (mainly soil composition and sunshine) seem to be suitable for the combination of PTES and solar panels in most French regions.

Finally, as with the ATES, the lack of information and the lack of dissemination of these systems in France is a major obstacle.

Chapter IV

Borehole thermal energy storage -btes

Conventional geothermal borehole systems and LT-BTES are highly developed. This is an option that is frequently, if not systematically, proposed for construction in some Scandinavian countries. The HT-BTES, which are the subject of this chapter, are much less frequent. The development is rather sparse.

Concept

As with aquifer storage, the goal of borehole storage is to improve the performance and sustainability of a storage-free geothermal-inspired system. However, while ATES have a hot and a cold bubble, a (HT-)BTES consists of only one storage reservoir. This one is therefore mainly used for heating, and possibly marginally for summer cooling.

This is a fairly versatile system, which is often used to store thermal energy from solar panels, but is sometimes used to store waste heat from Domestic-waste incineration plant (DWIP) or industrial processes. As the thermal energy is stored in the rock, the constraints on injection temperatures are indeed less severe than when the heat transfer fluid is water from an aquifer. However, the thermal performance is not as good: the storage density is three to four times lower than that of water, and the dissipation is important because it is not an isolated medium. The origin of thermal energy in BTES systems is summarized in Figure 4.1.

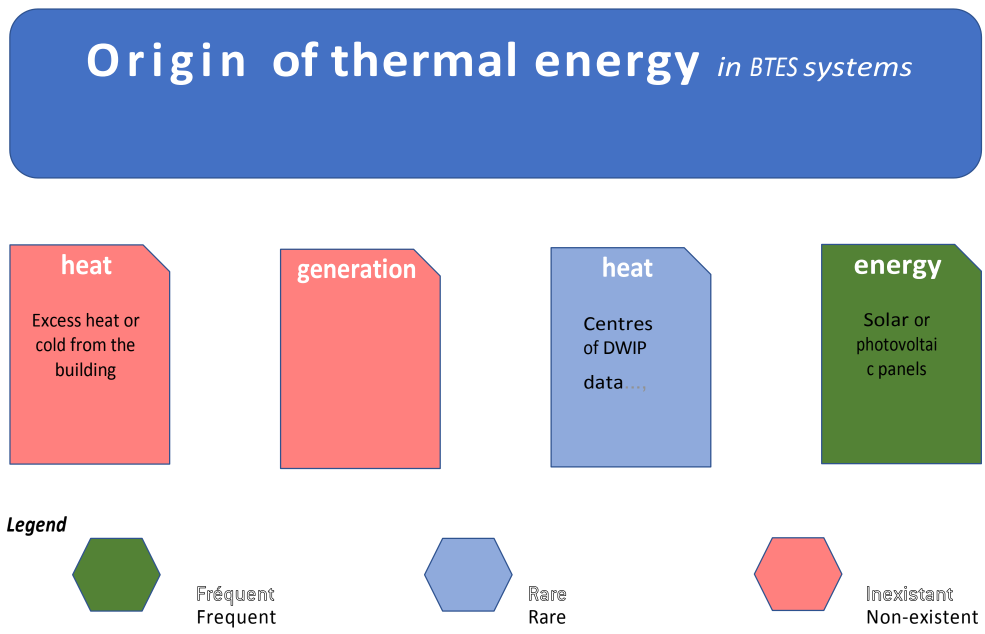

Fig. 4.1. Origin of thermal energy in BTES systems

Residual heat is not listed as a source since we are only dealing here with HT-BTES.

As these are mainly used for heating and domestic hot water, they are installed in sites where the need for heat is greatest (see Fig. 4.2).

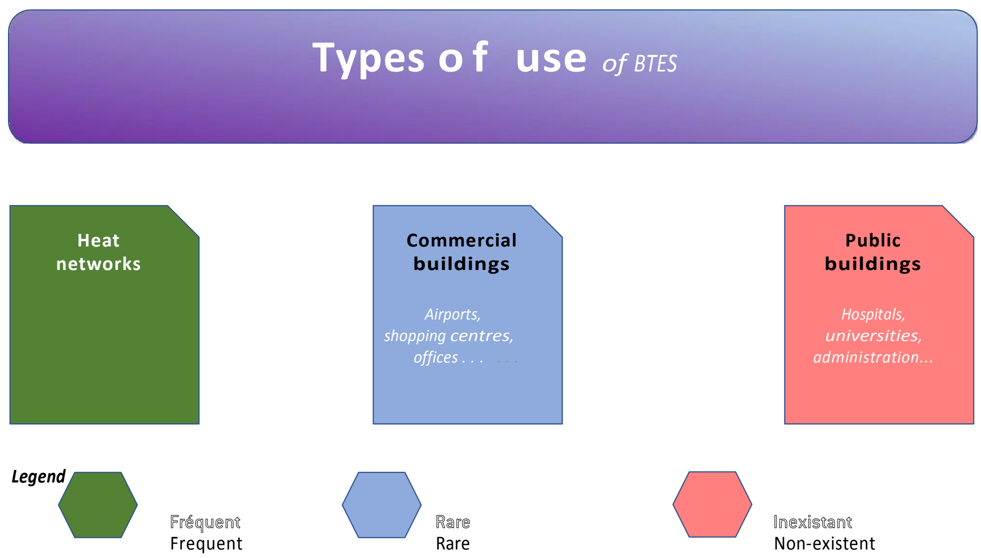

Fig. 4.2. Type of use of BTES systems

These are often groups of a few dozen houses connected by a heating network. There is also evidence of some use in office buildings. Due to the geometry of the borehole field, the greater the number of boreholes, the lower the relative heat loss. The BTES storage is therefore only interesting for relatively large installations

As shown in Figure 4.3, this implies that balancing hot and cold demand is not necessary..

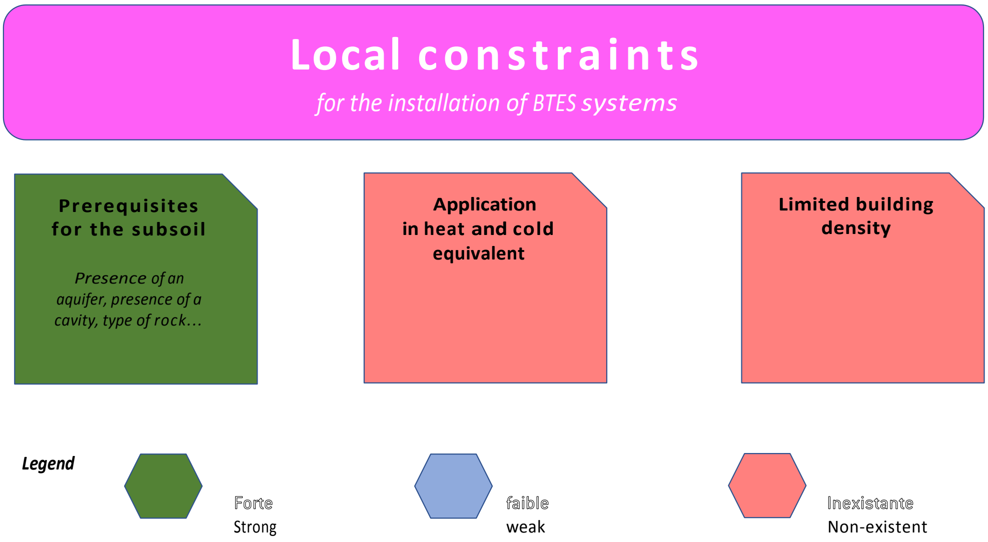

Fig. 4.3. Constraints for the installation of BTES systems

Density is not a constraint, as it is an underground system with a very low ground occupation. However, conflicts of use of the subsoil may arise in dense cities (sewers, public transport, car parks, road tunnels, historical heritage, etc.). The constraints on the subsoil are multiple: its composition influences the cost of drilling, and this must be taken into account when assessing the economic feasibility of a project. The composition also influences the efficiency of the storage, since the dissipation of the stored heat is related to the thermal capacity of the rock. Finally, groundwater movements also have an impact on the effectiveness of BTES storage.

Current market

The very good performance of LT-BTES discouraged the development of HT-BTES for several years. However, the recent concern for decarbonisation and the interest in renewable and recovered heat is now motivating the deployment of these systems in several countries.

The Heatstore project has identified 17 functioning borehole field storage systems *[12]*, some of which are shown in Table 4.1.

Location	Year	Usage	Origin of heat	Number of probes	Depth (m)	Energy injected (MWh/year)	Efficacity
Mol, Belgium	2002	Residential building	Fatal heat	144	30	130	-
Drake Landing, Okotoks, Canada	2006	Network of 52 houses	Panels solar panels	144	35	780	50%
Crailsheim Germany	2008	Heating network	Panels solar panels	80	55	1135	-
Emmaboda, Sweden	2010	Office building	Fatal heat	141	149	3800	-
Brædstrup, Denmark	2013	Heating network	Panels solar panels	48	45	400	63%

Table. 4.1. Examples of BTES in operation. Source: ***[8, 12, 31]***

Unfortunately, there is little public information on costs. To assess the investment cost for drilling only, a range of 50 to 100€ per meter drilled can be assumed. To this must be added the cost of materials for each borehole casing. These are usually U-tubes or coaxial tubes made of high density polyethylene. The Brædstrup BTES, for example, cost €260,000, of which €148,000 was for drilling. Its maximum thermal capacity is 600 kW - this implies that this installation would not fall within the legal framework of small-scale geothermal energy in France (cf. p. 14 1.4.Probe field (BTES)) ***[31]***.

As with PTES, when the stored energy comes from solar panels, the coverage rate, i.e. the proportion of thermal energy needs covered by the solar panels, can be drastically increased with borehole storage. In Crailsheim, Germany, the heating network supplies 260 flats, a school and a gymnasium, and the solar panels are installed on the roofs and on a noise barrier. The annual heat requirement is 4,100 MWh, of which more than 50% is covered by solar energy. In the Drake Landing housing estate in Canada, solar panels are installed on the roofs of garages and cover 97% of the heat requirement ***[8]***.

Some actors involved in aquifer storage are also involved in borehole storage, as some of the expertise is common to both: this is the case of If Technology, If Tech International or ICAX. Similarly, companies or research institutes qualified for pit storage also have expertise in BTES, such as Solites or PlanEnergi. The French start-up Accenta has developed a low-carbon boiler room and intelligent control software tools to efficiently manage the production, storage and restitution of heat and cold from various sources (e.g. waste heat from air conditioners and solar panels), particularly for warehouses.

Research and development

There are several research projects in France concerning borehole storage, which mainly seek to optimise the storage and de-storage of heat in the ground according to the production from different sources and the demand.

The ABC Storage project, initiated in late 2017, involves BRGM, Accenta and Mines ParisTech. A demonstrator has been built on BRGM's geothermal platform in Orléans and includes a field of 13 probes 100 m deep coupled with a solar thermal production unit, a solar photovoltaic production unit and a thermodynamic machine simulating a 3,500 m^2 tertiary building. The aim is to optimise the intelligent control of heat storage and extraction in the BTES ***[32]***.

The Sunstone project, launched in 2018, is coordinated by the National Institute of Applied Sciences (INSA) in Lyon, and involves BRGM, the engineering firm Tecsol and the Sorbonne University computer science laboratory (LIP6). It aims to develop a software tool for controlling heating networks that include solar panels and an inter-seasonal storage system in borehole fields ***[33]***.

As part of Heatstore, one of the six pilots selected concerns the storage in BTES of heat from 260 m^2 of solar panels, to cover the heating needs of Storengy's administrative premises on the Chémery site. BRGM and Storengy are involved in this project, which began in 2019 ***[12]***.

Hurdles in France

BTES systems are few in number, and commercial deployment is almost non-existent in France. The lack of information and expertise is therefore, as for most inter-seasonal thermal energy storage techniques, a major obstacle to their development in the country.

The many experiments underway could contribute to the dissemination of these techniques, whose technological maturity is already quite high, and could reach 8 or 9 following the various experiments underway on demonstrators. Indeed, even if incremental progress on storage management or on the materials used for the probes will make it possible to improve the economic and ecological performance of BTES, this technology is essentially mature and the obstacles to its deployment are not technical.

However, as with aquifer storage, the lack of integrated business models that take into account all costs, benefits and stakeholders is a major obstacle to the development of these techniques, whose investment costs are significantly higher than the initial costs of alternative systems.

From a regulatory point of view, HT-BTES can be classified as small-scale closed-loop geothermal energy if their depth does not exceed 200 m and if the maximum thermal power is less than 500 kW. As for ATES, a simple declaration is then sufficient. However, large installations exceed the capacity threshold. As with the ATES, there is considerable legal uncertainty and obtaining authorisation is a complex process.

Due to the diversity of the French subsoil, some regions are well suited to borehole storage, while others are less so (flow too great to preserve the storage, thermal capacity of the rock not adapted). Moreover, HT-BTES operate with an external thermal energy source, which makes their installation conditional on the presence of such a source (solar panels, waste heat, etc.).

Finally, to be profitable, a HT-BTES must generally be associated with a heating network. These systems are therefore particularly interesting as a replacement or supplement to a thermal energy source for an existing heat network, or for the construction of a new town quarter to be equipped with a heat network.

Cavity storage -CTES

Cavity storage is in the minority among the STES. This can be explained by the fact that it has only recently become a subject of interest (after a few early and inconclusive experiments). Today, the important potential of former oil reservoirs and flooded mines in Germany, France, the Netherlands or Finland is beginning to be developed. However, due to their regulatory complexity, such projects are generally only implemented with the involvement of the public authorities.

Concept

Examples of thermal energy storage in cavities or mines are few and far between, both in terms of the type of energy stored and the use made of the reservoir.

The first systems were implemented in Sweden. In the early 1980s, the Avesta (15,000 m3) and Lyckebo (120,000 m3) reservoirs were specially excavated to store energy from solar heating plants *[34]*. In Lyckebo, stratification was used to create a hot bubble (90 ºC) and a cold bubble (40 ºC), see Fig. 5.1. These CTESs are still in operation today, but the solar installation at Lyckebo has been replaced by wood-fired boilers *[36]*.

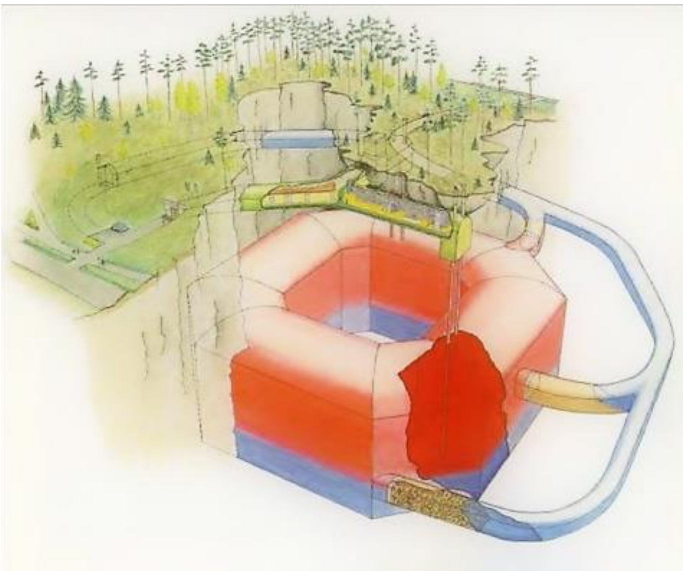

Fig. 5.1. CTES in Lyckebo (Sweden). Source: [35]

Although these demonstrators showed the possibility of such storage, the construction of a cavity specifically dedicated to thermal storage proved too costly under current conditions to be competitive with other energy sources. The use of underground reservoirs previously used to store oil was therefore proposed. In Oxelösund, Sweden, a 200,000 m3 cavity has been used to store waste heat from a steel mill. However, this storage facility is no longer in operation today. In Oulu, Finland, two reservoirs with a volume of 190,000 m3 have been converted to CTES. They store heat from a cogeneration plant as well as waste heat from a chemical industry plant [37].

Water from flooded mines was used from the 2000s onwards. In the first phase of the Mijnwater project in the city of Heerlen, the Netherlands, water was drawn from an old mine shaft at a depth of 825 m at a temperature of 35 ºC and then injected after use by a heat network into another shaft at 17 ºC and used for cooling. This system is then similar to a LT-ATES where the mine water replaces the aquifer water. In its second phase, starting in 2013, the infrastructure was transformed into a smart grid integrating, among other things, demand control, heat exchange between the different components of the grid and thermal energy production by multiple sources (cogeneration, solar energy, waste heat) [38]. This network is managed by a dedicated company, Mijnwater B.V.

Research and development

There are several CTES projects underway or under consideration in Europe. In the context of Heatstore, the use of a former coal mine in Bochum is being studied [12]. The estimated volume of 24,739 m3 would be used to store an estimated 165 MWh of energy, which corresponds to the annual heat requirement of the adjacent building of the Fraunhofer Institute for Energy and Geothermal Technology (IEG). By equipping the building with solar panels, the entire heating demand could be covered by solar energy. The partners involved are Fraunhofer IEG and Delta H Ingenieurgesellschaft.

In Helsinki, the old oil tanks in the Kruunuvuorenranta district are 50 m deep and have a volume of 300 000 m^3. They could be used to store surface seawater heated in summer. The waste heat from the buildings would be a secondary source of thermal energy. Of the 350,000 m^2 under construction in this new district, one third of the heat requirement could be covered by this CTES ***[39]***. The partners involved are Helen and Skanska.

In France, the site of the Yvon Morandat mining shaft in Gardanne, the largest mining shaft in Europe with a depth of 1,100 m, has been converted into an eco-district. A start-up incubator, hotel accommodation and some fifty SMEs are linked by a heating network. This will be fed by the 35 million cubic metres of water from the mine. An intelligent network of solar panels, photovoltaic panels and heat pumps will enable this resource to be managed in an optimal way and avoid temperature drift ***[40]***. ADEME, BRGM and Dalkia are involved in this project, which is scheduled to come on stream in winter 2020.

Finally, the Démosthene research project (Demonstrator of thermal energy storage in partially flooded underground quarries) is studying the possibility of using mines with little or no flooding in Hauts-de-France to store thermal energy. A demonstrator was built in Saint-Maximin (Oise) in 2019 ***[41]***.

Chapter VI

Outlook: storing thermal energy, a way to reduce France's emissions?

The term "inter-seasonal thermal energy storage" covers a variety of technological solutions. The thermal energy stored can be solar energy collected by solar panels, thermal photovoltaic panels, or surface seawater; it can come from industrial processes or data centres or from cogeneration; it can also be the waste heat from a building. The types of storage reservoirs are also varied: shallow or deep aquifers, rocks, underground cavities, pits filled with water and sometimes gravel. Finally, these technologies are integrated into the energy system in a variety of ways: the production or recovery of thermal energy can be decentralised or concentrated, and the distribution can be to a single building or to a heat network.

This implies that these techniques are perceived in different ways by the actors involved: they can be considered as an improved or more sustainable version of geothermal energy, as a way to increase the coverage rate of a solar panel installation, as a way to valorise waste heat throughout the year, or as a way to optimise heating and cooling installations. In all cases, it is a question of ensuring the optimal use of a thermal energy source that produces at a given moment while the demand only occurs in the following season.

At a time of energy transition, and given the importance of heat and cooling demand in energy consumption and greenhouse gas emissions, a better use of resources is desirable.

Several obstacles to the development of STES techniques in France were presented in the previous chapters. In order to accurately assess the potential of these techniques and to identify the levers that will enable these obstacles to be removed, four areas seem to require further study.

Firstly, the integration of STES into the French energy system should be addressed. Some technologies are designed to be integrated into heating networks, of which France has few: the interest in developing these networks and the possibility of renovating existing networks to integrate STES should be studied. On the other hand, recent advances in research on so-called 4th or even 5th generation heat networks, at low temperatures (40 to 80ºC) and very low temperatures (25 to 40ºC), have demonstrated their capacity to reduce heat losses due to transport and to diversify heat sources, thus constituting thermal smart grids *[42]*. In such a context, the use of STES may be more beneficial. Furthermore, the interweaving of thermal storage within the entire French energy mix offers new perspectives, particularly concerning the problem of storing electricity from intermittent sources or excess nuclear production, the potential of which will have to be assessed. Finally, the issues related to the materials needed for STES technologies (supply, transformation, recycling), central to all low-intensity energies, will have to be addressed.

The current regulatory framework will then be analysed in order to identify developments that would allow the use of the new technology for any construction or renovation with a floor area of more than 1,000 m^2. New techniques, such as LT-ATES, could be added to this list. Finally, in addition to simplification and incentives, the prohibition of certain practices could encourage the use of STES. For example, the Netherlands has initiated an ambitious transition regarding gas use, which includes the objective of disconnecting the entire residential stock from the natural gas network by 2050 ***[43]***. In particular, the Climate Agreement adopted on 28 June 2019 establishes as a general rule the disconnection of all new buildings from the natural gas grid (and for at least 75% of them during the transition period, from 1 July 2018 to 31 December 2021) ***[44]***.

Thirdly, the issue of availability and accessibility of local geo-hydrological and climatic information should be addressed. The characteristics of aquifers (depth, composition, flow velocity), underground rocks and climatic variations between summer and winter strongly influence the performance of STES, in particular ATES and BTES. Identifying and gathering useful data (or collecting them when they do not exist) and making them available in a single place, as is done for geothermal energy on the geothermies.fr website, would allow interested actors to make a rapid local pre-feasibility study, and would then boost the use of STES in the appropriate regions.

Finally, while satisfactory profitability has been demonstrated for several projects, and the potential to reduce greenhouse gas emissions has been confirmed on numerous occasions, business models adapted to STES are struggling to emerge in France. Conducting and making public detailed use case studies would provide a better understanding of the investment and operating costs, as well as the savings and emission reduction potential of such techniques. Modelling of costs and avoided emissions, taking into account the price of carbon, electricity and gas, as well as their emission factors, would allow a quantified evaluation of this potential. In addition, a mission involving investors, builders, energy producers and suppliers and consumers (individuals, companies, the State, local authorities, social landlords) could be set up to develop suitable business models. This mission could also assess the opportunity to create local heat markets, involving several suppliers (data centres, DWIP, solar heating plants, etc.) and consumers (building owners, companies, administrations, etc.) connected by a heating network.

abbreviations

ATES	Aquifer Thermal Energy Storage
BRGM	Bureau de Recherches Géologiques et Minières
BTES	Borehole Thermal Energy Storage
CTES	Cavern Thermal Energy Storage
DWIP	Domestic-waste incineration plant
IEA-DHC	International Energy Agency - District Heating and Cooling
KIC	Knowledge and Innovation Community
LT-ATES	Low-Temperature ATES
HT-ATES	High-Temperature ATES
MTES	Mine Thermal Energy Storage
PCM	Phase Change Material
PTES	Pit Thermal Energy Storage
SHP	Solar Heating Plant
STES	Seasonal Thermal Energy Storage
TCS	Thermo-Chemical Storage
TES	Thermal Energy Storage
TTES	Tank Thermal Energy Storage

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Storing heat when demand is low and using it in the following season reduces the need for heat as well as the associated greenhouse gas emissions. Cold can also be stored to cover summer cooling needs due to climate change.
Installations using the various techniques identified at different scales and depending on the environment, exist, particularly in Europe, but practically none in France. These technologies and their deployment in different countries are reviewed in this paper and the economic relevance of each is examined. This paper is the first step in the work of the Academy of Technologies to assess the potential of inter-seasonal heat storage in France from a technical, economic and regulatory point of view. This is the first time that a heat pump has been installed in France.

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