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Novel combinations of aquifer thermal energy storage with solar collectors, soil remediation and other types of geothermal energy systems.

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ABSTRACT

Aquifer Thermal Energy Storage (ATES) system make use of the groundwater to exchange energy with the building: in winter, groundwater is pumped from the warm well to the buildings heat exchanger and the building extracts heat from the groundwater as energy source for the heat pumps, while the groundwater will be injected in the cold well at lower temperature; in summer, the direction will be reversed and groundwater will be pumped out of the cold well to the heat exchanger, where the building will gather cold from the groundwater. ATES combined with solar collectors at two sites in Belgium and the Netherlands proved to allow for additional efficiencies and energy savings. Pilot sites showed promising results for combining ATES with groundwater remediation by enhanced natural attenuation for chlorinated solvents. Pilot sites were also realized in two countries with a less mature ATES market, Spain and Italy. In Spain an innovative hybrid technology between a closed loop and an open loop system has been tested, allowing ATES to be used also in water scarcity conditions. In Italy, a small scale integration with a cold low temperature district heating system has been realized. Technical and economic performances of the pilots are briefly described. The lessons learnt in the pilots provide useful insights for the replication of these solutions.

1. INTRODUCTION

In Europe, the heating and cooling sector is currently responsible for half of the annual energy consumption and relies for the 75% on natural gas (European Commission 2016). Developing a strategy to make heating and cooling more efficient and sustainable is a priority for the Energy Union (European Commission 2016).

The key challenge of increasing the share of renewables in the heating and cooling sector is attributed to the seasonal offset between thermal energy demand and supply. To tackle this seasonal mismatch, the Thermal Energy Storage (TES) solutions have been developed. Underground Thermal Energy Storage (UTES) is a characterized by high storage efficiencies and high storage capacities and is therefore the preferred choice for long-term TES (Fleuchaus et al 2018).

Aquifer Thermal Energy Storage (ATES) systems make use of an aquifer to store excess thermal energy from buildings connected to it by injecting or withdrawing groundwater (Lee 2013). The basic working principle is depicted in Figure 1. In winter, groundwater is pumped from the warm groundwater well to the building where a heat pump is used to extract the heat from the groundwater for a comfortable climate inside the building. The cooled groundwater is simultaneously injected in the cold well. In summer, the flow direction is reversed: extracting the previously stored cold water from the cold well for cooling the building (directly or through a reversible heat pump, depending on cooled groundwater temperature) and again charging the warm well for winter.

This operation creates cold and warm water wells that increase energy efficiency of space heating and cooling. ATES suitability depends mainly on subsurface characteristics as it relates to the feasibility of storing heat in aquifers which is due to physical and geological properties. Moreover, the associated buildings need to have a heating and cooling demand.

ATES systems are often applied for large buildings rather than single building or house, such as utility buildings like hospitals, shopping malls and office buildings.

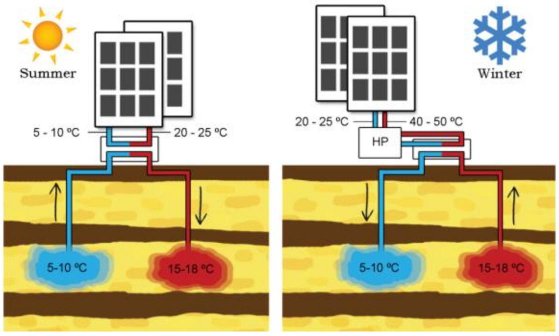

Figure 1: Illustration of the basic working principle of a low-temperature seasonal ATES system. Left: in direct cooling mode while storing heat for winter. Right: vice-versa in heating mode supported by a heat pump while storing cooling capacity for summer.

This paper is based on the results of the E-USE(aq) demonstrator project. E-USE(aq) was co-financed by EIT Climate-KIC. The paper presents an analysis of the market barriers to ATES development focused on 5 European countries and the lessons learnt from six pilot plans in Europe where different innovative combinations of ATES have been tested to tackle the identified barriers.

2. ATES MARKET

Market for ATES solutions varies considerably. ATES developments were mainly carried out in the Netherlands, while this technology is now also picked up in other countries, such as Belgium, Denmark, Germany, Sweden, the US. In the Netherlands ATES systems are a standard construction option and currently more than 2500 plants are installed (Figure 2). This results from a combination of positive factors including favourable subsurface properties, supportive policy initiatives and high commitment among market parties. Other European countries show great potential as well, based on the characterization of their subsurface. Despite this, the current level of implementation outside the Netherlands lags behind at European and worldwide level (Fleuchaus et al 2018).

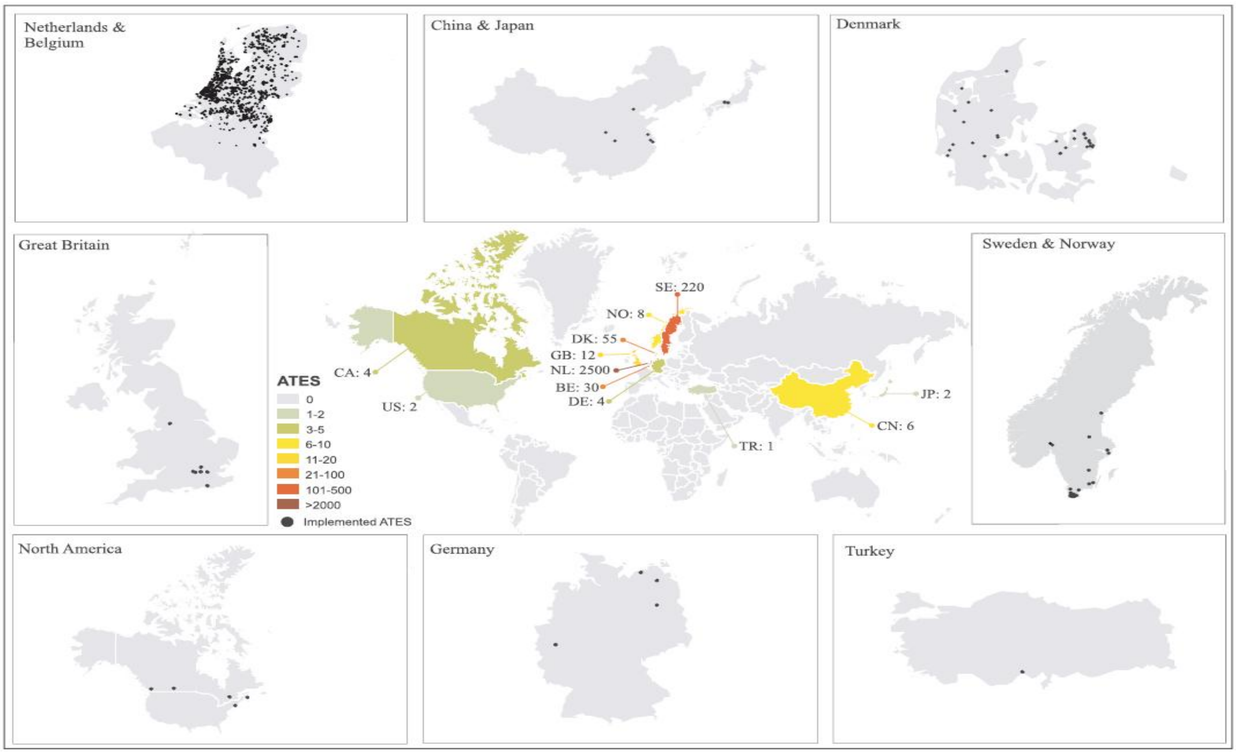

Figure 2: Worldwide distribution of ATES systems from Fleucheus et al, 2018.

The main barriers to ATES adoption in Spain, Italy, the Netherlands and Belgium were analyzed by the authors by means of a survey to selected stakeholders. Results showed that barriers can be grouped according to ATES market maturity:

1. ***General barriers***: quality levels of ATES system, legislative barriers, separation of knowledge and skills in the supply chain for ATES implementation and realization, uncertainty about ATES impact on groundwater characteristics.
2. ***Mature markets barriers***: interference between ATES systems, interference with polluted groundwater.
3. ***Novel markets barriers***: awareness, lack of knowledge, large initial investments, unfamiliarity with the underground and its characteristics.

In order to pave the way to a stronger market uptake of ATES systems, the identified barriers have been tackled by testing a combination of ATES and innovative solutions within the EIT Climate-KIC funded project E-USE(aq) – Europe wide use of sustainable energy from aquifers. level. Six pilot sites in four different countries have been designed and realized, which are described in the following section.

3 PILOT SITES DESCRPTION

The full description of pilot sites can be found in Pellegrini et al 2019. Figure 3 below summarizes the market barriers which have been addressed in the specific pilot site.

Figure 3: Overview of market barriers and solutions tested in the six pilot sites described.

Main barriers and solutions	Pilot sites					
	Nules (ES)	Bologna (IT)	Ham (B)	Delft (NL)	Utrecht (NL)	Birkerod (DK)
1. Legislative barriers	X	X			X	X
2. Familiarity	X	X	X	X	X	X
3. Optimize energy balance with district heating		X				
4. Optimize energy balance and sustainable use of ATES: integration of PVT with ATES			X	X		
5. Contaminted sites: ATES and bioremediation					X	X

3.1 Dynamic Closed Loop (DCL®) probe for ATES in water stressed conditions

In most regions of Spain groundwater pumped to the surface is treated as industrial wastewater, which then complicates permitting procedures. In order to overcome this barrier, a technological solution has been developed. The DCL® probe (Figure 4) is a hybrid solution between a closed loop and an open loop system, coupling the advantages of both. In fact, groundwater is not extracted from the ground (as in an open loop system), but the heat exchange is increased if compared with closed loop system because the groundwater flows along the closed loop tube and heat exchanger.

This system does not require an additional borehole for groundwater reinjection, since the water only flows between two different layers of the same well. The standard DCL probe system consists of a borehole and a probe with 25 kW heat exchange power, and a flow rate of 3-4 l/s. The solution is considered a closed loop system and therefore the authorization process in Spain can last only up to 3 weeks.

A geothermal heat pump system with four DCL® probes has been installed in Nules (Spain) to maintain the water temperature of a municipal swimming pool at 28°C. The Spanish pilot plant is in operation since the end of 2016.

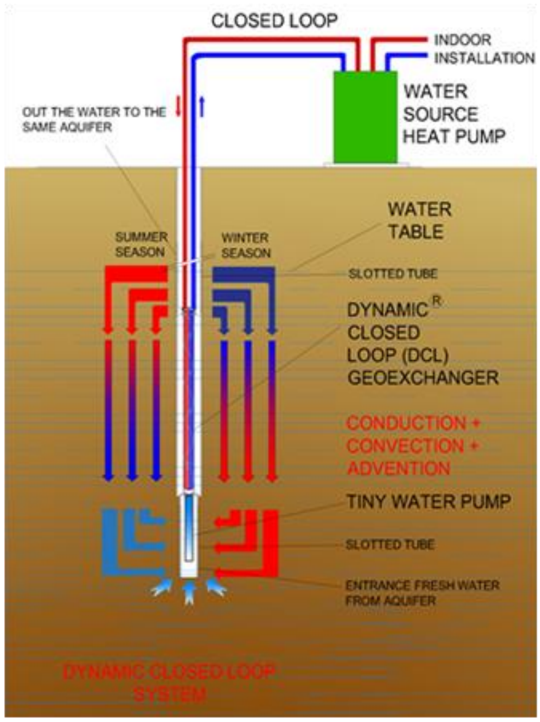

Figure 4: Scheme of the DCL® probe system tested in the Spanish pilot site.

The DCL® probes working data have been registered on a weekly basis: in particular, the temperature and water depth variations in the groundwater have been monitored in three piezometers around the DCL® probes and in a fourth piezometer placed at a certain distance from the DCL® probes, in the thermal plume direction (Figure 5).

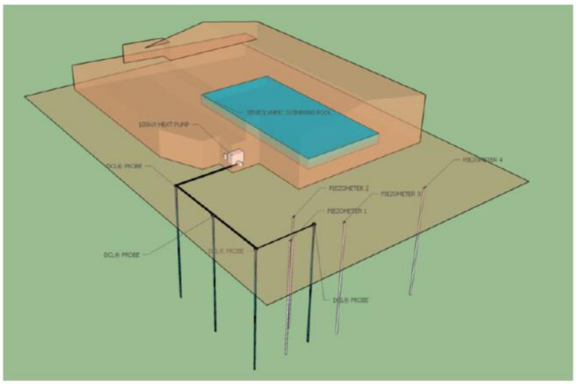

Figure 5: Scheme showing the wells positioning at the public swimming pool in Nules, in black: DCL probes, in red: monitoring wells.

3.2 ATES in combination with cold low temperature district heating

In Bologna, a small scale cold low temperature district heating (LTDH) system is tested. In general, a LTDH network has the ability i) to supply low temperature district heating to space heating and hot water preparation, ii) to distribute heat with low grid losses, iii) to recycle heat from low temperature sources, iv) to integrate thermal grids into a smart energy system, and v) to ensure suitable planning, cost, and motivation structures. In particular, by introducing some additional decentralized heat supply, a cold LTDH can be realized, which is a hybrid system that can use a lower supply temperature in the distribution network. This lower temperature is sometimes called an intermediate temperature, since it is lower than the actual customer temperature demand. The heat supply is then guaranteed by using local temperature boosters, such as boilers or heat pumps.

The Italian pilot plant in Bologna, located at Terna electric distribution station of Martignone has 3 extraction and 3 injection wells (Figure 6) able to cover a space heating peak demand of 160 kW and also a space cooling peak demand of 140 kW with an overall mean groundwater extraction rate of 3.5 l/s. Four monitoring wells have been installed to verify the impact on the plant during operation and evaluate further arrangements to improve ATES efficiency. The ATES system in Terna is a recirculation system. Paramount information for a correct design of the system were the buildings energy audit and the knowledge of subsurface system properties by tracer tests, pumping tests and chemical-physical analysis. Depending on the season, the extracted groundwater is heated up or cooled down by a heat exchange through a secondary circuit, being the primary one the groundwater extraction-injection wells pipeline. The secondary circuit feeds the heat pumps/chillers, which are placed in two substations that are connected to the buildings served by the pilot plant. The peculiarity of the pilot plant is that some rooms need space cooling all over the year, and so they are fed with cold water by a dedicated chiller. A similar approach can be also used at a larger scale to integrate e.g. waste heat or waste cold streams. The pilot plant at Terna will be operational in the summer of 2019.

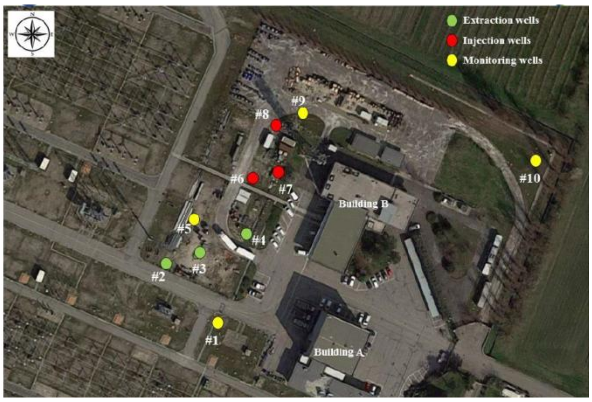

Figure 6: Wells positioning in Bologna pilot site.

3.3 Energy optimization between different ATES buildings and integration with PVT panels

Seasonal storage can overcome the temporal mismatch between availability of solar heat and the demand for heat. ATES storage can also allow heating and cooling demands to be offset on an annual basis, through use of a warm and a cold well. However, in buildings and climates where heating demand is larger than cooling demand (e.g. Northern Europe), a supplementary source of heating is usually required to achieve this annual balance. Solar thermal collectors can sustainably provide the extra required heating capacity. In addition, this solar heat usually can be stored at higher temperatures compared to the temperature produced by space cooling from the cold well, thus further increasing the energy efficiency in heating mode. Hybrid PVT panels like Virtu® give an extra added value to ATES system since PVT panels produce simultaneously solar heat and power: so, the electrical power required to run the ATES system heat pump is also generated from a sustainable source, reducing the reliance on the power grid, and moving further towards a carbon neutral system. This can be managed by a combination with solar thermal collectors as shown in the Belgian pilot and the Dutch pilot in Delft.

In the pilot site in Belgium, installed in a newly built logistic center, it is shown that solar panels can be used to store additional heat as well as cold. The ATES system in this pilot consists of 2 groundwater wells screened between 80 m bgl and 160 m bgl for the extraction and infiltration of the groundwater. Besides the 2 production wells, 2 measuring wells with level ducts have been drilled in the field, in order to confirm to the permit requirements. The monitoring wells installed in the same borehole as the warm and cold well and the stand-alone monitoring wells were then equipped with fiber optic cables to monitor the evolution of subsurface temperatures. The ATES system is connected with 35 PVT-panels placed on the roof of the office building, accounting 18,2kW of peak power production. In the pilot these panels can be used in 3 different ways: 1. Generate domestic hot water; 2. Charge the ATES with solar heat to restore ATES thermal balance; 3. Charge the ATES with extra cooling capacity (in winter time) to restore ATES thermal balance. The pilot has been operational since 2016.

In Delft pilot site, the ATES system is used as heat exchanger between two existing buildings, one already connected to the ATES system presenting a heat surplus and another one with a very large heat demand. A novel hybrid solar collector, Virtu® (Figure 7), which features a vacuum tube to enable higher thermal efficiency in cool climates, is installed in the pilot site. The surplus of heat from one building and the solar heat from 120 Virtu® PVT panels can be stored in the ATES system and transferred to the other building which decreases the overall energy use and enlarges the available cooling capacity during summer. The installed Virtu® PVT tubes account for a projected heat output of 25 MWh/year, combined with the annual heat surplus of 50 MWh/year from one of the buildings. PVT panels installation has been finalized in August 2018.

Figure 7: Installed Virtu® PVT panels at Delft pilot site.

3.4 Combining ATES with (bio)remediation

Most often ATES systems are located in urban areas, which are frequently affected by groundwater contamination. In particular, chlorinated solvents are often observed as contaminants in urban areas (see Figure 8 for the situation in The Netherlands).

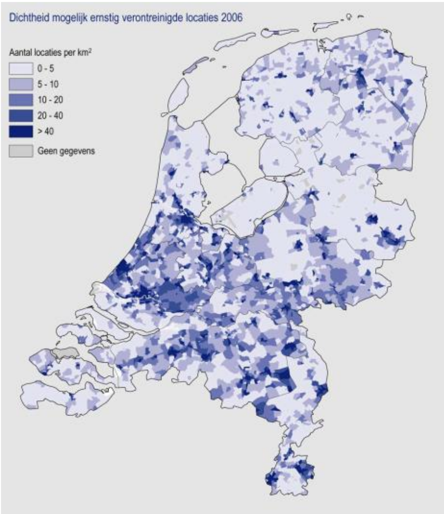

Figure 8: Location of 400.000 serious contaminated sites in The Netherlands (MNP, 2007).

At two different sites, the combination of ATES and bioremediation of groundwater aims at the acceleration of biodegradation of contaminants like volatile organic compounds (VOC). Especially the elevated temperature of 17°C in the warm well plays an important role in the acceleration of biodegradation, as at higher temperatures microorganisms show higher microbial activities. Laboratory research showed that optimization of other parameters like i) right redox condition and ii) presence of bacteria that can perform reductive dechlorination are relevant boundary conditions to reach higher biodegradation rates. In laboratory studies itwas shown that the combination of ATES and bioremediation of chlorinated solvents leads to a N10-fold increase of the biodegradation rate compared to natural attenuation (Ni et al 2015).

The first ATES system in contaminated groundwater was operated at Strijp S, Eindhoven, The Netherlands (Slenders et al. 2010). This system was a recirculation system in which the groundwater pumping regime was designed to avoid the groundwater to move away from the original position and no specific increase of the temperature of the groundwater was aimed at.

In the Welgelegen pilot in Utrecht (The Netherlands) a monowell ATES systems functioned already for several years in a slightly contaminated groundwater. The aim of the Utrecht pilot study was to stimulate bioremediation at the ATES system by bioaugmentation. In 2017, the ATES system was expanded with an injection well and monitoring wells that aimed at the acceleration of the biodegradation. Since then the system is a real ATES and bioremediation system.

The second ATES and bioremediation system is located at the site Hammerbakken, near Copenhagen (Denmark). This site has been chosen by the Capital Region of Denmark for a proof of concept of the ATES and Bioremediation concept at a high concentration of VOC.

4. RESULTS

4.1 ATES and DCL probe

The plant installed in Nules has been operational since the end of 2016 and full monitoring has been performed since November 2017 including both groundwater temperature as well as chemical characteristics, together with energy consumption data.

Monitoring data from the groundwater wells showed a slight improvement of the groundwater quality. The implementation of the DCL system has reduced sulphate, nitrate and chloride concentrations, which are commonly high in the aquifer where the system is installed.

The energy use is compared to the Heating degree days (HDD) that have occurred during these years, HHD are a measure for the heating demand, depends on outside air temperature. As for the energy performance, the heating demand in 2017 and 2018 was about 60% higher compared to 2016, however, despite the 28% larger heating demand, in 2017 the gas consumption was 53% lower, compared to 2016. In 2017 and 2018 the heating demand was about the same (2% difference), but as a result of improved control of the DCL system, the savings went even further down by 37%.

4.2 Ates and bioremediation

In Danemark, at the Birkerod site in Copenhagen, the pilot was realized at the end of December 2017 and monitored thereafter in 2018. The ATES recirculation systems showed to operate as expected, whereas biodegradation was not stimulated in the first 6 months, as the redox was too toxic to allow biodegradation of chlorinated solvents. In December 2017 the pilot was built based upon a recirculation system at relatively high temperature (20°C).

In June 2018, electron donor was added at the site to lower the redox conditions. After July reductive dechlorination was monitored up to a rate of 30%. However only DCE was formed and no significant other products as VC and finally ethene were formed. In early November a Dehalococcoide (DHC) bacteria culture was added, which readily resulted in a high dechlorination degree of already about 78% in monitoring well 1 within 2 weeks. The ATES system as such functioned well without clogging by the presence of measurable oxygen concentrations in the first half year of operation.

In Utrecht, the Netherlands, a concentrated culture of DHC bacteria was injected in the warm layer of the Nieuw Welgelegen ATES system to stimulate the reductive dechlorination of chlorinated ethenes that are currently contaminating the first aquifer in this area. The pilot study is complex and involved numerous analyses, tracer tests and implementation of novel techniques (such as bioaugmentation and soil mesocosm analysis). Even if further monitoring is required, the results are promising and suggest reductive dechlorination of vinylchloride is occurring from multiple line of evidence (favorable redox conditions, decreasing VC concentrations at the bioaugmentation injection; increasing ethylene concentrations). The bioaugmentation process did not cause well clogging, nor did it hamper the operation of the ATES system.

4.3 ATES and energy balance with PVT panels - Ham site

In the first operational year, the temperature difference over the ATES system was different in winter compared to the summer because of the ‘unloaded’ start of the installation. The second year, the installation starts with loaded wells because of the previous operational season and its energy demand. This justifies the balance in temperature difference in the second operation year between heating and cooling season. The higher energy demand for both heating and cooling is also represented in a higher water displacement, indicated by the top of the green line, which is higher than the first operational year.

A first analysis consists of the comparison between the Key Performance Indicators (KPIs) put forward in design and realized during the first and second year of operation. The first year of operation shows a higher cooling demand than estimated, while the heating demand covered by the ATES was 10% lower. The second year of operation, the cooling demand was even 48% higher than assumed during design, while the heating demand was slightly higher (9%) than estimated.

Based on the monitoring data, a seasonal performance factor for heating with the heat pump of just under 4 can be calculated (electricity use of ATES pumps included). The cooling delivered to the building consists of direct cold of the ATES in free chilling combined with mechanical cooling from the heat pump. Hence a combined seasonal performance factor for the complete cooling production was calculated (electricity use of ATES pumps included). An SPF of 6,03 was found (Figure 9).

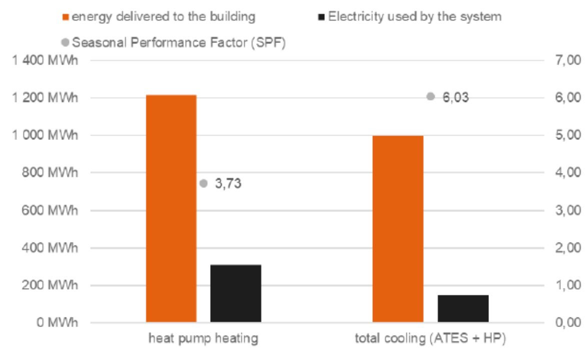

Figure 9: Actual system efficiency in terms of energy and seasonal performance factor of the Ham pilot site for the heat pump heating and total cooling production.

Even if the total cooling efficiency is quite high and rather impossible to obtain with other technologies that use active cooling, it is yet it is lower than the anticipated SPF. This deviation is due to the fact that during the second year of operation up to 55% of the cooling demand was covered by active cooling with the heat pump. This high amount of active cooling can be partly explained by the extremely warm weather in 2018, but can be significantly reduced by optimizing the set points of used in the HVAC controls (control of warm water and chilled water temperatures). If the hourly cooling demand is compared with the actual ATES cooling capacity at every moment in the cooling season, a free chilling potential of 83% of the demand is found. If this potential would be fully used a Season Performance Factor of 14,91 would be possible for the total cooling efficiency.

The economic evaluation of the business case showed that after only 3 years break even will be reached, leading to an internal rate of return (IRR) of 35,0%. The net present value of the investment is as high as 347.780,0 EUR.

Delft site

The Delft ATES pilot has focused on addressing the key challenge of improving energy matching over multiple seasons through the addition of renewable heat source and heat sharing between buildings. The economic benefits of an ATES system can only be analysed when an annual cycle is created.
This balance can be partly achieved on a site-wide basis by balancing the heating and cooling demands of different buildings, as shown in this case with the Tetra and ZZH buildings, i.e. where one building has a higher cooling demand and the other a higher heating demand. This is a key learning for future ATES projects, that it is beneficial to include within a project multiple buildings with differing energy requirements, which thereby leverage the benefit of inter-seasonal

storage while maintaining long term storage temperature balance.

5. CONCLUSIONS

First results from the pilot sites show that the implemented technological solutions generated benefits from techno-economic and environmental perspectives (e.g. solar energy harvesting in Belgium and The Netherlands and heating delivered to the swimming pool with ATES in Spain without groundwater withdrawal). It is demonstrated that ATES systems can be applied under strongly varying conditions in different European countries and through different innovative technological solutions. To further strengthen these results, continued investigations and long term monitoring and evaluation of projects is needed, also including an economic perspective. This study was carried out within a limited number of countries; although both our literature review and pilot results show many similarities among barriers across the world, specific solutions may not be appropriate or feasible in some countries.

For Europe-wide adoption of ATES, much more attention to the technology still has to be attracted from the investors side and from the potential site owners. In dense urban settings, ATES demand for subsurface space may exceed the available space in the local aquifer. Mutual interaction between systems is a potential thread to optimal and sustainable use of the aquifer. With the latest insights in planning of well locations and operation, mutual interaction does not have to have a negative effect; it can also work positively on energy output, when properly managed.

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