SOIL ENERGY AS SMART LOW CARBON TECHNOLOGY FOR COST-EFFECTIVE CLIMATE MITIGATION

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1. Introduction

Our soils can provide sustainable energy. Aquifer Thermal Energy Storage (ATES) is a smart way to re-use heat and cold in buildings and it is widely recognized as promising technology for sustainable energy. Global demand for heating and cooling in the built environment accounts for about 40% of total primary energy consumption. ATES is a simple way of meeting that demand by using the soil. The Climate-KIC project 'Europe-wide Use of Sustainable Energy from aquifers' – E-USE(aq) – demonstrated how ATES systems can be implemented in several countries. It included six pilot projects in five countries that will generate a flywheel effect for the introduction of ATES systems throughout Europe.

2. How does ATES work?

See figure 1:

- Cooling buildings with a climate control system (air conditioning) produces heat that can be stored (using a heat exchanger) in an aquifer instead of being released to the atmosphere as with conventional air-conditioning systems; the soil isolates the stored energy like a thermos flask.
- The heated groundwater can be used in the winter to heat buildings. The water cools down as it releases

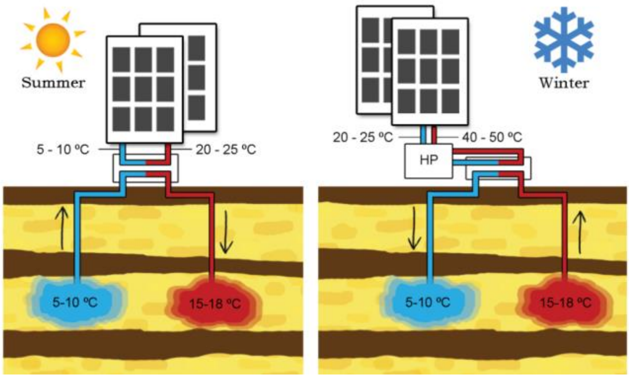


Figure 1: Use of soil energy by ATES; © KWR, Martin Bloemendal

heat.

- The resulting cold is stored separately in the winter so that it can be used effectively again in the summer, and so on.
- The system involves the creation of both a warm and a cold groundwater reservoir, enhancing efficiency.

See for more information: https://www.deltares.nl/en/projects/europe-wide-use-soil-energy-ates/

3. Identification of barriers and opportunities for ATES in Europe

Why is aquifer thermal energy storage not widely applied in Europe, yet? The Climate-KIC project Europe-wide Use of Energy from aquifers - E-Use(aq) - identified three types of barriers: general barriers for all countries and specific barriers for countries with an immature and mature market. In the E-Use(aq) project it is also found that all barriers can be overcome and sometimes can even be turned around to opportunities.

General barriers and solutions for all countries:

1. Knowledge and skills are commonly divided between consulting, contracting and operation and maintenance companies. Especially, there is often an insufficient integration of underground system knowledge (like the wells) and the installation above ground (such as the heat pump). While this asks for different experts, users possess inadequate operational knowledge. E-Use(aq) showed that knowledge and skills can be integrated by good team work; see § 4.1. Continuing involvement of ATES providers during operation is important, especially for ignorant users.
2. Uncertainties originating from unfamiliarity with the underground and its characteristics. However, with proper subsurface site investigations and sufficient groundwater monitoring, adequate predictability is possible; see § 4.2.
3. Disappointing quality levels and limited robustness of the installation can be the consequence when unqualified companies design, install and/or operate ATES systems. Inadequate designs and insufficient operational management will then lead to unsatisfactory performance and a negative reputation. Within E-Use(aq) experienced Dutch partners cooperated with competent partners in other countries to show that ATES technology is not in its infancy anymore and that it can be a reliable source of sustainable energy; see § 4.1.

Barriers and solutions for countries with an immature market:

1. Because of lack of knowledge and experience, general public, property developers, building and utility companies as well as governments are unfamiliar with soil energy. E-Use(aq) improved knowledge and public awareness by events and publications; see § 4.1.
2. As a result of the unfamiliarity with the technology, there is a lack of adequate regulations. Instead of guidelines to hold on to, often long and uncertain permit procedures have to be faced. E-use(aq) assisted inexperienced authorities to facilitate ATES; see § 4.3.
3. People presume relatively large initial investments with uncertainty about the savings during operation. However, in the Netherlands a pay-back time of on average 7 years is realized; often significantly lower especially when also cooling capacity is needed, sometimes somewhat higher when mainly heat is required. Some of the pilots in the E-Use(aq) project realized lower pay-back times; see § 4.4. Increased efficiencies can be achieved by energy balance optimizations, see § 4.5 and § 4.6.

Barriers and solutions for countries with a developed market:

1. 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. See § 4.7.

2. Interaction with polluted groundwater is likely in urban areas. Improper design and operation may lead to contaminant spreading and/or migration. But an integrated ATES-remediation approach with for instance optimization of redox conditions and increased temperatures enhancing biodegradation can accomplish groundwater remediation. See § 4.8.
3. A negative impact on groundwater quality is often feared. Such fear is not necessary, when quality standards are met (see § 4.1) but sustainable use and sufficient monitoring (see § 4.2) are important to allow local authorities to issue a permit, together with energy balance as a permit prescription.

In the next section it is described in more detail how specific barriers were tackled in the project and how these can be turned into opportunities. The resulting expected climate impact is described in the final section.

Preliminary results were published in Science of the Total Environment: Low carbon heating and cooling by combining various technologies with Aquifer Thermal Energy Storage (Pellegrini et al, 2019); see https://www.sciencedirect.com/science/article/pii/S0048969719301524.

4. Results from barrier analysis and pilot plants

4.1. Improving knowledge, quality and public awareness

In order to draw European attention to ATES, E-Use(aq) started pilots in several European countries, that show how to overcome barriers: two in the Netherlands, with a developed market, one in Belgium with a growing market, and three in the immature markets of Spain, Italy and Denmark. In the Netherlands a lot of knowledge and experience is already acquired. Also, a legally enforced certification scheme is valid since 2014 for all companies working on ATES design, building and operation. By cooperation of Dutch and foreign partners in the realization of the pilots, knowledge and experience was successfully transferred. A wide range of ATES applications was included in the pilot selection: besides basically classical ATES with doublets of cold and warm wells, in the Netherlands (Delft), Belgium and Denmark, also a monowell system was demonstrated in the Netherlands (Utrecht) as well as a system with underground heat exchange in Spain, while in Italy a recirculation system (without actual storage) was installed. With public events and publications about the pilots and the overall projects, a wider public, with especially potential applicants of the technology, was informed, for instance municipalities in Belgium (see figure 2). Operations of all pilots are supposed to continue, so that permanent showcases stay available as central points for further proliferation of the technology.

Figure 2: Belgian public event with site visit of pilot ATES system in Ham; © Deltares, Nanne Hoekstra

4.2. Underground characterization and monitoring

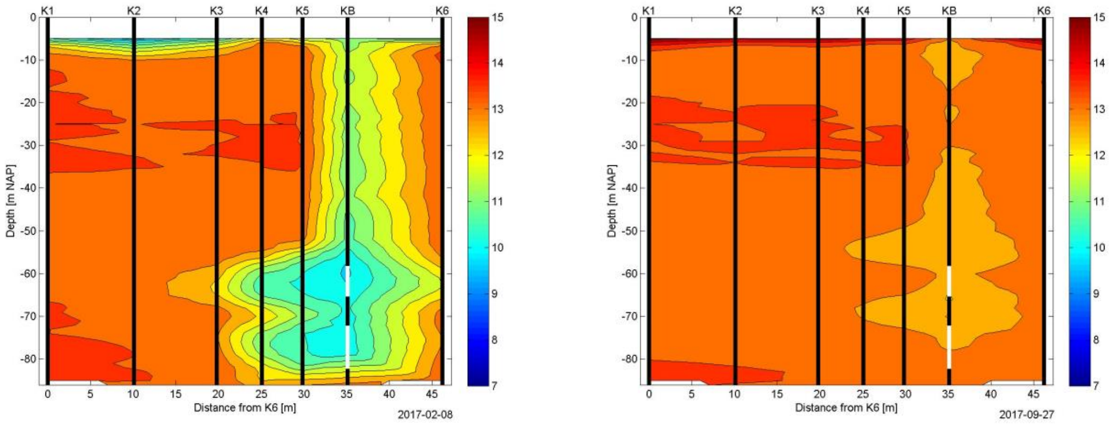
In the Netherlands, nation-wide information about underground characteristics is readily available. However, this is information on a regional basis, which is not always detailed enough for applications of local groundwater use like ATES systems. For this, a detailed soil stratification investigation – when not available already for the local situation – is highly recommended, especially to avoid mixing of groundwater from different layers with varying geochemical characteristics, which can cause clogging problems. This was done for all pilots. In order to reduce costs, the boreholes for the soil stratification investigation can be combined with placement of necessary wells, either for groundwater extraction or infiltration or for monitoring.

For the pilot in Ham (Belgium) soil stratification was assessed carefully during placement of the wells. It turned out that the separating layer underneath the aquifer was located much deeper than expected. So, during the drilling it was decided to install much longer screens then originally designed. This increases the capacity of the system considerably. The additional drilling costs are in this case small compared to the advantage of higher groundwater flows and consequently more energy yield.

Figure 3: At the Belgian site, continuous temperature measurements (on the left a picture of an ATES manhole, with an orange glass fiber on the right-hand corner) were combined with periodic elaborative geochemical assessments (on the right a picture of field equipment in operation); © Deltares, Nanne Hoekstra & André Cinjee

Compared to the Belgian pilot, the water bearing layers at the pilot sites in Nules (Spain) and Italy (Bologna) are very thin. So, well screens were positioned extremely carefully, based on a detailed soil stratification characterization. In Birkerød (Denmark) it was especially important to characterize the geochemical conditions, because of the partly unsaturated conditions of the aquifer, which was a challenge for both the ATES application and the remediation (see § 4.8).

Based on the soil data, model calculations provide the necessary information about energy yield and use of space. However, available data are usually not accurate enough to tackle soil heterogeneity. Depending on the scale of the heterogeneity and the coincidence of functions in the often crowded underground of cities, additional information can be gathered by high resolution temperature distribution measurements, using fiber optics. This technology was demonstrated in the pilots in Delft and Utrecht (Netherlands) and Ham (Belgium); see example in figures 3 and 4.



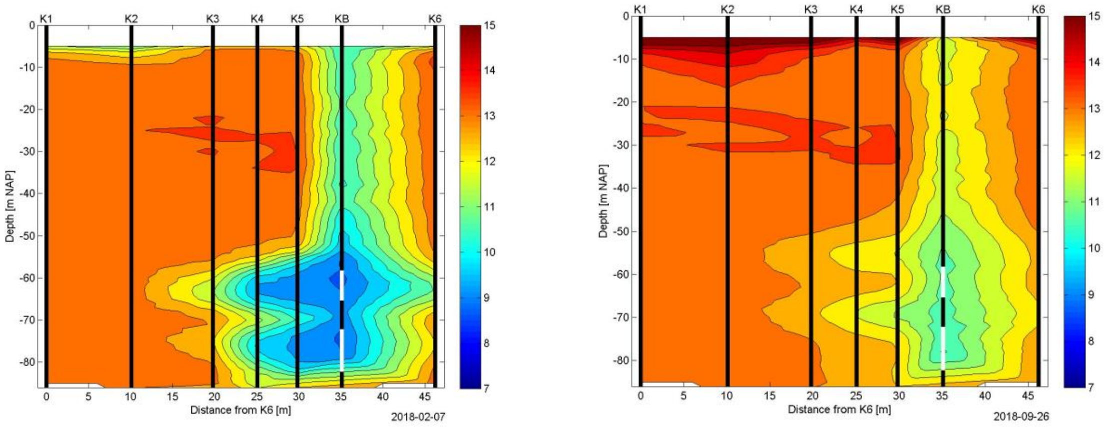


Figure 4: Results of high-resolution temperature distribution measurements in Delft pilot site underground; © Deltares, Pieter Doornenbal

In the Belgian case, also groundwater quality was elaborately checked before starting up the ATES system and after a few years of operations. In the relatively pristine aquifer at the site, no negative effects of ATES system operations itself on quality groundwater were observed.

4.3. Tackling legislative barriers

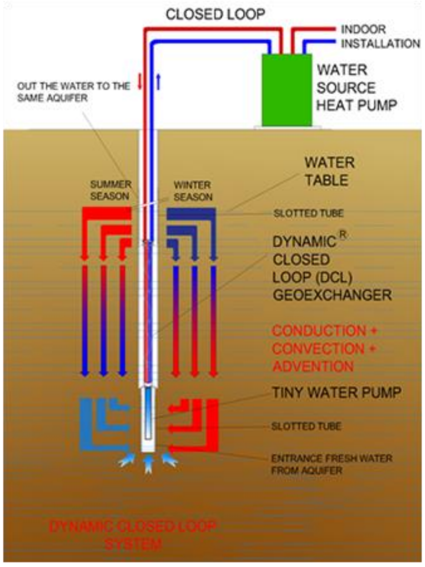


Figure 5: Schematics of DCL® system, © Itecon; José Salido

In the preceding project it appeared that in Germany influence outside premises is legally problematical. This was an important reason that a pilot was not realized in Germany. So, changes in German legislation seem to be inevitable for the proliferation of ATES. However, in Spain a technical solution was applied to counteract a legal prohibition of infiltration. Since a return stream is considered to be waste water, also Spanish legislation makes application of ATES virtually impossible. The practical solution found involved the application of the Dynamic Closed Loop system (DCL®), a system that combines the advantages of a closed loop soil energy system and open ATES; see figure 5). Since groundwater stays underground, requirements that oppose ATES are circumvented. The municipality of Nules that was actively involved in the project is very enthusiastic about the results and is already initiating the installation of more comparable systems. Also, other local authorities in the region that were informed (see § 4.1) are interested in the system and have made installation plans, in spite of the opposing legislation.

In Italy, consortium partners faced a lot of bureaucracy, because of doubts about aspects of the new technology at the departments of the Emilia-Romagna regional authorities. But by frequent contacts between consortium partners and regional officials during the preparation of the pilot – soil investigations and system design optimizations were executed by mutual agreement – a lot of information has been shared and consequently confidence was gained. At the event that was organised on site, public servants informed the project team that permission procedures for new systems can now be dealt with much faster.

In Belgium, legislative barriers hardly played a role, just as in the Netherlands, where standardized procedures haven been developed. However, for the Delft site temperature restrictions on infiltration water can become relevant in the future but usually they can be lifted for pilots. Regulations against contaminant migration are relevant for the Utrecht site, but the local authority, that is also responsible for groundwater contamination is involved in the pilot. In Denmark, the situation is comparable with the Utrecht site since the Capital Region of Denmark is involved in the project as initiator.

4.4. Analysis of business cases

In the Netherlands a typical pay-back time for ATES systems is about 7 years, although the differences can be big due to local conditions. When the main driver for installation is cooling capacity, lower pay-back times are possible. Comparable pay-back times seem attainable in other countries. In the Italian pilot, pay-back time is somewhat longer because of the necessary pioneering activities (soil investigations, design adaptations, difficult permit procedures) but with help of the already acquired information, new systems can be installed much cheaper in this region. The Spanish DCL® system is very cost-effective, with a pay-back time of only about 3 years. Also, in Belgium such a short pay-back time was realized, but partly because the owner negotiated quite low prices for electricity. With a more common electricity prize level, pay-back time would be about 5 years. That is still quite low because of the very thick aquifer that made long well screens possible and consequently large groundwater flow volumes with high energy production. The pay-back time for the addition of Virtu® PVT panels (see § 4.5) is now with 8 years somewhat higher as the average pay-back time for the ATES system itself but is expected to go down when PVT production volumes increase. Additional costs for dealing with contaminants (see § 4.8) have to be compared with separate remediation costs. Calculations proved that the integration of ATES and bioremediation (ATES+) applied in Utrecht is significantly more inexpensive than all other remediation options. Compared to cleaning of the soil before start of ATES operation, the combination system is even about a factor 4 cheaper.

4.5. Energy balance optimization by integration with PV/T

For optimal functioning of ATES systems an equal need for heat and cold on an annual basis is necessary. Of course, a precise balance is hard to obtain, even in Western and Central Europe, where the heating capacity needed in winter is roughly comparable to the cooling capacity needed in summer. In Northern Europe heating demand exceeds cooling demand and in Southern Europe, it is the other way around. In the Delft and Ham pilots therefore, energy balance optimization by a combination with cooled solar panels is demonstrated. This provides several additional advantages. With photovoltaic (PV) cells, as implemented in Ham, electricity needed for the water and heat pumps, is provided in a sustainable way. Preventing temperature increase of PV-cells due to solar radiation increases electricity production yield significantly. This can be done by cooling them (PV/T). The energy from the cooling-water is subsequently stored in the soil. Electricity used by heat pumps can be reduced when captured solar heat makes higher temperature heat storage possible. The solar panels are also suitable to harvest cold. The Delft pilot is used for the development of yet another combination: ATES and PV-cells integrated with solar heat collectors, Virtu® see figure 6, in order to harvest and store more solar heat than conventional PV/T-cells. In the Delft case, the existing ATES system produced too much heat, while the cold stored was already depleted before the end of the cooling season. By enlarging soil energy application aboveground, encompassing another building with a large heating demand, and adding additional heat to the underground by Virtu, a much more robust system is created. Using the additional heat capacity enables the production of more cooling capacity, by creation of a larger cold-water reservoir, so that a better energy balance is within reach.

Figure 6: Virtu® PV/T-panels connected to the ATES system serving the office building in the rear; © Naked Energy, Christophe Williams

4.6. Energy balance optimization by integration with district heating

ATES is attractive because it makes in a quite simple manner possible that surplus heat in summer seasons can be used in winter seasons, while surplus cold in winter season is used in summer, with minimal losses of energy. Also, differences in supply and demand of thermal energy on smaller time scales can be met, for instance within 24 hours, when days are warm, and nights are cold. But apart from temporal differences in supply and demand of heating and cooling, there are also spatial differences that could be overcome by a smart energy grid, e.g. when factories produce heat while nearby houses need heating. Such symbiotic cooperation's between providers and users of thermal energy can be incorporated quite easily when district heating systems are already operational. Of course, this provides cooperation of several parties, but they will find each other when governments provide incentives to reduce CO_2 emissions, like a price on emitted CO_2. Such a smart grid is also compatible with ATES: heating and cooling demands at different places are met in the first place and only surpluses and shortages of thermal energy are counterbalanced by infiltration and extraction from the soil.

On a small scale, the use of a heating grid is demonstrated in some pilots. In Ham, with intelligent computer programming, heating and cooling demands are first met between rooms as much as possible and only what is left is provided by or stored in the groundwater. In Bologna, some rooms with computers always need cooling, which provides year-round heat for other rooms, so only additional heat, or even more cold, is provided by the recirculation system (see figure 7). In Delft, the surplus heat, produced by an office building, that was until recently stored in the underground can now be used since a connection with a large experimental hall was made.

Figure 7: Visit at the Bologna site as part of the Italian public event with an ATES manhole in front and one of the buildings included in the district heating system test in rear; © WUR, Tim Grotenhuis

4.7. Dealing with mutual interaction between ATES systems

In areas with a lot of systems close to each other, interference between wells is imminent. When cold water enters warm well reservoirs, efficiency can drop considerably. Because of the inaccuracy of modelling outcomes, authorities often choose for certainty in avoiding interference when giving out permits. Consequently, a lot of underground space is not used.

But, when parties cooperate, possibly lead by a coordinating (municipal) agency, interference can also enhance efficiency by smart spatial planning, for instancing creating warm and cold lanes. To accomplish this, it is very important to have a good knowledge of the thermal plume around the wells, which differ in practice from model calculations. For this, high resolution temperature measurements can be helpful. Because of the cautious choices of authorities nowadays, a lot of additional underground space can be used, so that makes that these comparatively expensive fibre optic measurements become cost-effective in crowded areas.

In the pilots in Delft, Utrecht and Ham on a small scale the thermal plumes of the system wells were made visible. In the cases of Delft and Ham no interaction between the wells of the system was observed, but in the monowell system in Utrecht some of the warm water in the upper layer seems to enter the cold thermal plume below, which indicates negative interaction with a - small - drop in efficiency within the system. This demonstrates how monitoring of underground thermal plume development can contribute on a larger scale to multi-ATES system planning and operation.

4.8. ATES enables redevelopment of contaminated sites

Based on geochemical data from the extensive monitoring well network present in the Dutch city of Utrecht, it was concluded that the mere presence of numerous ATES systems did not lead to provable significant degradation of contaminants. Expected positive effects from mixing of reactants and heating of the groundwater by ATES could not be determined, most likely because of lack of optimal geo-biochemical conditions, e.g. suboptimal redox conditions, low organic matter concentrations and consequently small numbers of the proper micro-organisms. On the Utrecht pilot site, these micro-organisms were introduced into the soil, close to the ATES system according to the innovative ATES+ concept; see figure 8.

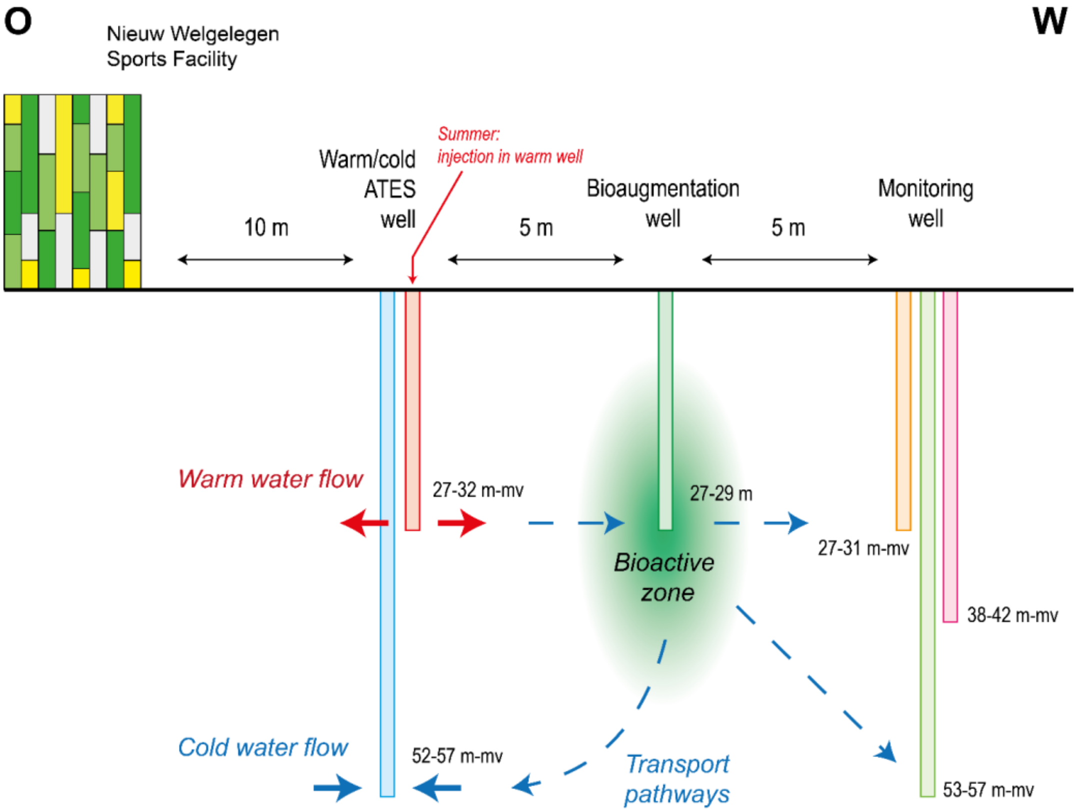


Figure 8: Schematics of Utrecht pilot; © Deltares, Gemma Spaak

Micro-organisms travelled through the ATES well screens without noticeable effect on system operations. A reactive zone was created in which degradations was enhanced considerably. Degradation continued for at least about a year, so repetitions of bacterial injections can be relatively limited and therefore it can be concluded that a cost-effective combination of ATES with groundwater remediation is possible. Lessons learned from the Utrecht pilot were immediately applied in the Danish pilot, with a more challenging contaminant situation and redox conditions far from optimal. For the necessary degradation process of reductive dechlorination, low redox conditions had to be enforced. Taking away oxygen also helps avoiding clogging problems in the ATES well screens by iron precipitation but at the same time forming of Sulphur precipitates has to be avoided. Redox conditions were successfully optimized and now degradation progress is being monitored.

5. Europe-wide Climate Impact from ATES

5.1. Future prospects for ATES market

The results of the pilot sites indicate that wider utilization of ATES in Europe is possible, compared to results of the inventory that was made in the preceding E-Use(aq) Pathfinder project. Especially the success of the specific DCL® system implemented in Spain, will enlarge the ATES market because even thin aquifers in water-stressed regions have proven to be suitable for this type of ATES technology. Furthermore, energy balance optimization measures will facilitate ATES in cases with differences in heating and cooling demand. This is important in Southern and Northern Europe, where the climate causes varying demands, but just as well in the rest of Europe, dependent on the types of buildings. Besides the solutions tested in this project, other measures are possible, like combinations with use of energy from surface water. The market can, with proper site characterization and monitoring measures, also be enlarged by denser ATES well setting that are needed in crowded urban areas. Lastly it is shown that ATES can properly be applied in polluted areas since it facilitates remediation by a combination with enhanced degradation of soil and groundwater contaminants.

Of utmost importance is continuation of the knowledge proliferation set in motion with the pilots as epicenters (see figures 9 and 10).

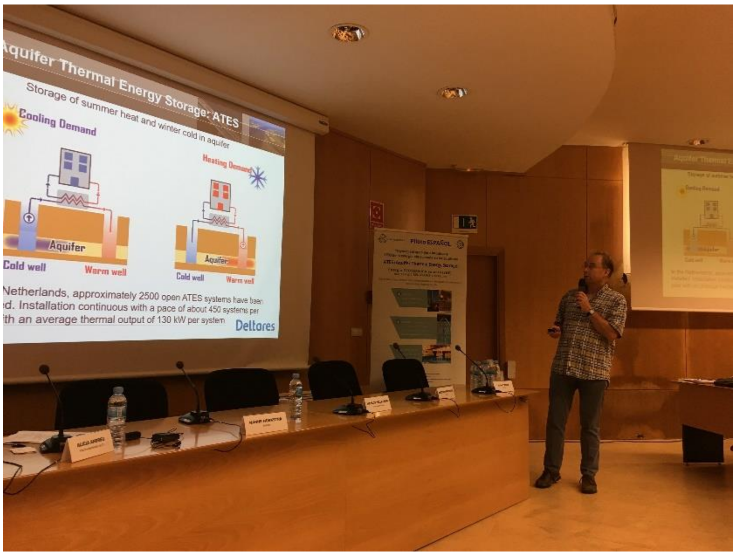


Figure 9: Knowledge proliferation to specialists by explaining ATES and the E-Use(aq) project to architects as part of the Spanish public event; © TU Delft, Martin Bloemendal & ITC, Alicia Andreu

5.2. Climate Impact Assessment

E-USE(aq) shows, through the realization of 6 pilots in 5 different countries, how ATES systems can be implemented, thereby starting a flywheel-effect for the promotion and adoption of ATES systems throughout Europe. Once awareness has risen, the installation of 50,000 systems throughout Europe in the next decade, is deemed achievable by the consortium: for example, on average 250 systems to be installed per year in 20 countries. With the CO_2 mitigation potential of 60 ton per system per year[1], these 50,000 ATES systems contribute to a total annual CO_2 emission reduction of 3 million tons CO_2 per year by 2030.

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[1] The registrations of ATES systems and CO_2 emission reduction accounting of the Dutch Government indicate that the average greenhouse gas (GHG) emission reduction per ATES-system is between 45 and 80 ton CO_2/year in the Netherlands (Originally derived from CBS Warmte/koudeopslag per province in 2008; update tabel 6.2.2 Duurzame Energie in Nederland 2008 and http://www.olino.org/articles/2011/09/19/warmtepomp-vs-gasketel), strongly depending on size, type of building and climate. Taking into account experiences with systems in other countries, an average of 60 ton CO_2/year is supposed to be a representative GHG mitigation potential value per system.

Figure 10: Knowledge proliferation to the visitors of the swimming pool where the Spanish pilot is situated by an information panel at the entrance with project details; © TU Delft, Martin Bloemendal & ITC, Alicia Andreu