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Low carbon heating and cooling by combining various technologies with Aquifer Thermal Energy Storage

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Abstract

A transition to a low carbon energy system is needed to respond to global challenge of climate change mitigation. Aquifer Thermal Energy Storage (ATES) is a technology with worldwide potential to provide sustainable space heating and cooling by (seasonal) storage and recovery of heat in the subsurface. However, adoption of ATES varies strongly across Europe, because of both technical as well as organizational barriers, e.g. differences in climatic and subsurface conditions and legislation respectively. After identification of all these barriers in a Climate-KIC research project, six ATES pilot systems have been installed in five different EU-countries aiming to show how such barriers can be overcome. This paper presents the results of the barrier analysis and of the pilot plants. The barriers are categorized in general barriers, and barriers for mature and immature markets. Two pilots show how ATES can be successfully used to re-develop contaminated sites by combining ATES with soil remediation. Two other pilots show the added value of ATES because its storage capacity enables the utilization of solar heat in combination with solar power production.

Finally, two pilots are realized in countries with legal barriers where ATES systems have not previously been applied at all.

Keywords: geothermal energy, aquifer thermal energy storage, heating and cooling, pilot plant, technological innovation, remediation, photovoltaic-thermal module, water scarcity.

1. Introduction

Aquifer thermal energy storage contributes to greenhouse gas savings

Reduction of greenhouse gas (GHG) emissions is one of the main global challenges (UN, 2015). Large scale adoption of sustainable energy technologies is needed to reduce the use of fossil fuels. The global demand for heating and cooling in the built environment accounts for about 40% of the total primary energy consumption (EIA, 2009, RHC, 2019). Therefore, the development and world wide application of renewable energy technologies in the field of buildings heating and cooling would contribute significantly to GHG emission reduction (Rosiek and Batlles, 2013, Moretti et al., 2013, IEA, 2007). Because many urban areas are in moderate climates with a distinct heating and cooling season (Bloemendal et al., 2015), a seasonal storage is very efficient for combined heating and cooling systems (Tomasetta et al, 2015, Epting et al. 2017). As a result, heat storage in easily accessible shallow (<300 m of depth) subsurface has received interest since the 1970's (Sanner, 2001). In particular, aquifer thermal energy storage (ATES) is a versatile type of seasonal thermal energy storage for larger buildings because it is relatively cheap and easy to achieve large capacities.

ATES adoption is diverse

Potential for ATES is present in many locations around the world (Bloemendal et al., 2015) and various ATES systems have been reported in operation for heating and cooling supply (Gao et al., 2017, Bertani, 2005). However, ATES developments were up-to-now mainly carried out in the Netherlands, while this technology is now also picked up in other countries, such as Belgium, Denmark, Germany, Sweden and the US (Lee, 2010, Fleuchaus et al., 2018). Despite this experience and developments in recent decades, ATES technology still requires further development, and its market is rather immature in many countries. Building systems, geohydrological conditions, legislation and societal perseverance vary strongly from country to country. Therefore, barriers that limit adoption may also be various and diverse. In order to significantly increase adoption, such barriers must be better identified and addressed. The goal of this research is A) to identify and categorize barriers for ATES adoption across Europe and B) identify and test possible solutions to overcome these barriers.

This paper presents the results of a barrier analysis for ATES implementation in Europe in section 3. Novel technological developments and scientific insights to overcome these barriers, are then used to transform the identified barriers to opportunities for development of ATES in section 4. Some of the solutions are implemented in pilot sites which are presented and discussed in section 4 and supplementary material.

The activities are carried out within the *Europe-wide use of sustainable energy from aquifers* project, which aims at improving and developing ATES technology via innovation. A description of the project goals and partners is given in the supplementary material.

2. Methods and materials

2.1. ATES characteristics and working principle

Seasonal underground thermal energy storage systems are often referred to as ground source heat pumps, and are essentially a combination of a heat pump and a system for exchanging heat with the subsurface (Sarbu and Sebarchievici, 2014, Omer, 2008). Usually two different main types of systems are distinguished:

1. Borehole thermal energy storage (BTES): a series of U-shaped pipes which carry a thermal working fluid that transfer heat to the surrounding soil via conduction. Usually applied in smaller buildings and single family homes.
2. Aquifer Thermal Energy Storage (ATES): a system using groundwater from two or more groundwater wells. Suitable for larger utility buildings like offices, hotels and hospitals.

ATES systems are more efficient and enable storage of larger quantities of heat because groundwater is used as a carrier for the heat (Figure 1). Cooling is provided in summer by using groundwater from the cold well; cooling down the building warms up the groundwater to about 15-18°C, which is then stored in the warm well. During winter, groundwater is extracted from the warm well, and together with a heat pump, provides heating to the associated building. The same groundwater is simultaneously reinjected at around 5-8°C in the cold well. Because ATES provides both heating and cooling, it is most suitable for buildings with both a cooling and heating demand. Moreover, ATES requires the presence of an aquifer. Therefore, the two most important environmental preconditions for applicability of ATES are presence of aquifers and a heating and cooling season (Bloemendal et al., 2015).

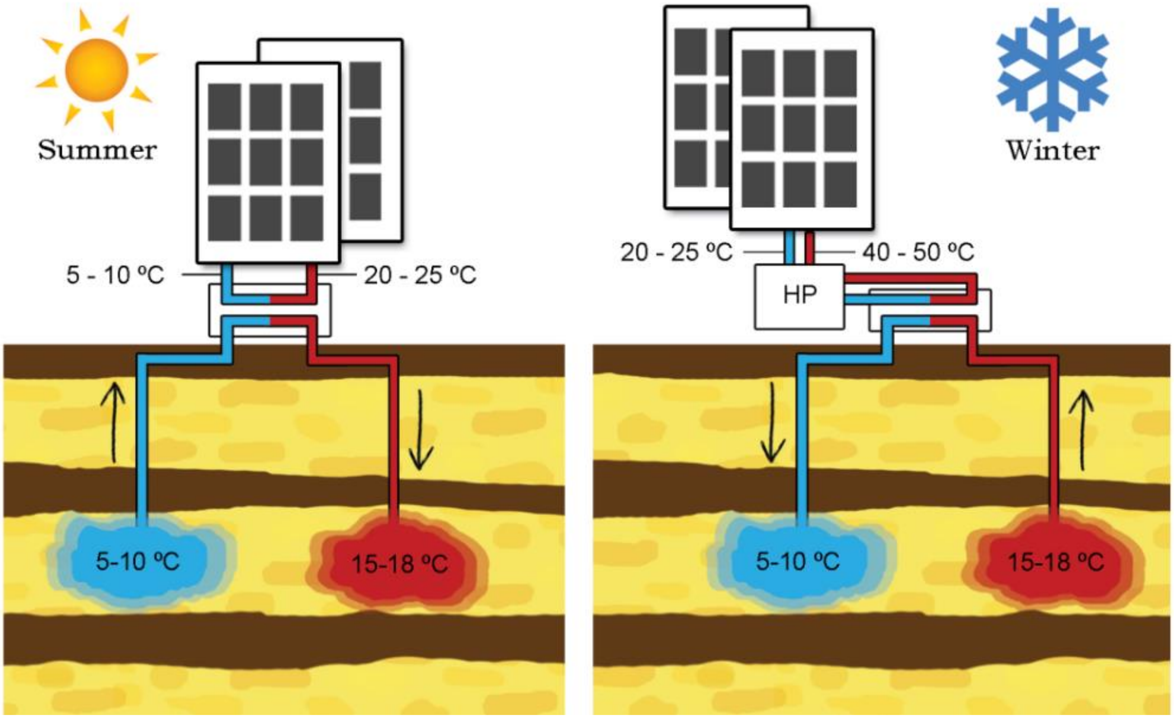

Figure 1. Illustration of the basic working principle of an ATES system. Left: in direct cooling mode while storing heat for winter. Right: in heating mode supported by a heat pump while storing cooling capacity for summer.

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2.2. Barriers identification

Literature study and a survey are the methods used to identify the barriers for development of ATES systems in order to obtain a representative geographical coverage. Following the conclusions of the literature review (Haehnlein et al, 2010, Regeocities, 2014, Monti et al., 2012, Forsen et al., 2008, Koenders. 2015), a questionnaire is set-up and sent out as a survey to partners across Europe with local knowledge and experience in the field (questionnaire questions are included in the supplementary material). Local experts received a survey and a total of 21 people returned the questionnaire, their answers were integrated by additional interviews. The countries involved with the survey are The Netherlands, Belgium, Italy, Spain, Germany and the United Kingdom (of which the latter two did not host a pilot plant in the subsequent project). Barriers in Eastern and Northern European countries were also available in the literature (Haehnlein et al, 2010, Regeocities, 2014, Monti et al., 2012, Forsen et al., 2008). Therefore, the barriers identified in this paper can overall be considered representative for the whole of Europe, although more focus has been paid to Western and Southern Europe. Consequently, some specific local barrier in North or Eastern Europe may be missing.

2.3. Identification and testing of solutions

Solutions for most barriers are trivial and are identified following logical reasoning, solutions used in other countries/fields, or are provided already in literature.

Basically, each barrier will limit ATES adoption to some extent. It is, however, not feasible to tackle all barriers simultaneously and it is also often difficult to identify which barrier limits ATES adoption the most, as often multiple barriers limit ATES adoption. Therefore, local partners have found suitable sites to test one of the proposed solutions to a barrier in a pilot project. The technological solutions selected for pilots are the ones needed for the specific barrier/solution in the project sites. The pilots are installed and monitored; results of installation processes are described in this paper, and where possible ethe performance is evaluated.

The pilot sites, the partners involved and the technology added to the ATES system are diverse; therefore, it was not possible to identify a uniform assessment framework. Also not yet each project has data available to evaluate. The assessment methods that were used for assessing the pilot results are straightforward and well documented in literature which are introduced in each pilot section in the supplementary material.

3. Results barriers and solution identification for ATES development and adoption

3.1 Barriers identification results and analysis

3.1.1. Literature review on ATES barriers

The worldwide ATES development has been well described by Fleuchaus et al. (Fleuchaus et al., 2018): they show that the main developments of ATES are present in the Netherlands. Most research on these systems are carried out by the Dutch, although also several reviews have been published on ATES systems in other countries (e.g. (Tomasette et al., 2015, Gao et al., 2017, Haehnlein et al., 2010, Rogen et al., 2015, Zhouet al., 2015)). The main topics addressed are reported below:

- Legislation: In earlier work Hahnlein et al. made an inventory of ATES legislation (Haehnlein et al., 2010). Legislation varies from country to country, all using the precautionary principle as a basis. Countries where groundwater is scarce are more restrictive than others. This study goes into more detail on identifying which sets of rules either foster or limit ATES adoption.
- Groundwater quality: Two research programs on the effects of ATES on groundwater quality were landmark studies (Koenders, 2015, Bonte, 2015), concluding that low temperature ATES systems like the ones discussed in this paper have negligible effects on groundwater quality. Nevertheless, still many research questions remain on how larger temperature changes (> 30°C) affect groundwater quality and how to deal with the changes in physical properties of

the groundwater around ATES wells. ATES wells placed in contaminated aquifers cause spreading and dilution of the contamination (Phernambucq, 2015). Ni et al. (Ni et al. 2014, Ni et al.,2015) carried out theoretical work on how ATES and decontamination can be combined. This paper starts from their findings to translate these into practice.

- System design: The Dutch industry organization developed design standards, mainly focusing on avoiding well clogging and integration of the ATES wells and heat pump in the building system (NVOE, 2006). Earlier and recent work of Doughty et al., Sommer et al. and Bloemendal and Hartog. (Doughty et al., 1982, Sommer et al., 2015, Bloemendal and Hartog, 2018) provided a theoretical basis for optimal use of subsurface space and how to deal with specific geohydrological conditions (e.g. groundwater flow, high density use of ATES, heterogeneity). This paper takes further steps in the integration with the buildings system and overall performance of the ATES system.
- ATES in practice: The permitted capacity of individual ATES systems in the Netherlands ranges up to 5,000,000 m^3/year, such large systems have multiple well doublets. However, the majority (~70%) of the systems are even smaller than 500,000 m^3/year, with only one or two well doublets (Bloemendal and Hartog, 2018). Depending on aquifer thickness, the associated thermal radius of influence around ATES wells ranges from 20 to about 150 m (Bloemendal and Hartog, 2018). Review and evaluation of the performance of individual ATES was until recently not required (Schultz van Hagen, 2013). The limited number of studies (Willemsen, 2016, Haaglanden, 2017) that have been carried out indicate that in general ATES systems save energy but not yet to their full potential; so, their operation can be optimized.

3.1.2. Survey results

The obtained results are fully described and available in the pathfinder project report (Hoekstra et al., 2015).

Quality level of ATES systems and suppliers

The quality level of ATES systems installation and suppliers was identified as a main general barrier. Design, construction and operation by unqualified parties results in poor performance of ATES systems. Poor quality of the work and/or material can generate malfunctions during operation and/or poor energy efficiency, affecting (potential) users' trust in the technology and eventually resulting in a negative reputation for ATES systems.

Knowledge and skills divided between consulting and contracting companies and operational staff

High efficiency of ATES systems requires not only a good design of the entire system, but most importantly appropriate operational control and management: the lack of the latter can cause poor ATES systems performance, despite proper design and construction. Different types of expertise are required to build and operate an ATES system, currently separated in a fragmented and often complex supply chain, e.g. construction engineers for the energy demand, specialized drilling contractors for the wells, geologists for hydrogeological characterization of the site, Heating Ventilation and Air Conditioning (HVAC) installers for heat pump, distribution and peak facilities. Such a fragmented supply chain requires a significant effort to obtain an integrated and robust ATES system that will function properly once in operation. Therefore, inadequate cooperation between different companies in an early stage, or the absence of a unique market player taking control and responsibility for design, construction and operational phase, is a barrier for optimal design and operational performance of ATES systems.

Mutual interaction between ATES systems

The demand for ATES is usually concentrated in urban areas with high building density. In cities, the demand for ATES may therefore easily exceed the available capacity of the subsurface: this may represent a natural threshold limit for ATES implementation. This aspect is considered to be the most important barrier for ATES adoption in countries with a mature ATES market. The issue of mutual interaction between ATES systems also requires proper management and planning. An important policy parameter for the planning of ATES systems is the minimum distance between individual wells. This is typically defined using the thermal radius (R_{th}) of the wells (Bloemendal and Hartog, 2018); in theory, this distance could be reduced significantly in an aquifer without ambient flow (Bloemendal et al., 2014, Sommer et al., 2015). Several studies show that a trade-off can be found between optimal use of the subsurface for total energy savings on one hand and individual ATES well efficiency on the other (Jaxa-Rozen et al., 2015, Bloemendal et al., 2018). Additionally, it is not widely known that mutual interaction between ATES wells in a dense, well-organized ATES well-field improves, rather than diminishes, the overall thermal performance of these systems because combining wells of the same type increases their efficiency a lot (Bloemendal et al., 2018, Sommer et al., 2015). The reluctance of groundwater management policy makers to allow a dense network of ATES systems has a negative impact on individual efficiency and overall energy savings. Another cause of this barrier is the lack of evaluation of the actual status of the groundwater system, which jeopardizes long term usability of the aquifer. Groundwater extraction and infiltration are monitored but their resulting thermal influence is not evaluated. Dutch practice shows that actual pumped volumes are much smaller compared to the design values, on average 40% of the permitted capacity is used. Ambient groundwater flow can affect both the individual ATES systems as well as downstream installed ATES systems. At ambient groundwater flow velocities <25 m/year this effect is negligible, while at higher groundwater flow velocities design changes are needed to maintain overall efficiency and avoid negative interaction (Bloemendal and Hartog, 2018, Bloemendal et al. 2018, Bloemendal and Olsthoorn, 2018).

Interaction with other subsurface functions

Next to interacting with each other, ATES systems also interact with other subsurface space use. Because of the shallow infrastructure (power cables, drinking water pipes, internet, sewerage, tunnels, parking garages, etc.) it is often difficult to find a location to install an ATES well in the shallow subsurface in densely built urban areas. This is, however, only a barrier during construction activities.

In the storage aquifer, interactions between ATES and/or other subsurface functions are dynamic and ongoing during the life span of ATES systems. The main interactions occur with groundwater production sites for industrial, agricultural use and for drinking water production as well as with remediation and management of contaminated groundwater. The potential conflict of ATES with groundwater production can be stronger in areas with water scarcity. Drinking water production and agricultural use are, however, hardly ever in conflict with ATES, because A) these groundwater extractions are (with some exceptions (Bonte et al., 2013)) usually located outside urban areas where ATES is applied, and B) the water quality change of the groundwater by ATES has a very limited effect on the groundwater quality (Bonte, 2015). Thanks to spatial planning, industries requiring large quantities of groundwater are hardly ever near areas where demand for ATES systems is high. On the other side, interaction between ATES and groundwater contamination are more likely to occur in urban areas with shallow aquifers. Two main problems need to be considered when applying ATES in or near a groundwater contaminated site. The first one is the legislation: due to application of precautionary principles it is often not allowed to affect/influence the pollution through ATES systems. The second one is a technical drawback: due to dilution and mixing of contaminated groundwater chemical and biological reactions with precipitation products may occur in or near the wells, resulting in clogging of the groundwater wells. However, with adapted system design (e.g. location and type of well, addition of other material for well completion) and an adapted maintenance program (e.g. more frequent backwash with chemicals), these problems can be avoided. Next to other subsurface functions, ATES may also interact with BTES systems (technology frequently applied in urban areas), nevertheless the mutual effect of ATES and BTES systems is usually limited (Drijver et al., 2013).

Lack of knowledge, experience and public awareness

Lack of experience and awareness of both ATES technology and heat pumps is an important factor limiting ATES adoption in new markets. Compared to gas boilers, HVAC installers consider heat pumps as “difficult” technology. Most of the smaller HVAC contractors are usually micro or small enterprises with limited awareness about the possibilities and recent advances of heat pumps and a lack of knowledge about subsurface characteristics and ATES potential. Therefore, ATES will not be offered as an option to clients of these companies, which are most often small buildings (around 100 kW or 10.000 m^2 floor space and smaller (Agterberg, 2016)). Despite the limited size of the single plant installation of such buildings, their large number (Agterberg, 2016) makes that the total energy saving potential is enormous, thus this barrier is of major importance.

Public awareness may also be an important driver or limitation for ATES adoption. Although outside of the scope of this research, the public opinion on ATES can become strongly affected by negative reputation originating from project failures. In some cases, the negative public opinion has even been caused by another type of geothermal technology than ATES (Fleuchaus and Blum, 2017, Grimm et al., 2014), so, despite numerous efficiently running projects, one failure can have large consequences for the public opinion.

Lack of adequate legislation

Legislation for ATES varies from country to country. In countries where ATES is widely applied, specific legislation has been designed or modified to regulate and/or stimulate the technology, while in countries with low application of ATES, legislation is lacking or poorly substantiated (Haehnlein et al., 2010). In general, legislation for ATES permitting is also complex and not uniform across countries, often leading to long, laborious and uncertain permitting procedures. In some countries (e.g. Spain and Italy) the responsible authorities involved for issuing ATES permits are many and vary as a consequence of administrative divisions, resulting in the fact that there are different procedures and assessment criteria to follow to obtain a permit, depending on where an ATES project is located. In addition to that, lack of knowledge at permitting authorities about ATES systems and their negligible environmental impacts may cause an additional barrier.

Financial aspects

In Southern and Eastern European countries one of the main barriers for application of ATES is uncertainty on their economic sustainability. The required initial investment is a barrier for implementing ATES systems: the combination of heat pump and groundwater wells require a significant investment compared to conventional HVAC systems. The uncertainty or lack of knowledge on the potential savings, the competition from cheap fossil fuels and the overall conditions of economic recession may prevent operators from investing in ATES.

No specific financial subsidies for ATES systems realization were found in the countries involved in the E-USE(aq) project survey (Hoekstra et al., 2015). Nevertheless, in most countries an ATES system installation can usually benefit from one or more subsidies financing heat pumps installation, energy efficiency actions (white certificates), renewable energy production (green certificates), buildings renovation etc., but the impact of such subsidies is generally limited to a marginal reduction of ATES system payback time.

Unfamiliarity with the subsurface and its characteristics

To evaluate the applicability of ATES systems, to ensure a proper design and most importantly to avoid malfunctions during operations, adequate technical knowledge of the local geo-hydrological characteristics is necessary. The main issues related to the geo-hydrologic conditions are: aquifer depth and hydraulic conductivity, well clogging and insufficient well capacity.

Energy balance

To sustain an ATES system, the thermal energy stored in the aquifer must be of comparable magnitude to the retrieved amount, to avoid short or long term temperature fluctuations. This implies that, ideally, the heating and cooling demand from the building associated to the ATES system should be equal. This is both a technical as well as a legal issue; it affects the individual operation of each ATES system (technical issue), but due to potential imbalance between warm or cold wells, this may also affect neighboring ATES systems (legal issue). Alternatively, the system performance can be optimized by storing extra heat or cooling capacity from other (sustainable) sources such as solar radiation (Paksoy et al., 2000, Kastner et al., 2017, Ghaebi et al., 2014.

3.1.3. Conclusions about barriers identification and analysis

The identified barriers strongly relate to the level of market maturity. For instance, interaction between ATES systems is a clear mature market problem because that will only occur when many systems are built in one area, while lack of knowledge and awareness preventing market development is a typical immature market problem. Therefore, the barriers can be categorized to general, immature and mature market barriers, resulting in:

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, energy balance between heating and cooling demand.
2. Mature market barriers: mutual interaction among ATES systems, interaction with polluted groundwater.
3. Novel market barriers: public awareness, lack of knowledge, large initial investments, unfamiliarity with the underground and its characteristics.

3.3. Solutions to overcome local barriers

Following the identification of technological and non-technological barriers, possible solutions are identified in order to overcome these barriers while stimulating, facilitating or regulating the ATES market.

1. Solutions for the general barriers.
    - Implement quality guidelines and certification to safeguard skills of personnel and the quality of ATES construction work and operation.
    - Monitor and evaluate the temperature distribution in the subsurface, e.g. by a monitoring network and/or numerical computational evaluation.
    - Use a general/cross-sector assessment framework to make an informed decision about allowing ATES, in particular in or near a contaminated zone and/or areas with groundwater stress.
    - Ensure that regulations are similar within a single country. Possibly also try to regulate and facilitate ATES application through a European framework directive.
    - Develop an assessment framework to evaluate the overall performance and associated level of energy savings as a combination of i) individual ATES system performance and ii) optimal and sustainable subsurface space use.

2. Solutions for mature markets barriers:
    - Use flexible ATES permits that allow increasing or decreasing the permitted capacity according to actual use. This then allows the spatial claims in the subsurface to be adapted over time, and safeguards optimal and sustainable use of the subsurface.
    - Improve ATES systems control systems to optimize long term thermal efficiency for both individual systems as well as for the overall efficiency of aquifers densely occupied by ATES systems.
    - Develop better technologies to enhance degradation of contaminants and to overcome the clogging problem related to the chemical reactions in areas with contamination.
3. Solutions for novel markets barriers:
    - Stimulate ATES adoption rates to create awareness by initiating pilot projects, show cases and progressive building energy efficiency regulation.
    - Stimulate ATES application by setting a high energy efficiency standard for new and/or renovation buildings by eliminating HVAC systems from the business case comparison.
    - Provide detailed suitability maps for regions/countries, indicating specific characteristics which influence installation cost and/or operational requirement.
    - Set up a scientific program to evaluate the environmental impacts of ATES systems in the European context, similarly like was already done in the Netherlands (Bertani, 2005, Bonte, 2015).
    - The introduction of specific financial subsidies for the realization of ATES system, to strongly reduce payback time and lead to an increasing number of installations. Governments could also help by bridging the gap between the site or building owner, who has to make the investment, and the site user or tenant, who usually profits from lower energy bills (Hoekstra et al., 2015). Through tax deductions on the investments, paid for by increases on fossil energy taxes, installation of ATES becomes attractive for both parties. Such a tax arrangement would definitely stimulate the construction of more systems. But it is not necessarily the government that would need to take this action; commercial organizations could also encourage business with ATES systems (Hoekstra et al., 2015). For instance, banks can create comparable incentives by initiating agreements that are profitable for all parties.

4. Preliminary results from pilot sites

4.1. Description of pilot sites

In this section the results of three of the six pilot plants are discussed to give an indication of some of the obtained results. The supplementary material presents extensive descriptions and results of each pilot site.

In this work, different innovative solutions (summarized in **Error! Reference source not found.**) have been implemented in the six pilot plants to overcome the technological barriers to ATES implementation that are present in mature markets (The Netherlands), developing markets (Belgium, Denmark) and new potential markets (Spain, Italy). Pilot plants main characteristics are summarized in **Error! Reference source not found.**.

Table 1. Innovative solutions tested in each pilot plant.

Main Barriers and Solutions	**Pilot sites**					
	Delft (NL)	Utrecht (NL)	Birkerod (DK)	Ham (B)	Bologna (I)	Nules (ES)
1. Contaminated site: combine ATES with bioremediation.		X	X			
2. Optimize energy balance and sustainable power use of ATES: integration of PV/T with ATES	X			X		
3. Optimize energy balance with district heating					X	
4. Familiarity	X	X	X	X	X	X
5. Legislative barriers		X	X		X	X

Table 2, Pilot plants main characteristics. (*) extraction and injection wells, .

Parameter	**Delft**	**Utrecht**	**Birkerod**	**Ham**	**Bologna**	**Nules**
N° of production wells (*)	1 + 1	3 + 3	1 + 1	1 +1	3 + 3	4
N° of monitoring wells	6	3	4	2	4	4
Wells' depth (m)	60-80	15-55	22-55	162.5	30	35
Max groundwater flowrate (m^3/h)	25	45	-	80	19.4	14.4
Max cooling power (kW)	30	-	-	1,300	140	-
Max heating power (kW)	70	-	-	650	160	109
Annual cooling demand (MWh)	160	525	-	900	49	-
Annual heating demand (MWh)	160	475	-	863	170	288

The non-technological barriers are also faced as the project consortium worked to build strong and cross-sectoral local partnerships. This is to guarantee a high level of skills and knowledge development and transfer, and to ensure an effective design and realization of the pilot plants. Furthermore, preliminary field tests are financially supported to increase the knowledge of groundwater characteristics (in particular, in non-Dutch pilots). The realization of robust monitoring systems is implemented in all pilot plants to effectively monitor not only the impacts of pilot plants' operation, but also to provide more guarantees to the public administrations. Finally, numerous publications, presentations and events created awareness and familiarity both at local as wells as at international level.

4.2. ATES at contaminated sites

In laboratory studies it was shown that the combination of ATES and bioremediation of chlorinated solvents leads to a more than 10-fold increase of the biodegradation rate compared to natural attenuation (Paksoy et al., 2000, Kastner et al., 2017). Evidence of this acceleration of bioremediation by ATES in plumes of chlorinated solvents contaminated groundwater would be a clear demonstration that contaminated groundwater could be treated with ATES. Bioremediation is tested at two different contaminated sites: in the aquifers of Utrecht (NL) and Birkerod (DK), with low and high concentrations of chlorinated solvents, respectively.

At the Utrecht Nieuw Welgelegen pilot site a mono-well ATES system has been operating for several years. The groundwater at the location of the Nieuw Welgelegen pilot is contaminated with chlorinated ethenes, mainly vinylchloride (VC), which exceed target concentrations set by the Dutch National Institute for Public Health and the Environment (RIVM).

The aim of the Utrecht pilot study was to stimulate bioremediation at the ATES system by bioaugmentation: inoculation with *Dehalococcoides bacteria* (DHC). For this a separate injection well and 3 monitoring wells were installed (see a scheme of the pilot plant in the supplementary material, Figure C3). The main mechanisms for increased biodegradation are threefold. Firstly, and most importantly, by inoculation of DHC a high concentration of specific biomass, able to degrade chlorinated ethenes, will be present in the system which should enhance biodegradation at optimal environmental conditions. Secondly, elevated groundwater temperatures in the warm well, in comparison to ambient groundwater temperatures, will generally lead to higher biodegradation rates and higher biomass growth rates. Thirdly, the added biomass can function as an electron donor, leading to lowering of the redox conditions which promotes reductive dechlorination.

The bioaugmentation pilot study at Nieuw Welgelegen showed that injection of a large volume of bacteria (4 m^3 with $2x10^8$ cells/mL) did not result in negative impacts such as well clogging and the ATES system operated normally. DNA measurements performed on soil and groundwater samples revealed that the introduced DHC bacteria attached to the soil matrix and migrated from the bioaugmentation injection well to the monitoring and ATES wells.

Although VC concentrations are generally low (<10 µg/L), several observations indicate that biodegradation is occurring. These include (i) decreasing VC concentrations at the bioaugmentation injection well (Figure 2), and (ii) the detection of ethylene during certain time measurements. According to the molar ratios for the conversion of VC, a reduction of 5 mg/L VC will produce 2.28 mg/L ethylene. This supports the field observations reported here, as VC concentrations were initially 2−6.6 mg/L, and ethylene was subsequently detected at 2.2−2.4 mg/L. Furthermore, redox conditions indicate that the reduction of VC is thermodynamically feasible.

The results of the Nieuw Welgelegen pilot study support earlier lab scale experiments where the effect of pumping by an ATES system on the distribution of DHC biomass was investigated (Ni et al., 2015). From this study it became clear that an increase of biomass over time accelerates the biodegradation of chlorinated ethenes and that the DHC could attach to the soil matrix.

The results showing decreasing VC concentrations over two summer seasons are promising as this provides a system design by which VOCl contaminations can be effectively biodegraded at relatively low cost, without any negative impacts on the ATES system.

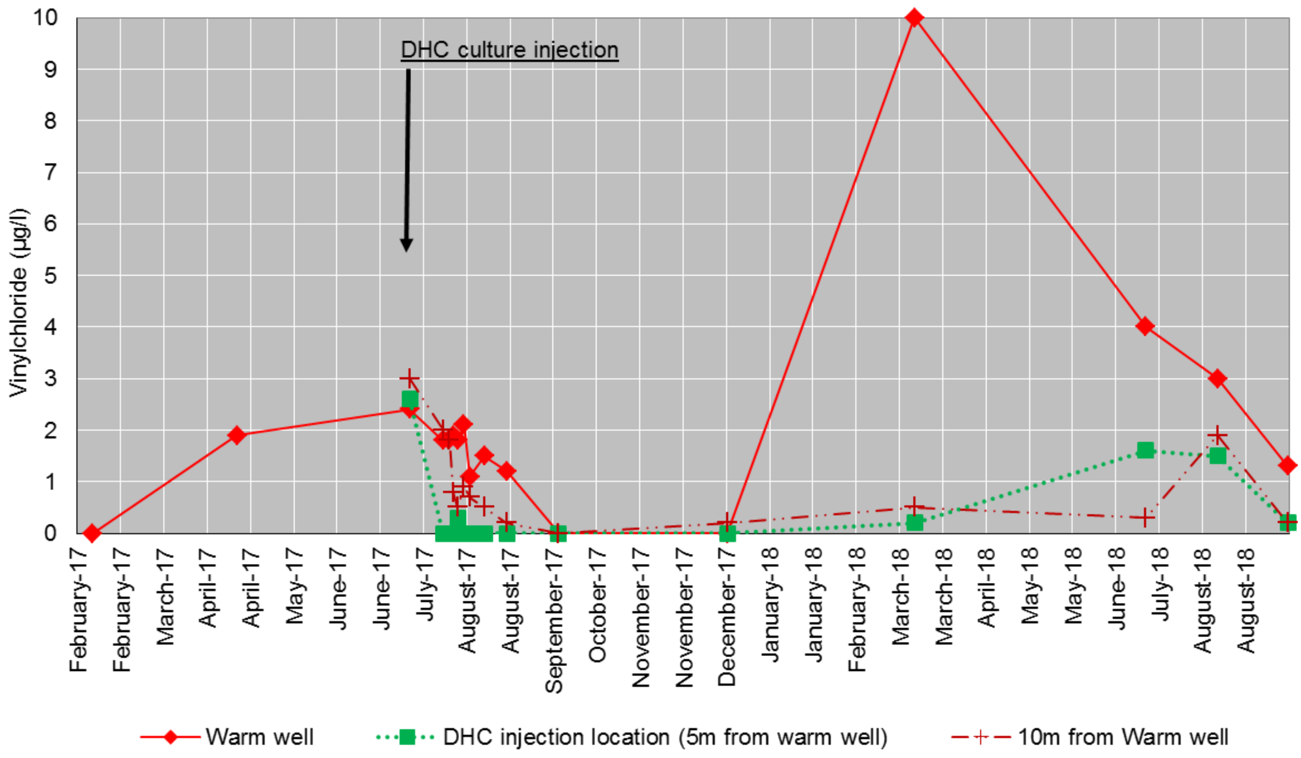

Figure 2. Concentrations of vinylchloride in the ATES-3 warm well and bioaugmentation injection well. The time of the DHC inoculation is also shown. Summer operation: injection in shallow warm well, water flows from ATES-3 to the

bioaugmentation well. Winter operation: extraction from warm well, injection in deep cold well. The VC concentrations increase during winter and decrease during summer due to the heterogeneous distribution of VC concentrations with depth (data not shown).

4.3. Energy balance requirement: integration of PVT technology in ATES systems

Solar collectors are used to obtain extra heat to meet the energy balance requirement. Using both solar heat and power would even further improve the energetic and economic performance of ATES systems as ATES systems also need electricity to drive heat pumps. Since in many climates solar heat is abundant in summer, while heat demand is largest in winter, seasonal storage of heat in an ATES system would utilize the potential excess heat production during summer.

Hybrid photovoltaic-thermal (PV/T) solar panels are a smart solution to combine heat and electricity production from solar energy in one device (Bianchini et al., 2017). The integration of PV/T technology in ATES systems will be tested for the first time at industrial scale in two pilots (Delft and Ham). In particular, in the Delft pilot an innovative PV/T system will be tested which is able to produce warm water at temperatures up to 70-80°C.

The ATES system in Ham, Belgium, consists of two wells of about 160 m deep integrated with PVT solar panels. The data presented in Figure 4 covers the first year of operation of the Belgian pilot (see spatial lay-out in the supplementary material). Figure 4 shows that the storage of cold water worked very efficiently as the temperature extracted from the cold well also is around the injection temperature of 8°C during the first part of the second cooling season and slowly increased to 11°C at the end of August 2017. Figure 4 also shows that after the initial period with cooling demand, the temperature in the warm well drops fast until it reaches the ambient temperature. This behavior is a result of the startup of the system at the end of the summer, resulting in limited storage of heat in the warm well. As a consequence, the temperature difference during heating operation is quite small and larger volumes from the warm well are necessary to provide the requested amount of heat, which then results in a depleted warm well already in January (thermal radius, $R_{th} = 0$). However, Figure 4 also shows that at the end of this first year (August '17) the warm well is charged with heat: the infiltrated temperature in the warm well is on average 17°C and the thermal radius is over 20 m. This indicates that during the 2017/2018 heating season the warm well will deliver warmer water, which means that a larger temperature difference will be realized and a smaller flow of water will provide the same amount of heat. Consequently, a smaller volume of cold water will be stored for each J of heat delivered. The cold well was not depleted at the end of the first year since the heating provided by the ATES was mainly realized by cooling down the cold well, and no heat was charged in the warm well.

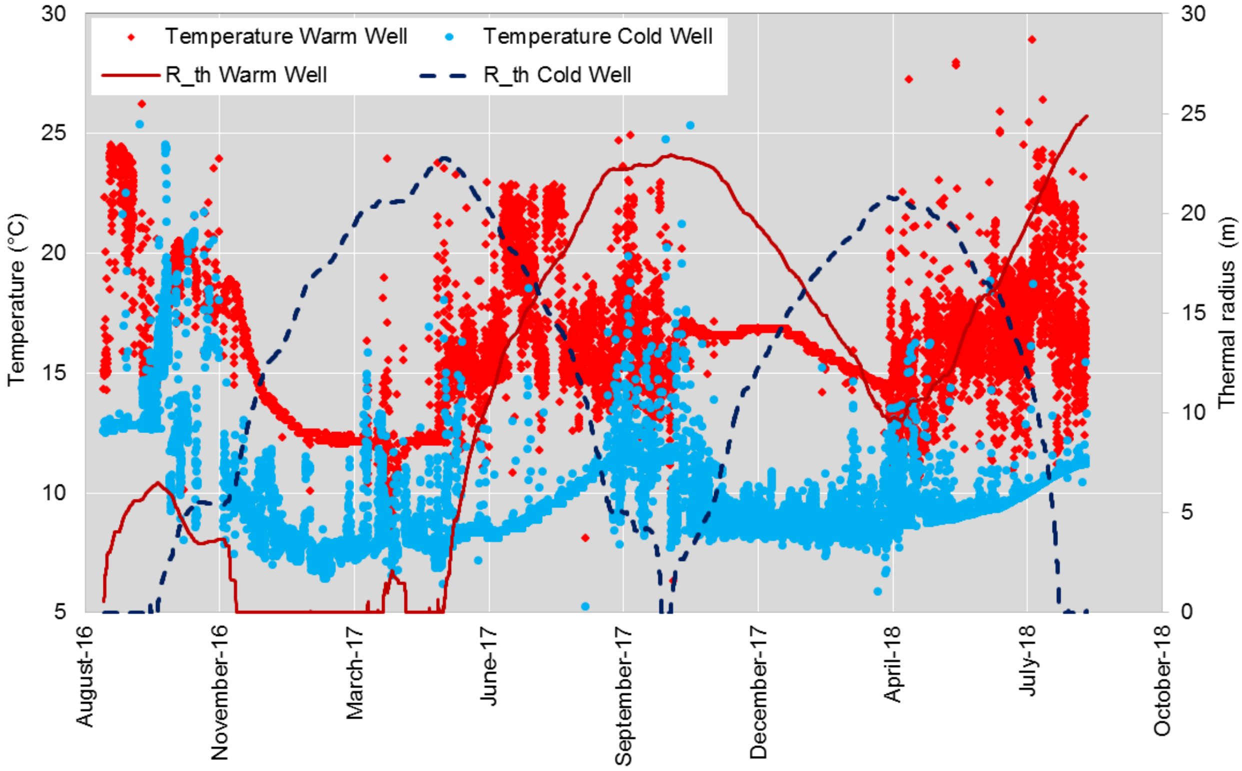

Figure 3. Evolution of temperature at the warm and cold wells and calculated thermal radius of warm and cold well at Ham site.

The main findings of the energy monitoring during the first year of operation are that: i) PVT panels cover 13% of the domestic hot water demand during the monitored summer period, ii) despite being in summer, almost 50% of the heating demand was covered by the gas boiler due to an error in the HVAC control, which was adapted later, and iii) direct cooling represents only 7% of the cooling provided by the ATES. The latter is a problem as it has an important negative impact on the overall energy performance. The reason for this high amount of active cooling was an error of the HVAC system: it was found that the temperatures delivered by the ATES were more than sufficient for free cooling (see Figure 3), but due to an error in the HVAC control the system was always put into active cooling mode. It is expected that in the second year of monitoring the full potential of the ATES in combination with PVT will be demonstrated, as it was found that after the modifications the system correctly switched to free cooling. These findings show how important it is to perform a thorough commissioning of the system, as mistakes in the programming of HVAC controls can have a serious negative impact on the performance of the systems.

4.4. Local legislation barrier overcome by dynamic closed loop probe system

In most regions of Spain groundwater pumped to the surface is treated as industrial wastewater, which then complicates permitting procedures. A solution to overcome this legal barrier is tested in the Spanish pilot plant, which is called Dynamic closed loop (DCL) probe. The DCL probe (Figure 4) consists of a series of small diameter tubes through which the thermal carrier fluid is circulated, similar to the approach in regular BTES. These tubes are installed in a groundwater well with a screen at the bottom and top, when groundwater is pumped from the bottom to the top screen, the rate of heat exchange of the closed tubes increase strongly. This system is a hybrid solution, with the advantages of A) closed-loop system, since the groundwater is not extracted from the ground, avoiding legal barriers, and B) open-loop system, wherein the heat exchange is improved because there is no longer heat exchange by only conduction because of the groundwater flow along the closed loop tubes. In this way the technology allows to obtain the permits, thus overcoming the legislative Spanish barrier regarding stringent limitation to water extraction for energy purpose. In the Netherlands mono-well systems are often equipped with a downhole heat exchanger, so groundwater flowing from one screen to the other does not leave the well. Such a construction also prevents groundwater from coming to the surface, and may be an alternative solution for the specific Spanish legislation.

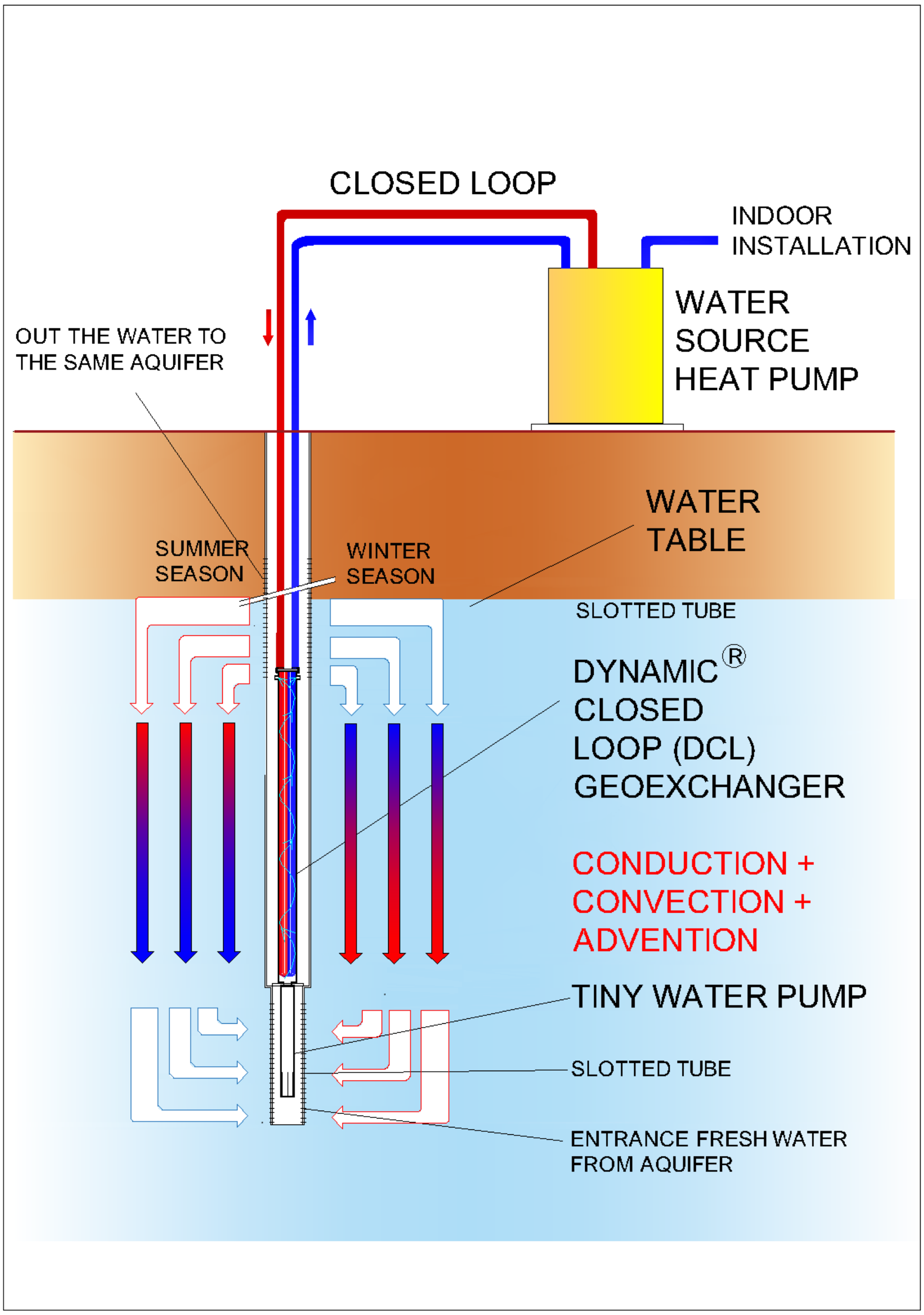

Figure 4. Scheme showing how the Dynamic Closed Loop (DCL) probe works.

A geothermal heat pump system with four Dynamic closed loop probes (DCL) probes have been installed in Nules (Spain) to keep the water temperature of a swimming-pool at 28°C. The Spanish pilot plant is in operation since the end of 2016. The DCL probes working data have been registered on a weekly basis, the temperature and water depth variation in the groundwater has been monitored in the three piezometers around the DCL probes and in the fourth piezometer placed at a certain distance from the DCL probes, in the thermal plume direction (see Figure C7 in the supplementary material for spatial layout).

Figure 5 shows the temperature variation of the piezometers, together with outside air temperature, the heating degree days and the total amount of heat that was transferred from the subsurface to the heat pump (the latter is only available from September 2017 onwards). Monitoring locations 1, 2 and 3 are in between the 4 DCL probes so their temperature response is well aligned with the moment the heat pump starts operating, September 2017 onwards. The temperature response in the downstream monitoring location (T4) has a delayed response as the cold plume arrived in March 17 and November 2017, also recovering of the temperature lags behind from the moment heat extraction stops. More years of operation should confirm sufficient recovery of the groundwater temperature after each winter.

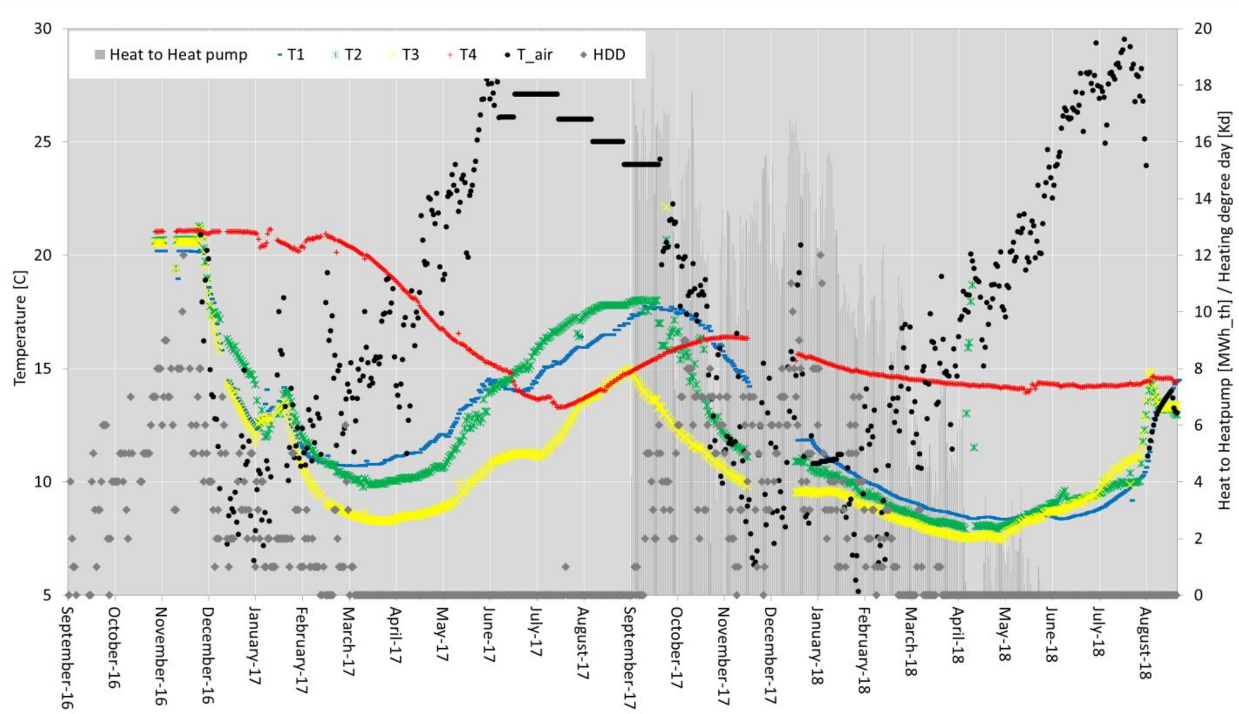

Figure 5. Temperature and level variation of the four piezometers in one year; also ambient temperature variation is included (measured starting from 16th December 2016).

Several groundwater samples have been analyzed to evaluate the impact of the temperature change on groundwater quality. No considerable changes have been detected, with the exception of the chloride concentration increase in the summer season, which is due to the more saline groundwater that is pumped from the deeper to the shallow screen. Further monitoring is still on going to evaluate the impact of DCL probes in the mid-to-long term on chlorides, nitrates, nitrites and sulfates. Finally, the overall energy efficiency analysis shows a yearly decrease in natural gas consumption of about 60%.

5. Discussion and conclusions

The use of aquifers for thermal energy storage has large potential in Europe and can lead to relevant benefits from the environmental and economic points of view. Nevertheless, still many barriers need to be tackled to significantly increase ATES adoption across Europe. The "Europe-wide use of sustainable energy from aquifers" project has initiated six pilot sites to show how to overcome some of the barriers that were identified by literature search and by a specific survey. The identified technological and non-technological barriers varied with the level of 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 market barriers: interference between ATES systems, interference with polluted groundwater.
3. Novel market barriers: public awareness, lack of knowledge, large initial investments, unfamiliarity with the underground and its characteristics.

The design and realization of six pilot plants in five European countries characterized by different ATES system diffusion, legislation, subsurface characteristics and climate (The Netherlands, Belgium, Denmark, Spain and Italy characterized by different ATES system diffusion, legislation, subsurface characteristics and climate) is a relevant step forward for ATES development in these countries and shows how some of the above mentioned barriers can be addressed.

Next to providing a clear overview on the barriers and possible solutions, the main contribution of this research is to show that barriers for ATES adoption can be overcome in practice. In most of the pilot cases it was shown that these barriers are overcome by combining ATES with other (renewable energy or groundwater treatment) technologies, leading to mutual benefits.

The solutions proposed and implemented in the presented pilot sites are highly replicable in similar situations in these and other countries, as they can be easily adapted to local conditions.

Discussion & Limitations

First results from the pilot sites prove that the implemented technological solutions showed 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.

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Supplementary material

A. About the Climate-KIC E-USE(aq) project

The E-USE(aq) innovation project, financially supported by the EIT Climate KIC Association of the European Institute of Innovation and Technology (EIT) in the frame of the Sustainable Land-Use theme, started on June 1st 2015 and brings together nine partners (Table A1). The co-funding by EIT-Climate KIC covered monitoring and site characterization costs for the pilot plants, while the plants themselves were co-financed by local industrial third parties. The project objectives include the realization of six different pilot plants in the following countries: The Netherlands (Delft and Utrecht), Spain (Nules), Italy (Bologna), Belgium (Ham) and Denmark (Birkerod). Partners' countries have been selected on the basis of different development and knowledge of ATES system at national level, while pilot sites have been identified according to criteria of techno-economic feasibility and of testing innovative technological solutions.

Table A1. E-USE(aq) project consortium.

Name	**Kind**	**Country**	**Activities**
Deltares	Research Institute	Netherland	Project lead and responsible for Utrecht pilot plant.
ASTER	Innovation Platform	Italy	Communication and dissemination.
Bologna University	University	Italy	Responsible of Italian pilot plant.
Ceramic Technology Institute	Research Institute	Spain	Responsible of Spanish pilot plant.
Delft University of Technology	University	Netherland	Responsible of Delft pilot

			plant.
Itecon	Company	Spain	Technology provider (Spanish pilot plant).
Naked Energy	Company	UK	Technology provider (Delft pilot plant).
Nomisma Energia	Company	Italy	Techno-economic analysis and business cases development.
Wageningen University	University	Netherland	Responsible of Danish pilot plant, collaborating in Utrecht pilot plant.

Completion of full-scale pilot testing, validation and demonstration projects in different European countries will prove the attractiveness and huge potential impact of large-scale ATES applications. A techno-economic analysis of each pilot will be carried on i) to assess and validate the innovative technologies tested, including smart combination concepts, ii) to measure environmental benefits (reduction of fossil fuel consumption and greenhouse gas production) and iii) to demonstrate the economic sustainability of ATES application. On the basis of this analysis it will be possible to draft potential business models to prove the technology marketability.

B. Survey Questionnaire

B.1 Geology, hydrogeological requirements and aquifer quality

We would prefer receiving maps with geological, hydrogeological information and salinity (or freshwater/saltwater) drinking water protection zones, groundwater pollution sites etc.:

1. Where are in your country suitable aquifers within 200 m below ground surface? The suitability of an aquifer for thermal energy storage depends on the transmissivity of the aquifer. The transmissivity of an aquifer is a measure of how much water can be transmitted through the soil. The transmissivity is calculated by multiplying the hydraulic conductivity (m/day) times the thickness (m) of the soil layer. The following transmissivities ranges are used to qualify the suitability of an aquifer for thermal energy storage.
    - Transmissivity < 100 m^2 /day: Unsuitable.
    - Transmissivity 100-1000 m^2 /day: Suitable.
    - Transmissivity > 1000 m^2 /day: Very Suitable.

Please give an areal estimate (percentage of the total land surface) for each transmissivity range and if possible place the different transmissivity ranges on a map. Which aquifers are used for drinking water, partially or totally? Give also an estimation of the percentage, if possible.

2. Which part of these aquifers is contaminated?
3. Do urban conglomerations and industrial resorts coincide with the presence of aquifers? Which ones? Give a surface estimate
4. Which aquifers are adjacent to surface water?
5. Is there evidence of conflicts in groundwater management between ATES systems and any other use of groundwater?

B.2 Legislation

In 2006 an Inventory of EU Legislation on Ground Source Heat Pumps (GCHPs) has been carried out. The report is attached to this questionnaire. One of the conclusions from the 2006 report is:

"The legislative framework is very different around Europe, and in some cases it represents a real barrier to the geothermal energy use."

We would like to ask you to review the report for your country and inform us:

1. Whether the legal framework in your country for ATES systems has, or will be, changed compared to the description in the 2006 inventory or not.
2. If the legal framework for ATES systems has, or will be, changed, please describe the new legal framework for both open and closes systems.
3. Who owns indigenous and introduced aquifer heat, especially in case of migration and crossing of property borders?
4. Is it obliged to balance heat storage and recovery, in other words do (combinations of) systems have to be energy neutral over a certain time?

Please, give special attention to certain types of areas where ATES systems are prohibited like drinking water protection areas and possibly contaminated water bodies.

B.3 Socio-economic parameters

1. How many ATES systems are already operational in your country? Please distinguish between major types, such as closed and open loop systems. What is the thermal capacity of these systems and how much groundwater is being pumped and infiltrated in open ATES systems?
2. In the Netherlands we often see the situation where aquifer thermal energy systems (ATES) compete with each other for the available space in the underground: the demand is larger than the capacity of the underground. That leads to interference between ATES systems, mostly in larger cities. Is dividing the available capacity for thermal energy

systems in the underground between different parties an issue: are there situations where the demand for ATES systems exceeds the capacity which leads to dividing problems.

3. What are common water temperatures in warm and cold wells? Are there any high temperature ATES? How high?
4. Are there national or local subsidies available which can be used for ATES systems. If so, please describe them.
5. How widely is district heating used? What are the perspectives for the future use of district heating?
6. What are the main competitive technologies for ATES systems in your country? Describe the future perspectives for these technologies. For what kind of ATES-related technologies do you see application possibilities?

B.4 Other barriers and opportunities

1. What kind of barriers, not mentioned above, do you see yourself for a wide application of ATES in your country?
2. What kind of opportunities, not mentioned above, do you see yourself for a wide application of ATES in your country?
3. Do you have other remarks that you deem relevant for our market assessment?

C. Pilot plants description

A brief description of the pilot plants is given in the following paragraphs.

C.1. Specific analysis on five European countries

In the following section a short summary is given for the countries where pilot plants have been realized to illustrate which of the barriers each pilot plant addresses.

The Netherlands (mature market)

Since the first ATES project in the Netherlands in Zwolle in 1984 (Fleuchaus et al. 2018), ATES showed a constant growth, while before the years of the recent economic crisis the growth became exponential. In fact, ATES systems have grown from around 200 in the year 2000 to more than 2,000 in 2012 (Fleuchaus et al. 2018, Bonte et al. 2013). Next to suitable hydrogeological and climatic conditions the clear legal arrangements for permitting have substantially helped to grow ATES, but the most important driver which is not present in many other countries, is the fact that ATES allows to meet the legally enforced energy efficiency standard for new buildings. However, while ATES is now a proven and well-known technology in The Netherlands, further improvements in terms of system efficiency and sustainability are still needed (Bloemendal et al. 2014, Sommer et al., 2015, Bakr et al., 2013.

As 70% of drinking water is made from groundwater in The Netherlands, the protection of groundwater is regarded as very important.

Contaminated groundwater might be a barrier in the application of ATES, as ATES pumping will spread and dilute the contamination (Zuurbier et al., 2013). Therefore, in The Netherlands regulation does not allow ATES systems in areas with contaminated groundwater (Bonte et al., 2011). But ATES systems can theoretically be situated and designed in such a way that their impact on contaminated groundwater bodies is either minimal or positive. Positive effects can be achieved by e.g. hydrological containment and enhancement of biodegradation by mixing with nutrient-rich water and/or increased groundwater temperatures (Slenders et al., 2010, Sommer et al., 2013).

Also the risk of mutual interaction between ATES systems is an important barrier for a mature market like the Netherlands. However, also in developing markets it may be good to take into account future ATES systems to make no regret decisions on well location and design.

Denmark (developing market)

In Denmark, the geothermal resources are available at relatively low temperatures, suitable for heat and cooling production. Both shallow and deep geothermal resources are used in Denmark. The number of smaller heat pumps extracting shallow geothermal heat has been assessed to be around 27,000 (Rogen et al., 2015). Shallow geothermal is mainly used for domestic heating via a series of closed loops at about 1 m depth. Vertical closed loop boreholes to around 150 m depth are also beginning to be used for domestic heating. Only few installations use an aquifer for heating and cooling. Recently, there is a growing interest in the application of ATES for the heating and cooling of buildings, and the first project of this kind was operational by the end of 2007 (Hendriks et al., 2008). Danish ATES market can be defined as a developing market, thus potentially facing both novel and mature markets barriers.

Belgium (developing market)

The application of the ATES technology is specifically interesting for the northern part of Belgium, due to ideal hydrogeological conditions. In 1996, the first ATES system was installed in Flanders (northern region of Belgium) at CERA Bank headquarters in Leuven (Dirven and Gysen, 1999). Since then, several ATES plants have become operational or are under construction in Belgium (Possemiers et al., 2014). Most of the ATES applications are used in the commercial sector such as hospitals and office buildings, where a large amount of cooling and heating is needed. Similar to the Danish situation, the Belgian ATES market can be classified as a developing market.

Italy (immature market)

Italy has a solid experience in the exploitation of geothermal energy for power generation: the first experiments of electricity generation from geothermal steam took place in Larderello (Tuscany) in 1904. Conversely, the development of other direct uses of geothermal resources is still very limited compared to other countries in Europe and throughout the world (Casasso and Sethi, 2017). Very low temperature groundwater resources can be found almost everywhere, but the development of heat pumps extracting shallow geothermal heat have been limited up to now, in particular for open-loop application, since it is no legislation in place for such systems. Instead, the use of closed-loop systems is regulated by Regional governments, and so more common, especially in Northern Italy. No ATES systems have been realized in

Italy so far for the same reason, although some lab scale tests have been carried out (Giordano et al., 2015). Therefore, Italy can be considered a new market for ATES systems.

Spain (immature market)

The shallow geothermal energy technological development in Spain comprises both closed and open loop systems. Installed closed-loop systems are estimated to have a total capacity of about 60 MW_{th}, while open-loop systems are estimated at 90 MW_{th} (Arrizabalaga et al. 2015). Exploitation of shallow geothermal systems in Spain is immature. The key barriers to overcome are the complex administrative process to get permits and the non-harmonised requirements at national level. In fact, each regional government has its own legislation and permitting procedure, thus resulting in a strong barrier for installation contractors. Another relevant barrier is the lack of knowledge of public administrations about ATES technology (Regeocities, 2014). Furthermore, the Mediterranean area is often characterized by water scarcity and in most cases groundwater is the main water source for urban, industrial and agriculture use. The consequence is that aquifers usually suffer over-exploitation.

C.2. Delft pilot plant (Netherlands)

The assessment follows the assessment methods described and used by Bloemendal et al. 2018.

The existing ATES system of Deltares campus in Delft (Figure C1) was chosen to install PVT panels. Deltares campus has several buildings of which two (called Tetra) are connected to an ATES system. One of the experimental laboratory buildings, which is called ZZH, was not connected to the ATES system but has a very high heat demand, while the buildings connected to the ATES have a heat surplus. Hence the solar heat from the PVT panels and the surplus of heat from Tetra can be stored in the ATES system and transferred to ZZH, thus decreasing the overall energy use and enlarging the available cooling capacity during summer for cooling of Tetra. Naked Energy has developed “Virtu”, an innovative hybrid solar technology which integrates standard high efficiency photovoltaic cells within an evacuated tube solar thermal collector. Virtu characteristics are shown in Table C1.

Figure C1. Schematic plan of Deltares campus with the location of different buildings/components indicated.

Table C1. Delft case characteristics, yearly expected energy flows and savings.

Parameter	**Value**
Heat surplus Tetra	50 MWh
Heat from PVT	25 MWh
Heat to ZZH	100 MWh (assuming COP of heat pump =4)
Gas use reduction	11,500 m^3 ~22 ton CO_2
Electricity use reduction	-25 MWh of chiller Tetra +27 MWh Heat pump -8 MWh produced by PVT Net saving: 6 MWh

The ZZH-building is heated with conventional gas boilers, while no cooling was applied. The low temperature heating from the ATES wells can be used in combination with a heat pump to supply preheating to the air handling units of ZZH, thereby reducing its energy demand from the gas boilers. Energy from 120 PVT tubes will be used to boost the temperature of the warm well during summer. During winter, heating from PVT can also be delivered directly to reduce the running of the heat pump.

Only limited performance data has been collected so far from the solar thermal array, since it was only finally commissioned in September 2018. However, initial data shows the expected level of heat generation during sunny conditions. The monitoring allow flow and return temperatures to be tracked as a function of time, sun intensity and water flow, enabling calculation of thermal power generation. Figure 10 and 11 show temperature and flow traces for 27-Sep-18, which was a clear sunny day and 30-Sep-18, which had partial cloud.

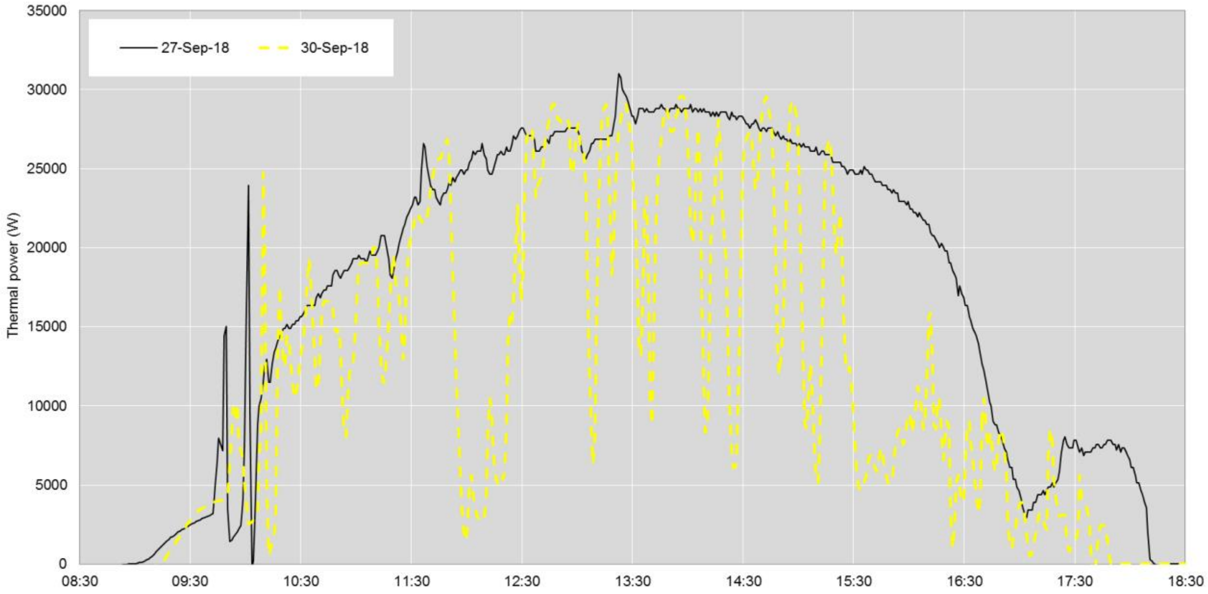

Figure C2. Thermal power output during 27-Sep-18, a sunny day and 30-Sep-18, a partially cloudy day.

From the data for the sunny day, the peak power output reached 30 kW, which was delivered at 43°C water return temperature. 30 kW equates to 250 W from each Virtu solar thermal tube. This is consistent with the output expected for late September; in summer the peak power will be typically 20-30% higher than this due to the higher sun elevation angle. On the partially cloudy day, the peak power was also close to 30 kW but it was more intermittent. Integrating the area under these curves gives the thermal energy production. This is calculated as 169 kWh for the sunny day and 115 kWh for the partially cloudy day. This is the amount of heat that can be contributed daily to building heating on the site or that can be stored in the aquifer.

The Delft ATES pilot at the Deltares site has focused on addressing the key challenge of achieving long term heating and cooling balance. The economic benefits of an ATES system are only achieved if a stable annual cycle is created, with the demand for heating and cooling balancing the generation and storage across several years. 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.

The pilot also aimed to address the long term imbalance between heating and cooling by installing a solar array, to capture solar heat during the summer. A novel hybrid solar collector, Virtu, which features a vacuum tube to enable higher thermal efficiency in cool climates, was installed in 2 phases. In the first phase 10 tubes were installed and tested for 1 year to enable system optimization (e.g. temperature control, freeze protection); in the second 120 tubes were installed, to give a 30 kW heat production capability. The second phase installation was close to the end of the project period and so the impact on aquifer well temperature has not yet been demonstrated. However well temperature measurements collected during the project have shown a clear trend to colder temperatures, demonstrating the decline in the energy density of the hot well that results from an annual imbalance in favor of heating demand. The pilot will continue to generate well temperature data over future years and should demonstrate the effect of the solar heat in slowing or reversing this trend and maintaining a highly efficient and sustainable ATES system.

C.3. Utrecht pilot plant (Netherlands)

The assessment follows the assessment methods described and used by Ni et al. 2014 and Ni et al., 2014.

The Nieuw Welgelegen ATES installation is supplying heating and cooling to the sports facility by 3 separate mono-well ATES (a Mono-well ATES system two well screens are installed in one borehole, warm in the upper and cold in the lower screen, see Figure C3, for schematic). In these mono-wells the warm water storage is always positioned above the cold water at sufficient distance to prevent potential mixing. In a geochemical report on the subsurface of the Municipality of Utrecht (Grotenhuis, 2016), it was argued that reductive dechlorination of COCs was not likely to occur due to unfavorable redox conditions. It is possible to alter the redox conditions in order to stimulate reductive dechlorination in the subsurface. However, altering the redox conditions is hardly possible when dealing with thick aquifers, which is the case for the Municipality of Utrecht, where the aquifers range from 50 to 200 m thick (Municipality of Utrecht, 2014). On the other hand, the original compound tetrachloroethene (PER) could not be found anymore in the subsurface of Utrecht, indicating that natural attenuation seems to occur at low rate in the first aquifer. However, still the intermediate vinylchloride (VC) is present in relatively low concentrations in the first aquifer of Utrecht. This compound is the most toxic and has an intervention value of 5 µg/l in groundwater.

In Utrecht pilot the combination of ATES and bioremediation is studied in a plume of contaminated groundwater at relatively low concentrations of groundwater. As from the earlier lab studies with similar sediment material from the city of Utrecht it was demonstrated that the redox conditions for reductive dechlorination were too high bio-augmentation is performed with a DHC culture to optimize the biodegradation circumstances. The bioaugmentation approach was developed by Bioclear Earth, a Dutch company that is already active in the field of Bioremediation for more than 25 years. An extra well for biomass injection as well as extra monitoring wells were installed in the pilot as addition to the existing ATES system to stimulate the bioremediation (Figure C3).

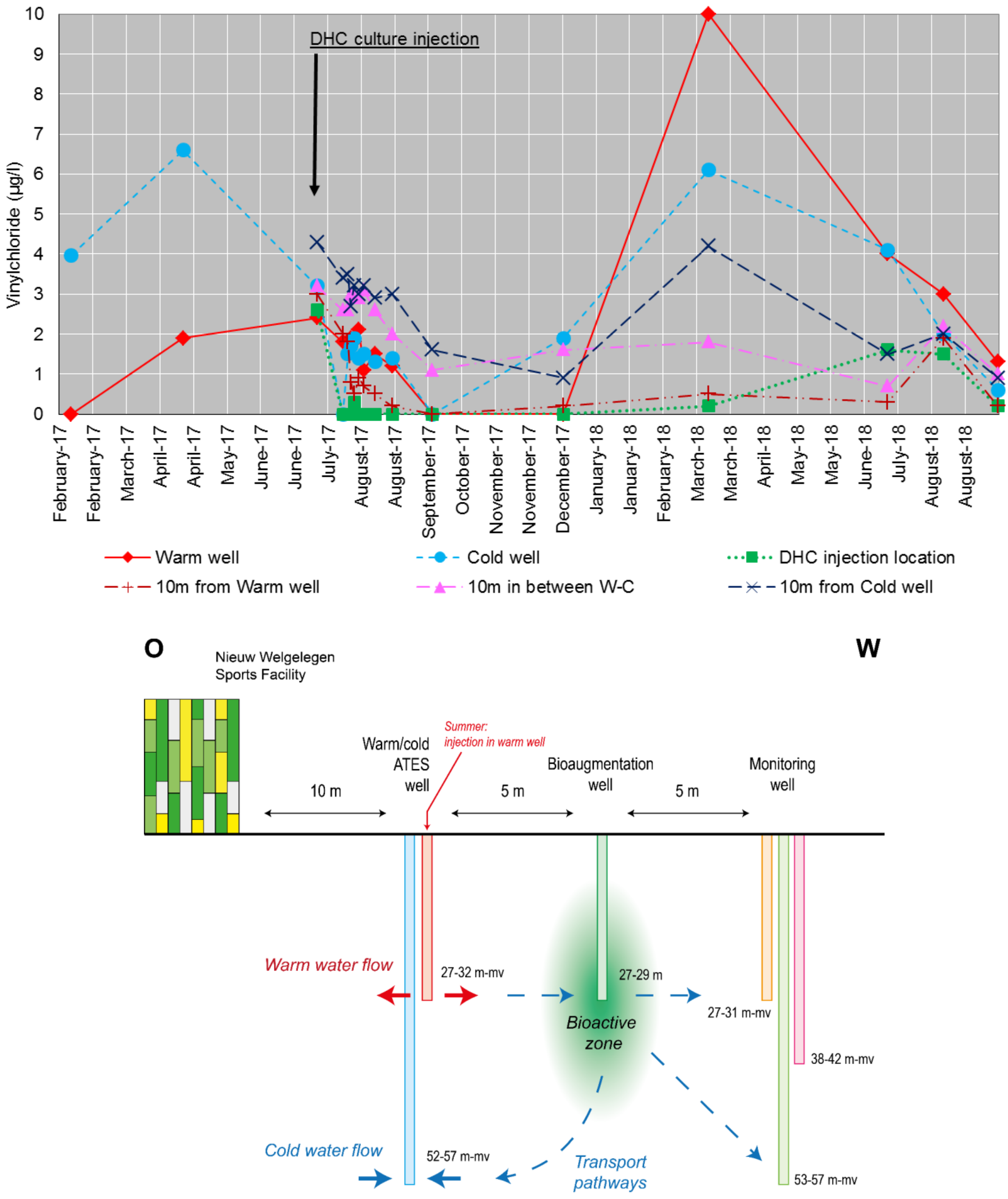

Figure C3. Schematization of Utrecht pilot plant operation during summertime.

C.4. Birkerod pilot plant (Denmark)

The assessment follows the assessment methods described and used by Ni et al. 2014 and Ni et al., 2014.

The use of ATES to stimulate bioremediation of high concentrations of chlorinated solvents is new, since the proof of principle for this concept was confirmed only at lab scale and in the Utrecht pilot this combination is under evaluation at industrial scale. However, in the Utrecht case the concentrations of the chlorinated solvents are relatively low and represent a traditional plume of chlorinated solvents. In Birkerod pilot plant (placed in The Hammerbakken 10 site) the concentrations of chlorinated solvent can be regarded as a source zone. So, this is the first pilot project in which a source of chlorinated solvents is treated by an ATES system. When this treatment shows to be successful it opens up a large market for the development of the combination of ATES and bioremediation.

The design of the ATES system (Figure C4) is based on two wells in which the groundwater is continuously pumped in one direction. The heat in the ATES system will be provided by the building at Hammerbakken 10. This will lead to a temperature increase of the groundwater which is the energy source for the stimulation for the biodegradation of the chlorinated solvents in the groundwater. To further optimize the biodegradation of the chlorinated solvents, the redox will be lowered by addition of electron donor (three injection wells, black circles in Figure C4). In a subsequent stage DHC bacteria can be added when needed. Four monitoring wells (orange circles in Figure C4) will be realized to continuously measure groundwater redox.

Figure C4. Danish pilot plant site.

ATES system should be completed by the end of 2017, and so monitoring activities will start on the beginning of 2018. The new experimental approach consists of three phases. In the first phase carbon sources and nutrients will be injected in both shallow and deeper groundwater layers downstream from the ATES injection well using carbon source injection wells (see black circles in Figure C4). Extraction and infiltration wells of the ATES system will be used to spread the carbon sources for an estimated period of 2-3 months. Simultaneously with the recirculation of the carbon sources groundwater heating will also start, since rate of the reduction processes for redox change will also be increased by elevated temperature.

In a second phase, if monitoring provides data that reduction of both upper and lower groundwater layers occur, the injection of both heat (through ATES system) and 6 m^3 of biomass in the carbon source addition wells will be tested. This second phase has an estimated period of 6-8 months to provide a thermal profile and increase temperature surrounding the injection wells and to give time for reductive dechlorination to occur.

Finally, based on monitoring of the extraction well (i.e. re-injected water) and monitoring wells in the influenced area on redox parameters, as well as VOC and microbial analyses, it will be possible to evaluate if it is necessary to re-inject carbon sources in the upper layer of the groundwater to suppress oxygen intrusion.

C.5. Ham pilot plant (Belgium)

The assessment follows the assessment methods described and used by Bloemendal et al. 2018.

The E-USE(aq) project Belgian pilot plant is a part of the project expansion of Nike’s European Logistics Center at Ham with a new, versatile and flexible storage facility (Figure C5). The new storage facility should set new standard in the logistics landscape and be an example on the European market. One of the sustainability topic addressed by the expansion project is the energy consumption. The project includes seasonal storage of cold and/or warm water in an aquifer, with the use of solar heat gained through 35 PV/T solar panels produced by Triple Solar to restore the thermal balance of the ATES warm well. PV/T solar panels are made by monocrystalline PV cells with an electric peak power of 260 W. The ATES system consists of 2 groundwater wells that have been drilled into the subsurface at a depth of 162,5 m in a specific geological formation. This formation consists of fine sand containing glauconite. The screen for the extraction and infiltration of the groundwater is installed between 80 m and 160 m (ground level). Besides the 2 production wells, 2 measuring wells with level ducts have been drilled in the field to confirm to the legislative requirements. The measuring well near the production well 1 (hot well) was drilled to final depth of the production well. Measuring well 2 was foreseen to be more shallow (in accordance with environmental legislation). Yet, in order to make a detailed measurement of underground temperatures possible, also measurement well 2 was drilled to final depth. The level ducts in the production and measurement wells were then equipped with glass fibres to monitor the evolution of underground temperatures. Four different monitoring wells equipped with optical fibers have been installed, at different depths and with different lengths.

Figure C5. Belgian pilot plant site.

The ATES system in Ham, Belgium, consists of two wells of about 160 m deep integrated with PVT solar panels. The data presented in Figure 4 and 5 covers the first year of operation of the Belgian pilot (see spatial lay-out in Supplementary material, Figure C5). Figure 4 shows that by 10th October 2016 approximately 13°C is extracted from the cold well, which can be considered the ambient temperature in the aquifer. To maximize direct cooling (i.e. the direct use of groundwater for space cooling) in the building during summertime, the injected water in the cold well in winter should be colder than approximately 8°C. In the first part of the heating season (until end 2016) the pump at the evaporator side of the heat pump ran constantly at full speed due to an error in the HVAC controls of the building. As a result, the water extracted from the warm well was not sufficiently cooled down by the heat pump and too warm water was injected into the cold well (see the triangle markers in Figure 4). The HVAC control strategy was modified by the end of 2016. From this point on, the volume averaged temperature injected in the cold well has been constrained and optimized and now lies around 8°C. These findings were confirmed by the subsurface temperature monitoring. Figure 4 shows that the storage of cold water worked very efficiently as the temperature extracted from the cold well also is around the injection temperature of 8°C during the first part of the second cooling season and slowly increased to 11°C at the end of August 2017. This is also confirmed by the glass fiber monitoring, as it can be seen in Figure 5, where the temperature measured at 100 m of depth in the cold well is compared with the volume averaged temperature of injected water.

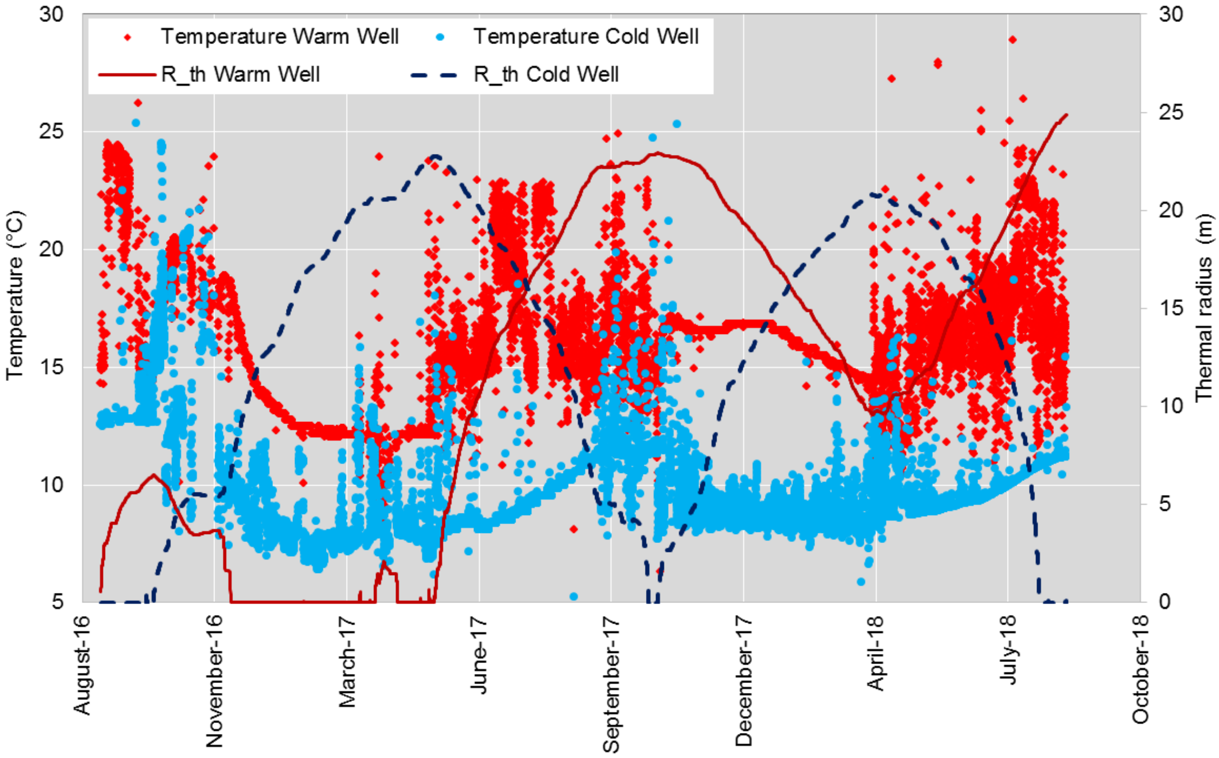

Figure C6. Temperature and volume of cold well during first year of operation at Ham site.

Figure 6 shows that after the initial period with cooling demand, the temperature in the warm well drops fast until it reaches the natural background temperature. This behavior is due to the startup at the end of the cooling season which did not permit storage of much heat in the warm well. As a consequence, the temperature difference during heating operation is quite small and higher volumes from the warm well are necessary to provide the requested amount of heat. When the temperature difference between the extracted water/injected water and the natural background temperature is taken into consideration, the amount of heating and cooling provided by the ATES can be split up in a contribution from the warm well and the cold well.

When analyzing the injected and extracted volumes it can be noticed that these are almost in balance, despite the larger annual cooling demand. This is explained by the larger temperature difference during cooling than during heating: in Figure 7 the distance between the temperature lines of the warm and cold well varies according to the flow direction, as can be seen from the jump in temperature when cold well radius starts to decrease in April 2017. However, Figure 7 also shows that at the end of this first year the warm well is charged with heat: the volume averaged temperature in the warm well is 17°C. This indicates that during the coming 2017/2018 heating season the warm well will deliver warmer water, which means that a larger temperature difference will be realized and a smaller flow of water will provide the same amount of heat. Consequently, a smaller volume of cold water will be stored per delivered kWh of heat. The cold well was not depleted at the end of the first year since the heating provided by the ATES was mainly realized by cooling down the cold well, since there was no heat charged in the warm well.

In the energy concept of the Belgian pilot, the geothermal heat pumps provide the main source of heating. Cooling is realized directly with cold groundwater (free cooling) or active cooling with the heat pumps (ATES as heat sink) or simultaneously with the heating. Energy flows were monitored during August 2017. During this period no charging of extra heat with the PV/T system was carried out, since the previous analysis confirmed that instead of charging extra heat, it will be necessary to charge extra cooling capacity during the next winter period.

The main findings of the energy monitoring are that: i) PVT panels cover 13% of the DHW demand during the monitored summer period, ii) despite being in summer, almost 50% of the heating demand was covered by the gas boiler due to an error in the HVAC control, which was adapted later, and iii) free chilling represents only 7% of the cooling provided by the ATES. The latter is problematic as it has an important negative impact on the seasonal energy performance. The reason for this high amount of active cooling was an error of the HVAC system: it was found that the temperatures delivered by the ATES were more than sufficient for free cooling (see Figure 4), but due to an error in the HVAC control the system was always put into active cooling mode. It is expected that in the second year of monitoring the full potential of the ATES will be demonstrated, as it was witnessed that after the modifications the system correctly switched to free cooling. These findings show how important it is to perform a thorough commissioning of the system, as mistakes in the programming of HVAC controls can have a serious negative impact on the performance of the system.

C.6. Bologna pilot plant (Italy)

There is no data avaialable yet to evaluate the results of this pilot.

Different sites have been identified for the installation of an ATES system in Emilia-Romagna region, and after a preliminary techno-economic analysis the Martignone electric station was identified as the most suitable site. Martignone station is placed near Bologna and it is owned by Terna, which is the Italian operator in electricity transmission grids. The station includes two buildings and the conditioned rooms have a volume of about 3,800 m^3 and were heated and cooled by electric and methane boilers and by an air-liquid chiller. The pilot plant was designed to completely substitute the methane boilers, while electric boilers and air-liquid chiller remain as back-up and integration units. Three reversible heat pumps and one chiller will be installed and fed by groundwater. Three extraction and three injection wells have been designed on the basis of preliminary pumping tests carried out by the end of 2016 (Figure C6). Further investigations are still ongoing (including pumping test involving all the extraction wells and dye tracing test) to evaluate if short circuit can occur between extraction and injection wells, and also to estimate warm and cold plume direction. Four monitoring wells have been installed to verify the impact on the plant during operation.

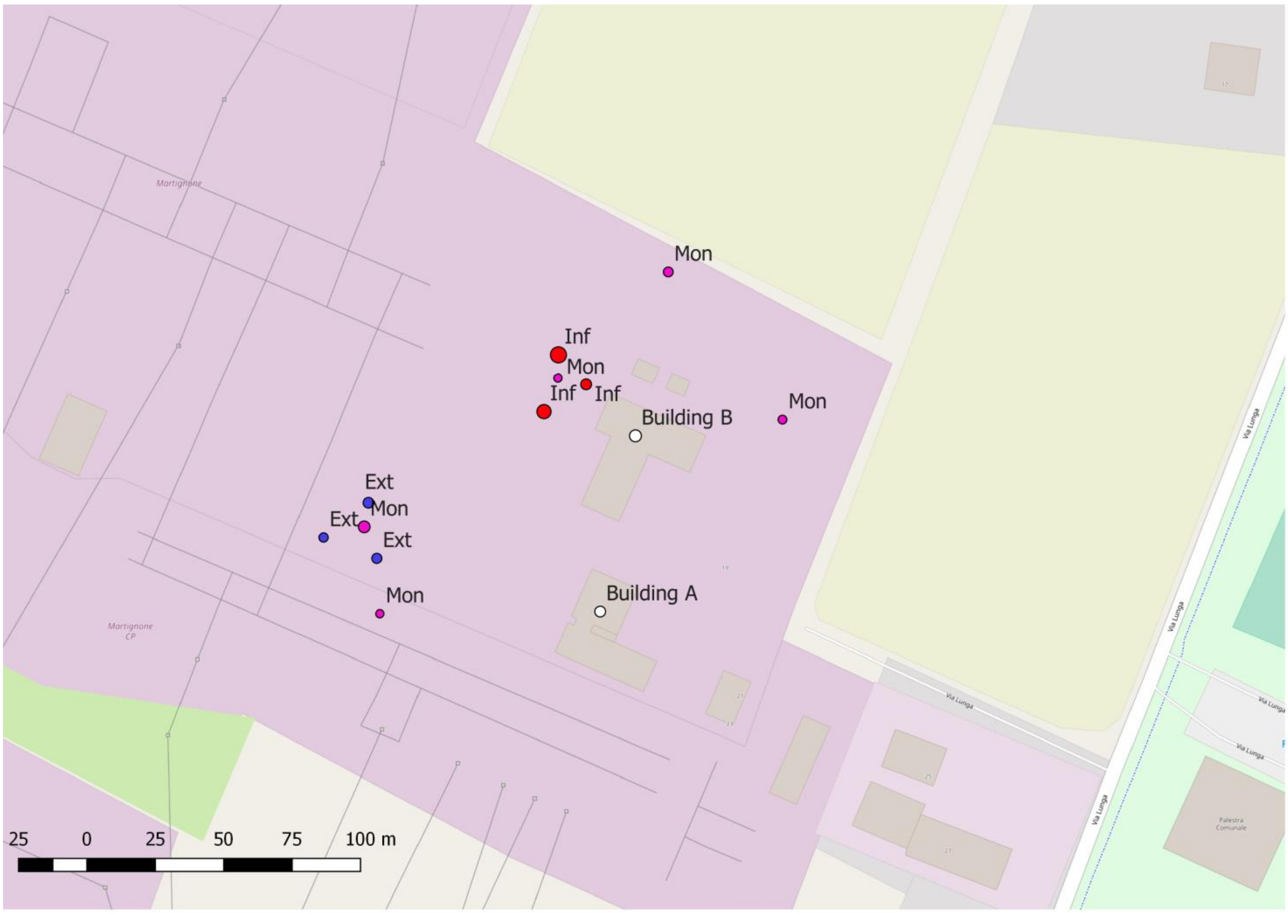

Figure C6. Wells positioning in the Italian pilot plant. Inf= infiltration wells, Ext= extraction wells, Mon = monitoring wells.

The peculiarity of the pilot plant is that there are some rooms in building B of Figure C6 that need cooling all year long. So, there is the opportunity to test at small scale the concept of CDH. Groundwater cannot be used directly to feed the reversible heat pumps and the chiller since it is characterized by very high hardness and high concentration of manganese. Manganese in particular is a potential cause of clogging. So, a secondary circuit has been designed to exchange energy with the groundwater and carry it to the heat pumps/chillers. As a result, in wintertime the heat that is extracted from the rooms to be cooled is transferred via the secondary circuit to the rooms that need to be heated, thus reducing the unbalance between heat storage and recovery in the aquifer. Pilot plant configuration does not allow the realization of an ATES system: the first two years of operation will be used to evaluate if and how an ATES system can be effectively applied. By the end of October 2017 all the wells have been completed and the realization of the above ground works started. The pilot plant is supposed to be switched on by the end of summer of 2018.

C.7. Nules pilot plant (Spain)

The assessment follows the assessment methods described and used by Bloemendal et al. 2018.

The Spanish pilot plant consists of a 109 kW_{th} groundwater source heat pump which has been connected to four DCL probes to maintain at a constant temperature of 28°C the main swimming pool of Nules sport centre (S-1, S-2, S-3 and S-4 in Figure C7). The heat pump has two scroll compressors of 50 kW each, which are activated in one or two power stages at the request of the system. The building has a dehumidification system by direct expansion in an air treatment unit, plus a fan coil system for heating and direct expansion split units with outdoor units for air conditioning. Also, the heating system of the pool originally installed has two boilers of 320 kW each that use natural gas. The heat produce by the heat pump is transferred to the pool with a heating loop using a heat exchanger in-line with the existing heating boiler circuits. Pilot plant configuration does not allow the realization of an ATES system; nevertheless, the pilot aims to show how shallow geothermal energy can be used efficiently and with no impact on groundwater characteristics thanks to an extensive monitoring of groundwater. Since the plant has already showed its ability to store cooling capacity in the aquifer, on a second phase it will be possible to implement the plant with cooling delivery and to evaluate if the ATES system can be effectively realized.

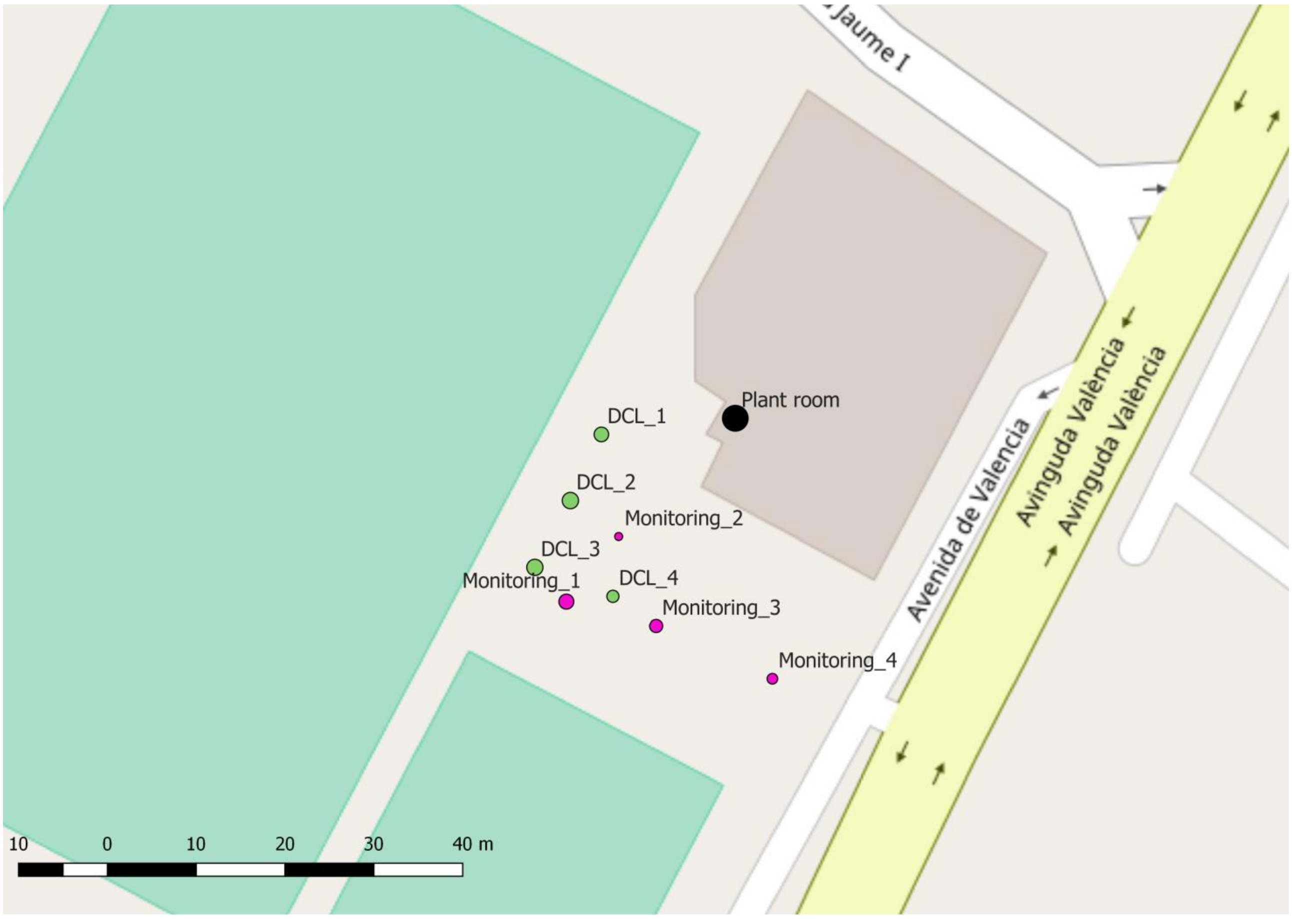

Figure C7. DCL and monitoring well positioning at the Spanish pilot plant.