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DOI
10.1016/j.scitotenv.2019.136142

Publication date
2020

Document Version
Accepted author manuscript

Published in
Science of the Total Environment

Increasing market opportunities for renewable energy technologies with innovations in aquifer thermal energy storage

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Abstract

Heating and cooling using aquifer thermal energy storage (ATES) has hardly been applied outside the Netherlands, even though it could make a valuable contribution to the energy transition. The Climate-KIC project "Europe-wide Use of Energy from aquifers" – E-USE(aq) – aimed to pave the way for Europe-wide application of ATES, through the realization and monitoring of six ATES pilot plants across five different EU countries. In a preceding paper, based on preliminary results of E-USE(aq), conclusions were already drawn, demonstrating how the barriers for this form of shallow geothermal energy can be overcome, and sometimes even leveraged as opportunities. Based on final pilot project results, key economic and environmental outcomes are now presented. This paper starts with the analysis of specific technological barriers: unfamiliarity with the subsurface, presumed limited compatibility with existing energy provision systems (especially district heating), energy imbalances and groundwater contamination. The paper then shows how these barriers have been tackled, using improved site investigation and monitoring technologies to map heterogeneous subsoils. In this way ATES can cost-efficiently be included in smart grids and combined with other sources of renewable (especially solar) energy, while at the same time achieving groundwater remediation. A comparative assessment of economic and environmental impacts of the pilots is included, to demonstrate the sustainability of ATES system with different renewables and renewable-based technologies. The paper concludes with an assessment of the market application potential of ATES, including in areas with water scarcity, and a review of climate beneficial impact.

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

1. Introduction

A transition to a low carbon energy system is needed to respond to the global challenge of climate change. 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 (Bloemendal et al., 2015). The basic working principle of ATES is described in Pellegrini et al., 2019a. Figure 1 shows schematics of three main design types.

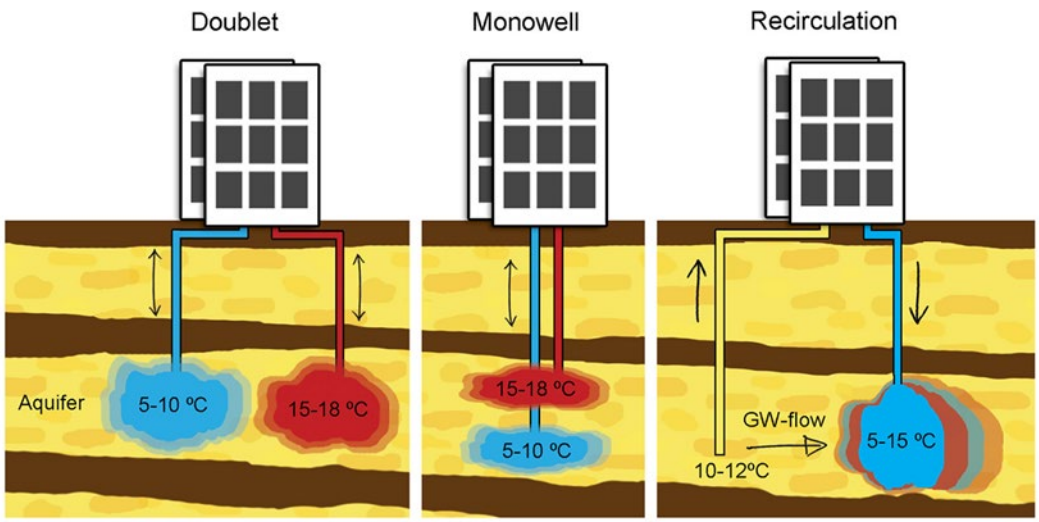


Figure 1. Schematic representation of ATES doublet, monowell and recirculation systems. The doublet system at the left is the most common. The monowell system in the middle, with the hot well on top of the cold well needs less space and has lower installation costs, since one borehole suffices. The recirculation system is preferable at high groundwater flows but is less effective, since infiltrated cold and heat are not reused.

Various ATES systems have been reported in operation for heating and cooling supply (Bertani, 2005; Gao et al., 2017; Fleuchaus et al., 2018): ATES have been developed and widely applied in the Netherlands in the last few decades, while this technology has been only recently picked up also in other countries, such as Belgium, Denmark, Germany, Sweden and the US. As a result, more than 2800 ATES are installed worldwide, but more than 90% are operating in the Netherlands alone. ATES reaches the highest efficiency if applied in buildings with high, constant and balanced energy demand over the year, such as offices, airports, universities, shopping malls and hospitals (Fleuchaus et al., 2018). Despite the high market potential, the adoption of ATES across Europe has been slow, mainly because of technical (building, subsurface and climatic conditions) and organizational/legal barriers (Haehnlein et al, 2010; Monti et al., 2012; Pellegrini et al., 2019a). Economic barriers are also present: though some feasibility studies can be found in literature (Schüppler et al., 2019), the majority of the studies only briefly summarised the economics of ATES.

After identification and classification of all of these barriers in the Climate-KIC project 'Europe-wide Use of Sustainable Energy from aquifers' – E-USE(aq) – the project team demonstrated how the barriers can be overcome by implementing six ATES pilot systems across five different EU-countries (Pellegrini et al., 2019a). At two sites (Delft-The Netherlands and Ham-Belgium) ATES has been integrated with hybrid photovoltaic or photovoltaic-thermal (PVT) panels, thus addressing the gaps of heating/cooling demand seasonal balancing and of heat pumps power consumption. At two other sites ATES has been combined with bioremediation (Utrecht-The Netherlands and Birkerod, Greater Copenhagen-Denmark) to demonstrate how ATES can be effectively applied in contaminated sites for bioremediation purposes. At a

Spanish site (Nules), located within an area affected by water scarcity, a system without groundwater extraction and infiltration has been installed in a swimming-pool. Finally, in an Italian site (Anzola dell'Emilia, Bologna) a recirculation ATES system has been realized to feed a small district heating and cooling network, to verify how ATES systems can be integrated in smart district energy grids. Figure 2 shows a map of the pilot plants locations, while in Table 1 a summary of main pilot plant data is given. More information about the pilot plants can be found in Pellegrini et al., 2019a and in the provided supplementary material.

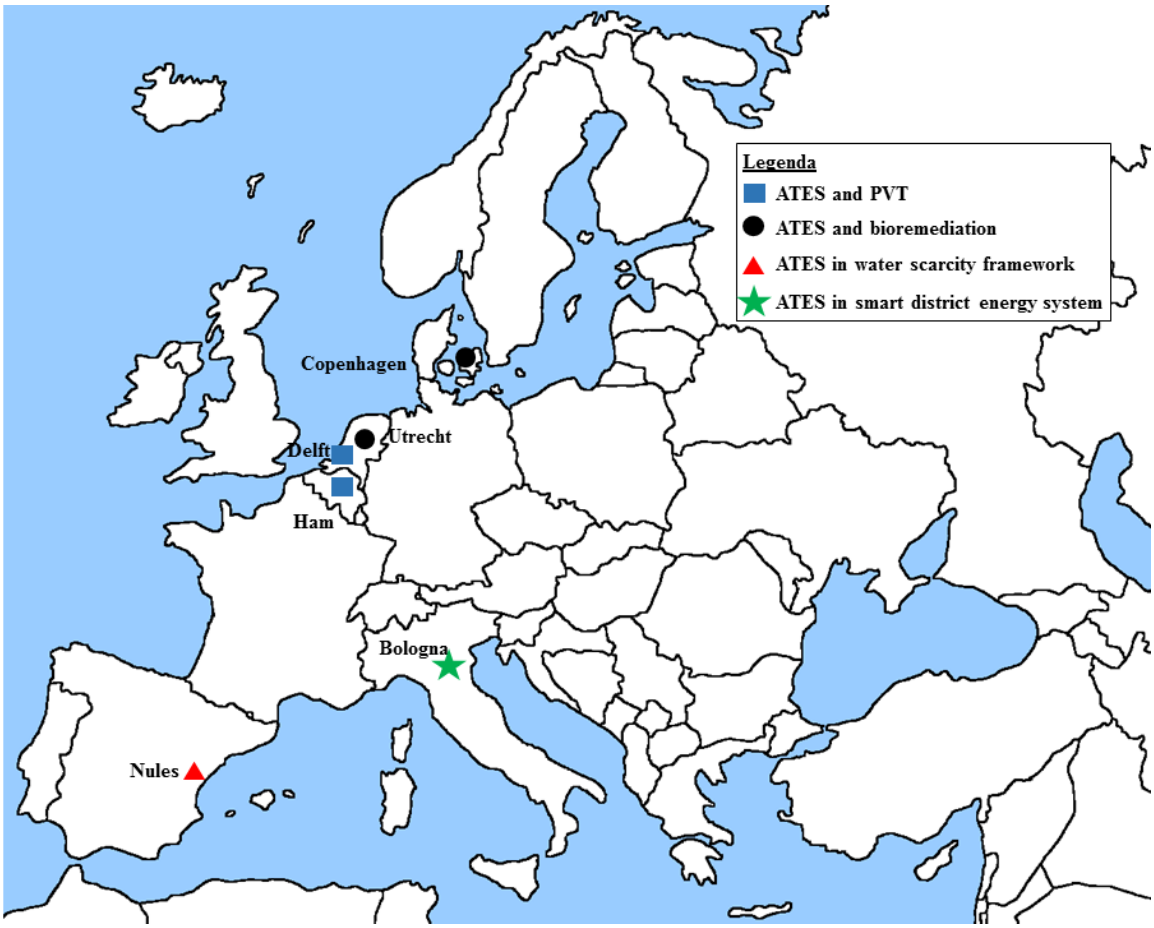


Figure 2. Map distribution of E-USE(aq) project pilot plants.

Table 1. Pilot plants main characteristics. (*) extraction and injection wells.

Parameter	Delft	Utrecht	Copenhagen	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	5	80	19.4	14.4

Max cooling power (kW)	30	-	No cooling	1,300	140	No cooling
Max heating power (kW)	70	-	No heating	650	160	109
Annual cooling demand (MWh)	160	-	No cooling	900	49	No cooling
Annual heating demand (MWh)	160	-	No heating	863	170	288

In Pellegrini et al., 2019a the outcomes of the barrier analysis and preliminary results of the pilot plants were discussed and solutions for overcoming the barriers were presented. The main topics addressed in previous research are reported below:

- Legislation: In earlier work Haehnlein 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. Barriers indicated and discussed in this work are: poorly substantiated legislation in Spain, a lack of legislation on combining ATES with remediation in Netherlands and Denmark, and complex regulation and poor expertise at the local government level in Italy.
- 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, many research questions remain on how larger temperature changes (> 30°C) affect groundwater quality, as well as how mixing of various groundwater qualities affects aquifer quality. This paper discusses how ATES can be combined with soil/groundwater remediation in Netherlands and Denmark.
- System design/integration: The Dutch industry organization developed design standards, mainly focusing on avoiding well clogging and on integration of the ATES wells and heat pump into 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). In this work, further steps are taken in the integration with the buildings system with solar collectors for energy balance (in Belgium and The Netherlands) and integration with district heating (in Italy).

The main objective of this follow-up paper is to present the key project results reached in the last year of pilot operations, which offer opportunities to enhance market uptake of ATES and pave the way for a larger scale adoption. In particular, results showed that i) improved site investigation and monitoring technologies can be effectively used to map heterogeneous subsoils, ii) ATES systems can be combined with other sources of renewable energy (especially solar) to

110 balance the energy demand over the years, iii) ATES systems can be designed to be included in smart grids and iv) ATES
111 systems can be effectively combined with groundwater remediation applications. A comparative assessment of economic
112 and environmental impacts of the pilots is included to demonstrate the sustainability of ATES system with different
113 renewables and renewable-based technologies. E-USE(aq) project demonstrated that ATES systems can be applied under
114 strongly varying conditions in different European countries and through different innovative technological solutions.
115 Nevertheless, further continued investigations with long-term monitoring and evaluation of projects are needed to
116 strengthen the results, including economic perspectives.
117

118 # 2. Methods & Materials

119 This chapter includes a description of the methods applied in the design, monitoring and assessment phases of the pilot
120 plants.
121

122 ## 2.1 Detailed underground characterizations through monitoring actions

123 One of the main technological barriers identified by E-USE(aq) project is the unfamiliarity with the subsurface (Pellegrini
124 et al., 2019a). This barrier is relevant in both design and monitoring phases, and can have a negative impact also in the
125 authorization/permit phase. For example, when well screens are situated in more than one water bearing layer, water of
126 different composition often mixes, which can result in chemical precipitation of for instance iron oxides or sulphides and
127 consequently clogging problems within the system, as has been observed numerous times in the Netherlands (van Beek,
128 2010). Therefore, detailed underground characterizations were used for the finalization of the pilot plants design and
129 monitoring in each site.
130 In particular, in order to obtain insight in the composition of the shallow subsurface and the quality of the groundwater,
131 geophysical well log measurements were performed at the Belgian and Dutch sites with a high resolution temperature
132 distribution multi tool, including:
133 - Gamma Ray (GR) measurement of the natural gamma radiation from the subsurface. Clay in general has a higher
134 gamma radiation than sand. For the GR-results the standardized unit gAPI (gamma-ray American Petroleum Industry)
135 is used. A high gAPI value indicates the presence of clay, a low value is an indication for sand, except when sand is
136 rich in clay minerals or in specific minerals such as Glauconite.
137 - Short Normal (SONO) measurement of electrical resistance (Ωm) in a specific zone (~0.5 m) around the tool. The
138 measured electrical resistance depends on the bore fluid, the diameter of the drilling, the groundwater and the
139 geological formation. Within an open hole with fresh groundwater, a relatively low electrical resistance indicates the

presence of clay and a relatively high electrical resistance is an indication of the presence of sand. In salt groundwater the difference is not easily made.

- Long Normal (LONO) measurement, which is based on the same principle as the SONO measurement, but with a larger range (~1.5 m), allowing more insight into the geological formation.
- Single Point Resistivity (SPR) measurement of the electrical resistance between the tool and a reference electrode near the well is measured. The results can only be used qualitatively.

Distributed Temperature Sensing (DTS) was performed with a fibre optics device (see Figure 3).

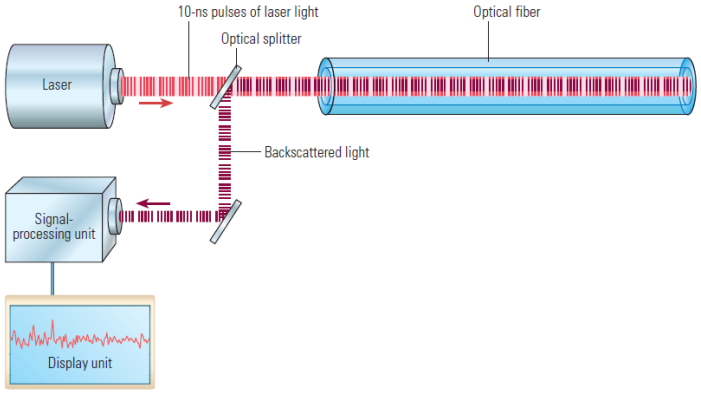


Figure 3. Temperature monitoring with fibre optics using raman backstatter DTS sensing.

Due to the harsh environment in the soil, data were collected in a single ended measurement manner using a double ended setup (see Figure 4). Thus, both available channels can be used to correct for attenuation within the cable and temperature offset. When a cable is damaged during the measurement period the double ended configuration setup doesn't work and for the whole cable the data would become worthless. Hence, both sides were measured but stored in a single ended configuration (see Figure 4b from Hausner et al, 2011). In this set-up it is possible to calibrate the single ended measurements afterwards, so that a higher accuracy of the measurements is achieved.

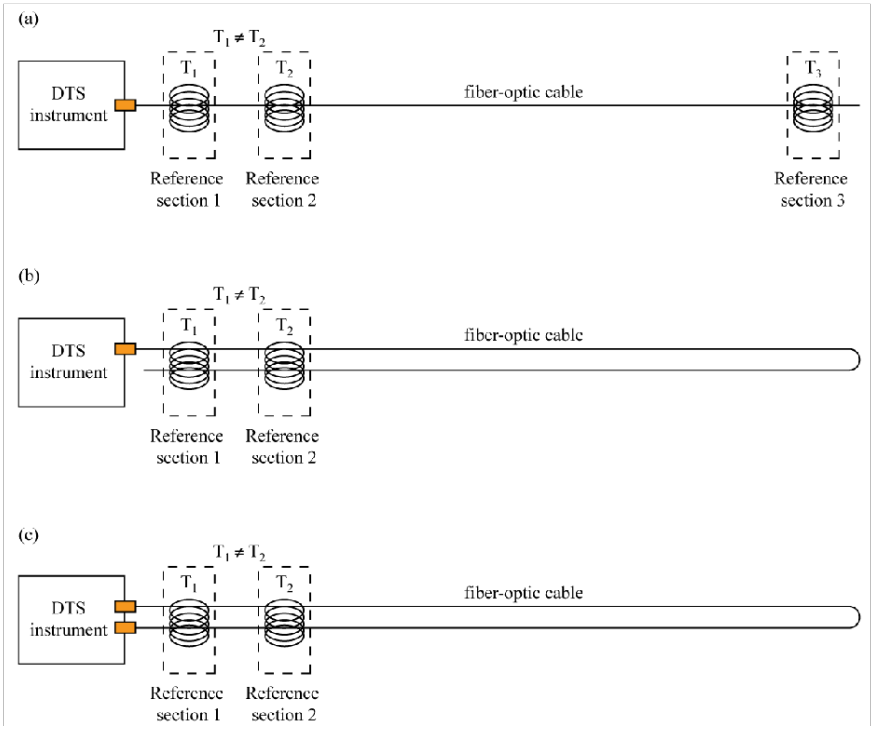


Figure 4. Experimental measurement set-ups (Hausner et al., 2011) a) Simple single-ended configuration; b) Duplexed single-ended configuration; c) Double-ended configuration.

For each position on the fibre optic cable it is possible to define an x, y, z position. With these positions it is possible to process the fiber optic data into temperature distribution profiles, which form the basis for 3-d visualisation. A commonly used setup is that the fibres are installed in the subsurface around ATES wells. At each position the fibres are connected to each other, so all positions can be monitored using only one channel connection.

2.2 ATES design for integration in smart district energy grid

The combination of ATES systems with district heating and cooling (DHC) networks has been obstructed by various techno-economic limitations: cooling networks hardly exist (Werner, 2017), high temperature networks complicate the use of sustainable sources of heat and the use of heat pumps (Kontu et al., 2019), and, finally, the economic model with cogeneration of power cannot be applied. In the last years a novel concept of DH network - the 4th district heating generation, also called “Low Temperature District Heating” (LTDH) - has been proposed (Lund et al., 2014), based on the following characteristics: i) to supply low-temperature thermal energy to new and existing customers, ii) to minimize thermal losses, iii) to integrate low enthalpy heat and iv) to become part of smart energy systems contributing to the transition towards a 100% renewable energy supply system characterized by the integration of different energy sectors. The LTDH definition identifies a wide range of temperatures: for example, a preliminary classification is proposed in

177 Averfalk et al. 2017 where “warm LTDH” and “cold LTDH” systems are distinguished based on the necessity to locally
178 boost the temperature at customer level.
179 Even if relevant barriers are still present in the development of LTDH systems (Pellegrini et al., 2019b), the combination
180 of ATES and low temperature DHC system is a promising solution for the implementation of a carbon-free heating and
181 cooling strategy. In fact, ATES systems can play a relevant role in the following fundamental topics related to existing or
182 new DHC systems:
183 - Increasing the efficiency of existing DHC networks: In the last few years, the selling price of power dramatically
184 dropped, and so the CHP business model is not sustainable anymore for DH networks. Since the use of reversible heat
185 pumps enables self-consumption of at least a part of the power produced by CHP plant, ATES systems can be seen as
186 a way to free the economics of DHC networks from the power selling price, and to increase the renewable energy
187 share.
188 - Seasonal storage: ATES systems can represent a key element in the seasonal efficiency increase of DHC networks,
189 since ATES systems are able to store excess heat in the groundwater in summer to be used in winter, and to store
190 excess cold in winter to be used in summer, that would otherwise be lost. ATES systems can be coupled with other
191 renewable sources (e.g. solar) and can add flexibility to both existing and new DHC networks.
192 - Decentralized heating and cooling production: ATES systems can be used in low temperature DHC networks as a
193 local and decentralized temperature booster or as a sink. So, ATES systems can balance temperatures of the cold
194 distribution network, thus favoring effectiveness and efficiency of the whole network. Moreover, ATES systems can
195 be used as decentralized heat/cold storage network elements.
196 - Power-to-heat and power-to-cool: reversible heat pump installation in DHC systems is a fundamental part in the design
197 of a smart energy grid, i.e. a multi-source grid integrating power grids, natural gas grids and DHC networks.
198 Converting electricity into heat (power-to-heat) or cold water (power-to-cool) through reversible heat pumps provides
199 flexibility for the electricity system, since operation is possible when electricity prices are low and/or when an excess
200 of electricity is produced by renewable sources (i.e. photovoltaics and wind turbines). When the ATES concept is
201 applied for power-to-heat and power-to-cool, there is the further benefit of using renewable energy as heat source or
202 heat sink and of allowing the storage of the heat and cold produced.
203 However, expertise and concrete projects in the field are limited and there is currently a lack of reliable and adequate
204 analytical tools and cost data to assess the technical-economic potential of ATES in combination with DHC networks
205 (Schmidt et al. 2018). The E-USE(aq) Italian pilot tried to overcome these barriers, since it combined a recirculating
206 ATES system with a cold low temperature DHC network.
207

2.3 ATES energy performance monitoring

Design and execution of the E-Use pilots were described in Pellegrini et al., 2019a with most relevant specifics, including site maps, in the supplementary material. Detailed descriptions can also be found in Hoekstra and Van Gelderen, 2019 (project website). Methods and materials for pilot plants operation, measurements and monitoring of energy balances were used in such a wide variety at the different pilots that they cannot all be described specifically within the limitations of this paper. Since only commonly used and as far as possible certified methods and instruments were applied, these details are not deemed relevant to the scope of this paper.

2.4 Impact assessment of ATES in combination with bioremediation on groundwater quality

In the Dutch pilot in Utrecht, complete Vinyl Chloride (VC) degradation was obtained within one day after bio-augmentation of a chlorinated solvent reducing bacterial culture, measured at the bio-augmentation well, which was situated approximately 5 m from the ATES well. Within a week, 90% contaminant reduction was also observed at the monitoring well, situated approximately another 5 m downstream. Although this large effect was only temporary, as shown in Pellegrini et al., 2019a, a year after bio-augmentation, a clear effect could still be observed. VC concentrations in the ATES well fluctuate over the season, but there also appears to be an unexpected distinct decrease in the ATES wells, 5 m upstream from the bio-augmentation well (Pellegrini et al., 2019a). Supposedly dechlorinating micro-organisms, found in the ATES wells, have most likely migrated upstream – in line with the interference between hot and cold layers shown in § 3.1 – via the cold well, to which deeper groundwater flows in the opposite direction, thus increasing the proliferation of degrading organisms via the ATES system. Pellegrini et al., 2019a also shows that in the bio-augmentation well, dechlorinating micro-organisms are still present one year after bio-augmentation. This provides evidence that the observed long lasting VC reduction is indeed caused by continued degradation, although this could not be proven by the presence of degradation products due to the low concentrations.

2.5 Economic data and assumptions

A crucial driver for increasing the Europe-wide implementation of ATES systems is demonstration of economically feasible systems. Through the analysis of the pilot plants realized in the E-USE(aq) time framework it has been possible to collect relevant data in different EU countries about the costs related to the design and installation, and operation and monitoring of different ATES system combined with several technologies. Pilot plants have been operational from a minimum of one to a max of four years.

2.5.1 ATES systems for heating and cooling purpose

Table 2 summarizes the relevant data used for the economic assessment of the different E-USE(aq) pilot plants characterized by heating and cooling purposes. The presented data have been used to feed an Excel sheet designed by Nomisma Energia Srl which automatically calculates the discounted payback period (DPP) for each pilot. DPP represents the number of years necessary to break even on the investment, while accounting for the discounted value of money (Short et al., 1995). DPP has been identified as an effective economic parameter to compare the different pilots with respect to investment payback and risk. The formula for DPP computation is reported in Equation 1, wherein the discounted yearly profit or loss is computed (cumulative cash flow, CCC). Yearly CCC are discounted through the annual interest rate i. Energy savings data have been measured for Delft, Ham and Nules sites, while in the case of Bologna pilot the energy figures are based on estimation. A peculiarity of the Italian pilot is the absence of power costs, which is due to the fact that the pilot plant owner is also the company manager of the Italian electricity grid and that the pilot plant is located in an electric station. As a result, power consumption of the pilot plant is negligible and not accounted. Nevertheless, this very specific condition is economically balanced by the high capital costs, as discussed in the following sections.

Table 2. Main economic figures of ATES pilot plants for heating and cooling purposes.

Parameter	**Symbol**	**Delft**	**Ham**	**Bologna**	**Nules**
Capital costs (€)	CAPEX	62,000	116,000	460,000	58,000
Specific capital costs (€/kW th peak)	-	886	178	2,875	532
Natural gas consumption without ATES (Sm3/year)	ER_{-NG}	11,500	188,000	24,000	36,000
Electricity consumption without ATES (MWh/year)	ER_{-E}	27	297	20	3
Natural gas consumption with ATES (Sm3/year)	$EATES_{-NG}$	0	58,100	0	14,315
Electricity consumption without ATES (MWh/year)	E_{ATES-E}	19	492	102	64
Natural gas cost (€/Sm3)	c_{NG}	0.55	0.53	0.96	0.70
Electricity cost (€/MWh)	c_E	170	94	0	141
Operation and Maintenance costs of ATES (€/year)	$C_{O\&M}$	2,000	16,000	2,000	266
Other costs of ATES system (€/year)	C_{other}	1,000	0	2,500	2,500
Annual interest rate (%)	i	6	6	6	4
Amortization period (year)	n	10	10	10	10

Average tax rate (%)	t_R	26	34	26	21
Depreciation rate used for tax (%)	d_R	5	0	5	3
Fiscal leverage (%)	f_L	0	0	0	50
Rate of deductible interest (%)	r_{DI}	30	30	30	30
Yearly incentives (€/year)	In	0	0	4,116 for 7 years	4,152 for 5 years
Co-financing incentives (€)	Inc	0	0	0	0

254

255 $CCC = - CAPEX – OPEX + OR + LA + TD$ (Eq. 1)

256 CAPEX includes all the capital costs (design, authorization/permit procedure, preliminary tests, realization and
257 commissioning of the pilot plants). OPEX can be computed as in Equation 2:

258 $OPEX = C_{O\&M} + C_E – R_E + C_{other}$ (Eq. 2)

259 where CO&M is the annual operation and maintenance cost of the ATES plant, Cother are other costs (i.e. administration
260 and insurance costs) related to ATES system operation, C_E and R_E are computed as, respectively, yearly energy costs of
261 the ATES system in Equation 3 and yearly energy revenues or the energy savings produced by the ATES system if
262 compared with the reference situation (i.e. before ATES installation) in Equation 4.

263 $C_E = \Sigma\, c_i \cdot E_{ATES\text{-}i}$ (Eq. 3)

264 $R_E = \Sigma\, c_i \cdot E_{R\text{-}i}$ (Eq. 4)

265 OR includes other yearly revenues, that are yearly incentives In and co-financing incentives Inc. An example of yearly
266 incentives are the white certificates, while an example of co-financing incentives are regional, national and European co-
267 funds. LA is the loan amortization, while TD is the tax deduction.

268

269 ### 2.5.2 ATES in combination with bioremediation

270 In cases where ATES can be combined with ground water remediation, a payback analysis of costs of energy or avoided
271 greenhouse gas emissions does not offer a complete picture. In these cases, the value of clean groundwater should also
272 be taken into account, which is hard to determine, and compared to standard remedial costs, which are evaluated in the
273 paper. Only rough estimates can be made for the total costs of a combined ATES + Bioremediation project, since the
274 frequency of bacterial batches to be grown and infiltrated into the soil per year is not yet known, because the long-term
275 durability of the bacterial mass is still unknown. Obviously, the number of batches will strongly influence the total costs.

For a rough estimation and comparison, a VOC contaminated groundwater volume of 100,000 m^3 is imagined. The specific and discounted treatment cost per cubic meter of contaminated groundwater can be computed for different technologies starting from the data summarized in Table 3. Remediation technologies costs and performances are based on expert judgement and the Dutch soil quality recovery guidelines, 2019.

Table 3. Main economic figures of different state-of-the-art technologies used for groundwater remediation.

Parameter	**1. Pump and treat**	**2. Bioaugmentation**	**3. Chemical oxidation**
Contaminated volume (m^3)	100,000	100,000	100,000
Treated volume (m^3)	1,000,000	137,600	100,000
Specific treatment cost (€ per treated m^3)	1.50	3.85	35.00
Treatment duration (year)	11.5	2	1
Annual interest rate (%)	1.5	1.5	1.5

For case 1, using traditional groundwater remediation technologies (i.e. pump and treat), normally ten times the contaminated volume must be pumped and treated to remove contaminants. For the hypotetical contaminated groundwater volume given above, the treatment of 1,000,000 m^3 will be necessary, with an average price of € 1.50 per m^3 (including often needed additional iron removal). The time required for the completion of the treatment is estimated as 11.5 years, based on a 10 m^3/h of flow.

In case 2, bioaugmentation technology is applied (like TCE/BEAT®) and low-density bacterial culture cultivated on-site are injected into the groundwater. The treated water is 1.4 times contaminated groundwater volume, with a specific treatment cost of about 3.85 €/m^3. Here, the required time to complete the treatment can be estimated at about 2 years. Finally, in case 3, groundwater remediation with chemical oxidation, e.g. with (per)ozone, would require one year against approximately € 3,500,000 of remediation cost, being € 35/m^3.

For ATES and bioremediation the calculations are based on a treatment period of 25 years in a new or existing ATES system, resulting in 50 cycles of groundwater flow through the activated zones and one batch of 10 m^3 of bacterial culture per year in order to obtain sufficient degradation capacity. In total 25 batches of biomass injection are necessary. It is possible to assume a cost of approximatively € 40,000 or € 20,000 per batch in the case of, respectively, limited or wide market up-take of the technology.

2.6 Climate impact of ATES systems

In the Netherlands, where ATES is more common, the registrations of ATES systems and the national CO_2 emission reduction accounting indicate that the average greenhouse gas (GHG) emission reduction per ATES-system is between 45 and 80 ton CO_2/year (originally derived from CBS, 2009, and van Agt, 2011), strongly depending on reference case, size, type of building and climate. On the basis of energy savings reported in Table 2, it has been possible to compute or estimate the equivalent CO_2 emission reduction produced by the ATES systems in each pilot. Equivalent CO_2 emission related to power consumptions have been computed by considering the mean efficiency of the thermoelectric plants for each country (see Table 4).

Table 4. Conversion factor of kg of CO_2 equivalent per Sm^3 of natural gas burned and MWh of electric power produced (Koffi et al., 2017).

Parameter	**Value**	
CO_2 emission from natural gas combustion (kg CO_2/Sm^3 of natural gas)	1.87	
CO_2 equivalent emission per power production (kg CO_2/MWh el)	342	ITA
	247	SPA
	451	NED
	196	BEL

3. Discussion

The chapter provides an interpretation of the main findings of the E-USE(aq) project by focusing in particular on how the integration of ATES with different renewables and renewable-based technologies can produce economic benefits as well as positive impacts on the environment.

3.1 Subsurface monitoring results

3.1.1 Belgian site

Results of state-of-the-art monitoring technology used for the Belgian pilot are shown in Figure 5. A combination of geophysical measurements and expert judgement generates an interpretation of the soil profile based on which a basic extraction/infiltration and monitoring well design configuration was suggested. However, at the time the wells of the ATES system had already been installed without characterization of the deep subsoil. During installation, it turned out that the aquifer was much deeper than expected, which provided the opportunity of installing considerably longer well

screens than originally planned, resulting in increased system capacity and a higher energy yield. In this case, it was possible to change the planned design quickly, otherwise this opportunity to increase capacity would have been missed.

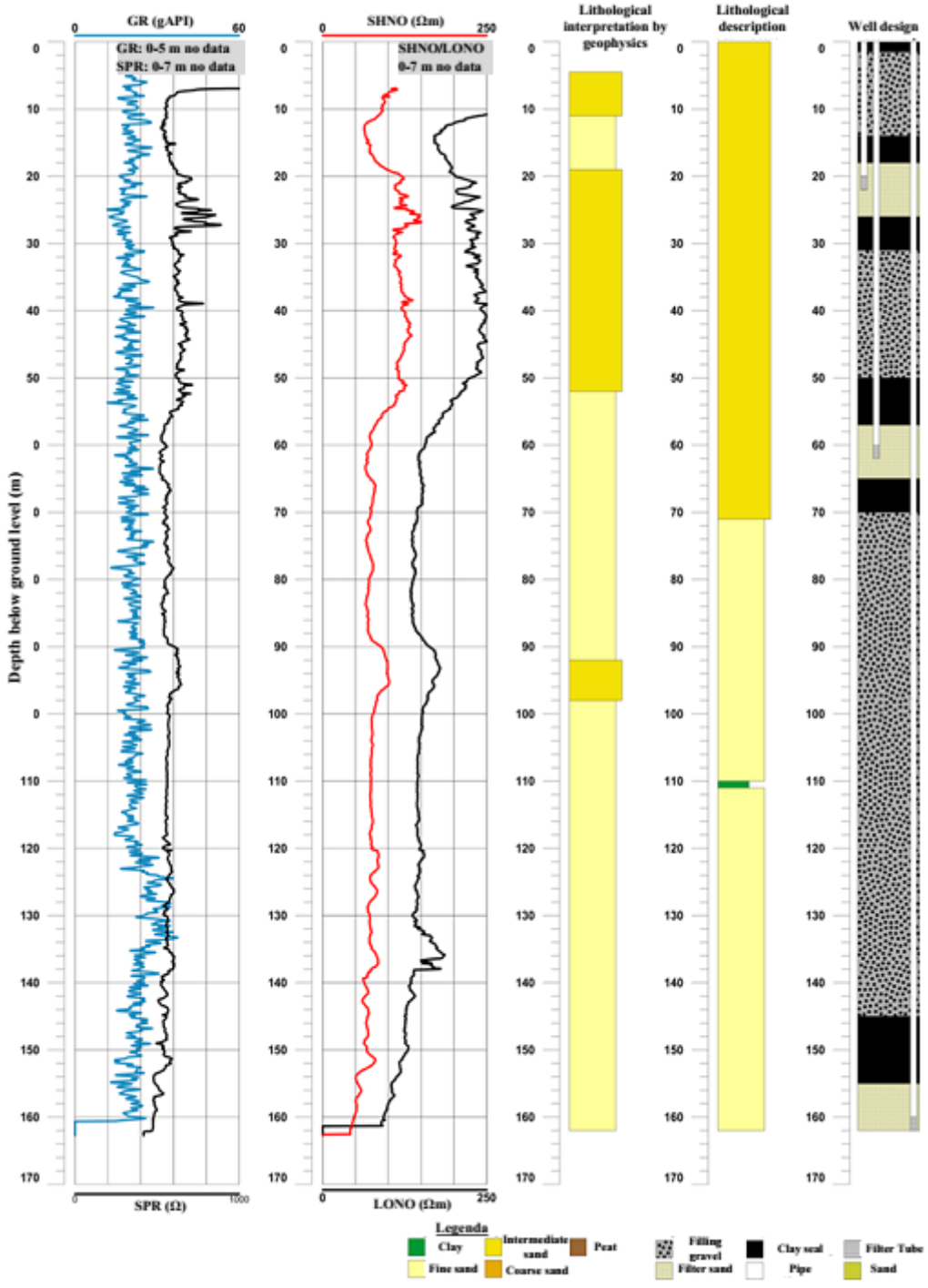


Figure 5. Illustration of combined geophysical measurements resulting in a soil profile and a well design. GR=Gamma Radiation; SPR=Single Point Resistance; SHNO=Short Normal; LONO=Long normal.

At the Belgian pilot, high resolution soil temperature distribution measurements were performed. The evolution of increased temperatures in the hot well and low temperatures in the cold well are illustrated in Figure 6, which shows the

vertical temperature distribution in measurement well 1, at 10 m downstream from the hot well. In this figure, temperature differences probably related to permeability differences can be observed within the aquifer, with lower permeabilities around 90 m – bsl and the lowest 40 m of the well screen. In the layers with the highest permeabilities, the sphere of influence will be the largest. The continuation of temperature monitoring could provide an early warning for possible development of clogging pinpointed at specific depths in the filter.

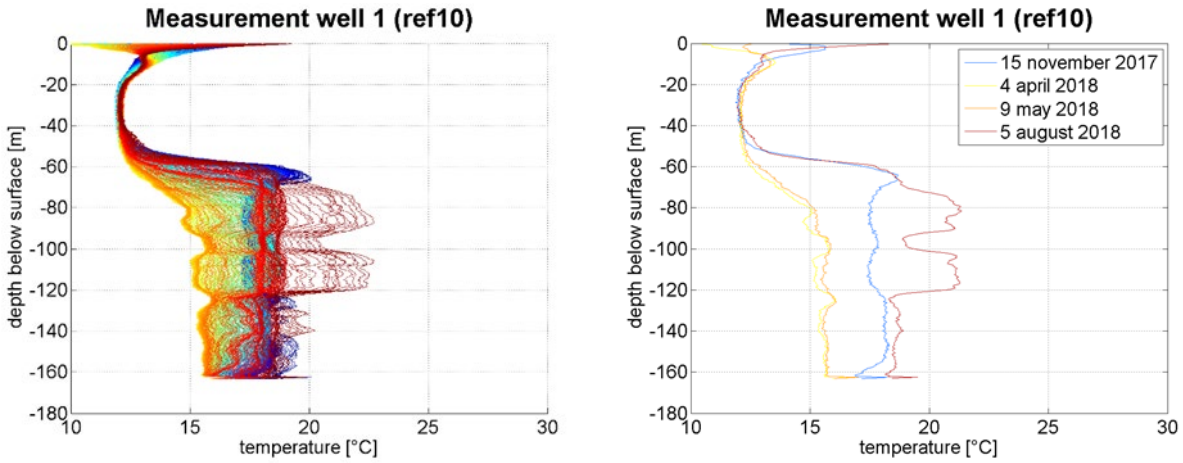


Figure 6. Temperature distribution in the monitoring well, 10m away from the warm well (01/10/2017 – 30/09/2018) in Ham (Belgium). Colors change gradually over time, starting with blue in September 2017 and ending with red in August 2018. Well screen is located between 80 – 160 m bsl.

Monitoring well 2, situated downstream between the two ATES wells, showed no sign of interference between the hot and the cold well (see Figure 7). This provides important information in assessing possibilities for implementation of additional ATES wells and / or systems in the proximity of the installed plant.

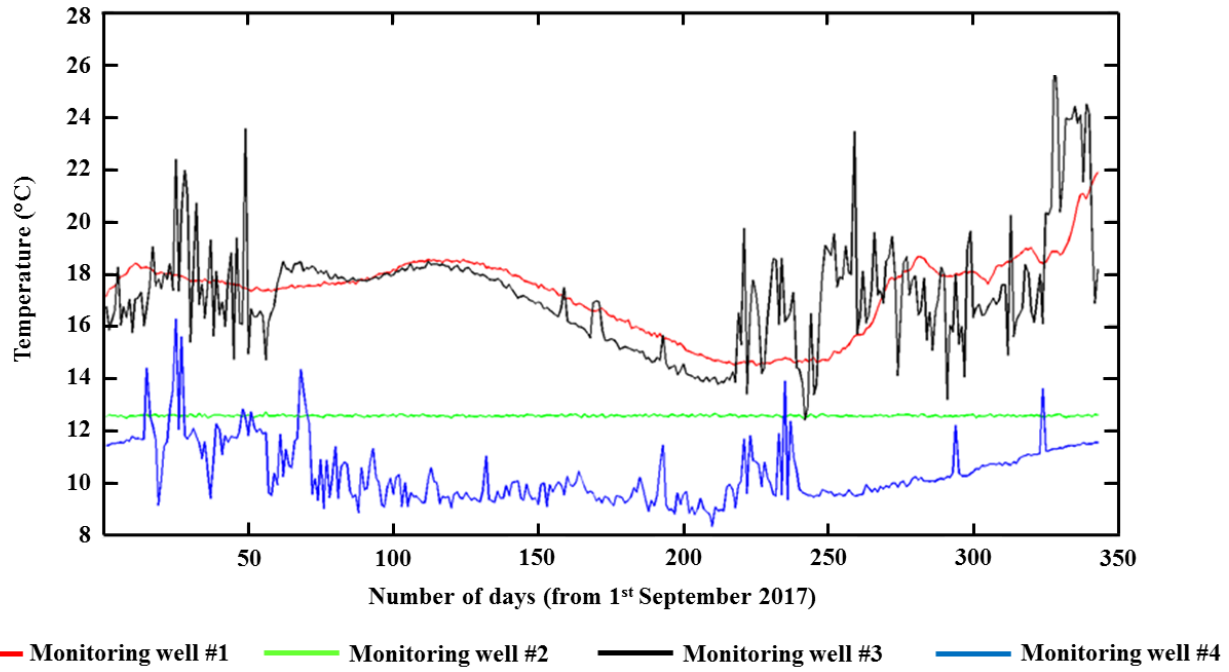


Figure 7. Temperature evolution in days after 1 September 2017 (day zero) at 80m depth for the 4 different wells in Ham. Monitoring well 1 is situated at 10 m downstream from the hot well (production well 1). Monitoring well 2 is situated further downstream between the hot and the cold well.

3.1.2 Spanish site

At the Spanish site, with a detrital multilayer aquifer of variable thickness from 50 to 270 m, in situ tests to determine flow velocity and permeability were carried out to define the best position of the monowell filters that would ensure minimal impact on aquifer properties in line with Spanish regulations for which it was specifically adapted (as described in Pellegrini et al., 2019a), resulting in a system that is also very suitable for thin aquifers.

3.1.3 Italian site

At the Italian site, only a small water bearing layer of (< 10 m) was found. The ambient groundwater flow was measured with a pumping and a tracer test (see Hoekstra and Van Gelderen, 2019; Conti et al., 2019) and found to be about 80-100 m/year, which is considerably higher than 25 m/year, that is considered as an upper limit for conventional ATES systems. Therefore, only a recirculation system (see Figure 1) was deemed possible at this site.

3.1.4 Dutch sites

In both Dutch pilots in Delft and Utrecht, high resolution soil temperature distribution measurements were performed. In the Utrecht monowell system probable interference between hot and cold layers could be observed, as illustrated in Figure 8. Figure 8 shows that at certain time intervals in summer a warm zone extends vertically into the cold zone, most probably

caused by the absence of an aquitard. Data suggest that the injection of warm water during summer has a 'downward influence', which is in contrast with the initial assumptions and modelling.

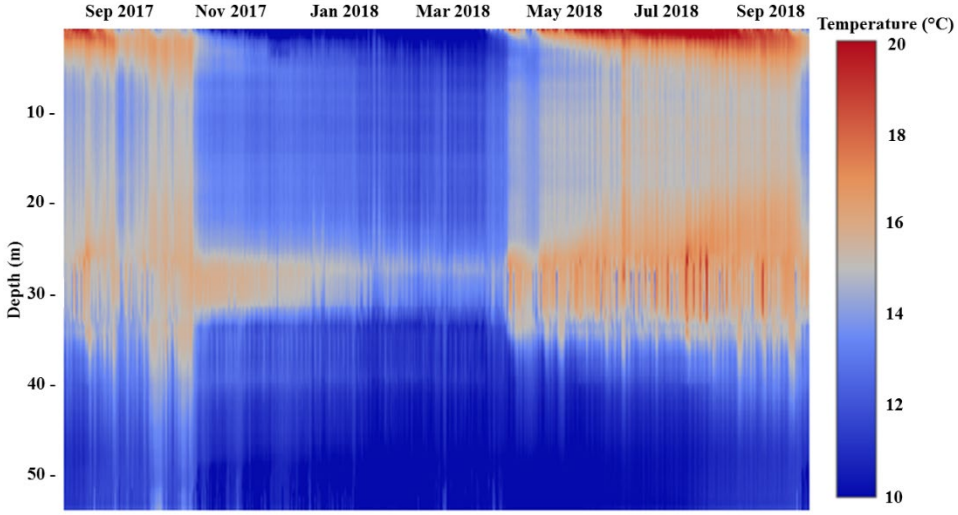


Figure 8. Temperature distribution in monowell (ATES-3) from September 2017 to October 2018. Scale bar (right) shows temperature range in °C. The positions of the warm (26 – 31 m bsl) well and cold well (49 – 56 m bsl) can be seen.

Figure 9 shows the temperature profile recorded in the middle well screen of the monitoring well, and from this it can be observed that the warm water also extends to this depth at the monitoring well (situated about 10 m from the ATES well), as temperatures are around 14-15°C during the summer period and decrease to 10°C in the winter period.

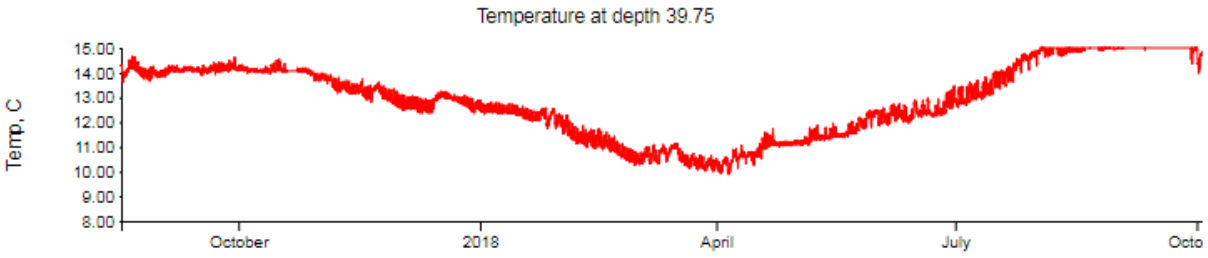


Figure 9. Temperature profile at the middle filter of the monitoring well (40 m). '2018' on the horizontal time axis marks January 2018.

Figure 10 presents spatial images of the temperature distribution around the cold well in Delft (Netherlands) at the peak of the heating season and at the end of the cooling season in 2017 and 2018. In the first year, it can be observed that there is less cold stored in the underground during winter, and that the cold reservoir is completely depleted at the end of the summer. In the following year, both climate conditions and operational system optimizations (Pellegrini et al., 2019a) allowed the storage of more cold, which was sufficient for the cooling demand.

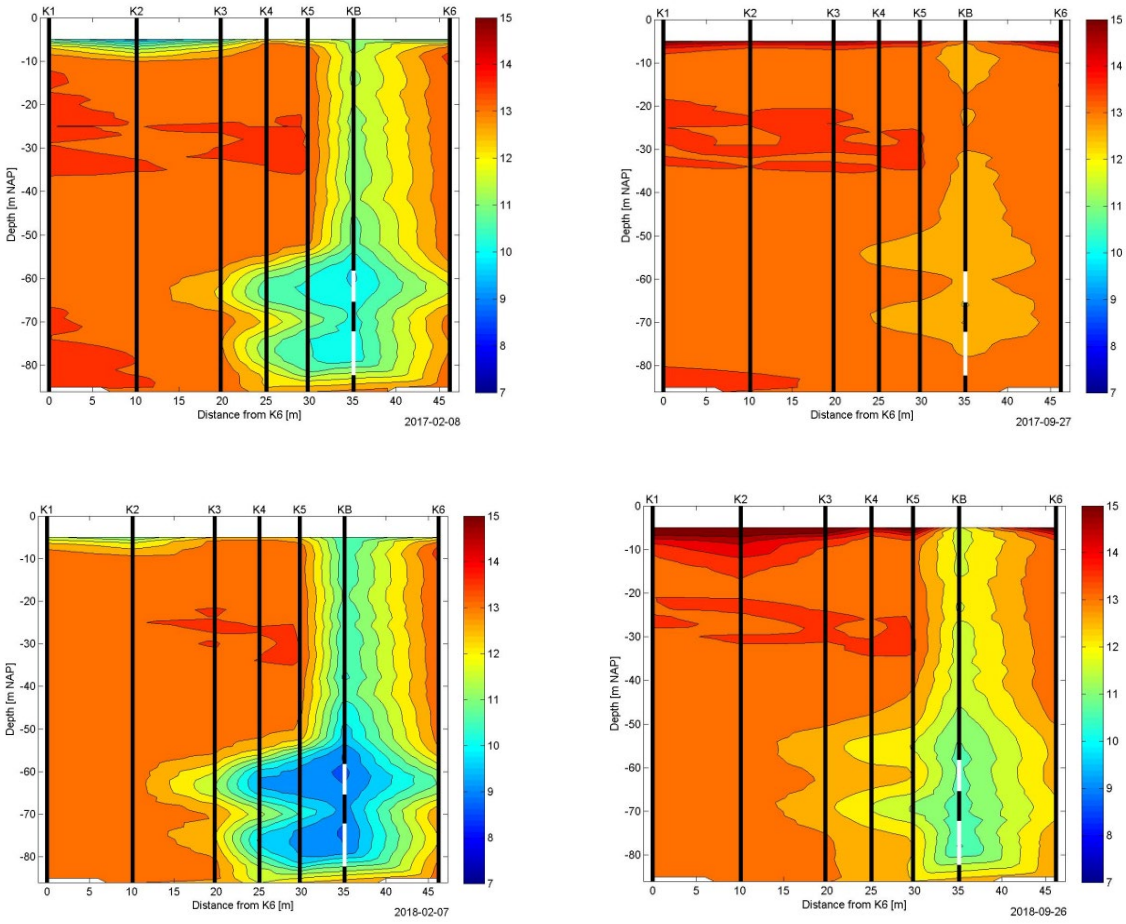


Figure 10. Spatial temperature measurements in Delft (Netherlands), derived from high resolution measurements in glass fiber cable at 6 distances around the cold well.

3.1.5 Danish site

The geology consists of a thin layer of fill. A layer consisting of sandy moraine clay to a depth of approximately 14 m bgl (+40 m above sea level) is found beneath the layer of fill. Under the layer of moraine clay, glacial melt water sand deposits are found with a total thickness of 44 m. The sand varies between coarse, medium and fine-grained sand in the top 24 m of the layer followed by 20 m of fine well sorted sand. Below the massive sand layer, the surface of the chalk is encountered, approximately 60 m bgl. The primary aquifer in the area is connected to the chalk and the overlying glacial melt water sand deposits, with an unconfined water table. There is a direct hydraulic connection between the glacial melt water sand deposits and the chalk in the area. There is no secondary aquifer. The water table is found about 21 m bgl. The top 3 m of the aquifer is described as brown/oxidized and below this the sediment changes color to grey and the conditions are anoxic.

3.2 ATES combination with district heating and cooling networks and smart grids

The Italian pilot plant concept has been developed to be highly replicable, including at a larger scale, with the aim of demonstrating the benefits of ATES and DHC integration on an operational electrical station. The plant consists of three extraction and three injection wells (plus four monitoring wells) that feed via a secondary circuit three reversible open-loop heat pumps, each one of about 70 kW_{th}, and one open-loop chiller with a nominal cooling capacity of about 55 kW_{th} (see Conti et al., 2019). The ATES pilot plant delivers thermal energy to two buildings located in an electric station near Bologna. One building includes also data centre rooms which need cooling throughout the year. Figure 11 shows a schematic of the Italian pilot plant. The novelty of the pilot plant design lies in the fact that the energy distribution system is a cold low temperature DHC network fed by the ATES system. Two substations (one for each building) are present. The geothermal energy source acts as the centralized heating/cooling unit, while the space heating and cooling demand is covered by the operation of the local reversible heat pumps or chillers. The secondary circuit works as a compensation element that is kept at an optimized temperature. In summertime all the substations work to produce cold water for space cooling. The secondary circuit has been designed to work at approximatively 20 °C, while the cold water is stored in the substations at 10-12 °C. In wintertime, warm and cold water need to be produced at the same time to satisfy both the demand for space heating and space cooling, the latter coming from the data center rooms. When the heat extracted from the secondary circuit for space heating exceeds the heat sunk in the secondary circuit for data center rooms cooling, the temperature of the secondary circuit decreases and is heated up by the geothermal source. In this case, the cold water tank is cooled down without using the chiller, but through a heat exchange with the secondary circuit. Conversely, when the heat taken from the secondary circuit for space heating is about the same or lower than the heat sunk in the secondary circuit for data center rooms cooling, the temperature of the secondary circuit would increase, and the chiller is put in operation to guarantee the data center rooms cooling. In this condition, the waste heat coming from the data centers is recycled via the heat pumps for space heating, and the geothermal source has limited or no contribution on the system. Therefore, the Italian pilot aims to demonstrate how the recycling of waste heat in a cold low temperature DHC network can be practically realized and how renewable energy sources, ATES in particular, can be used to compensate the mismatch between heating and cooling demand, if present. The ATES system aims to substitute the existing natural gas boilers and water-to-air chillers. Nevertheless, the ATES pilot plant is integrated with the existing water-to-air chiller and two electric boilers of 57 kW_{th} each (one for each building), which are connected to the water tanks and can be used as back-up unit of the ATES system for space heating or cooling.

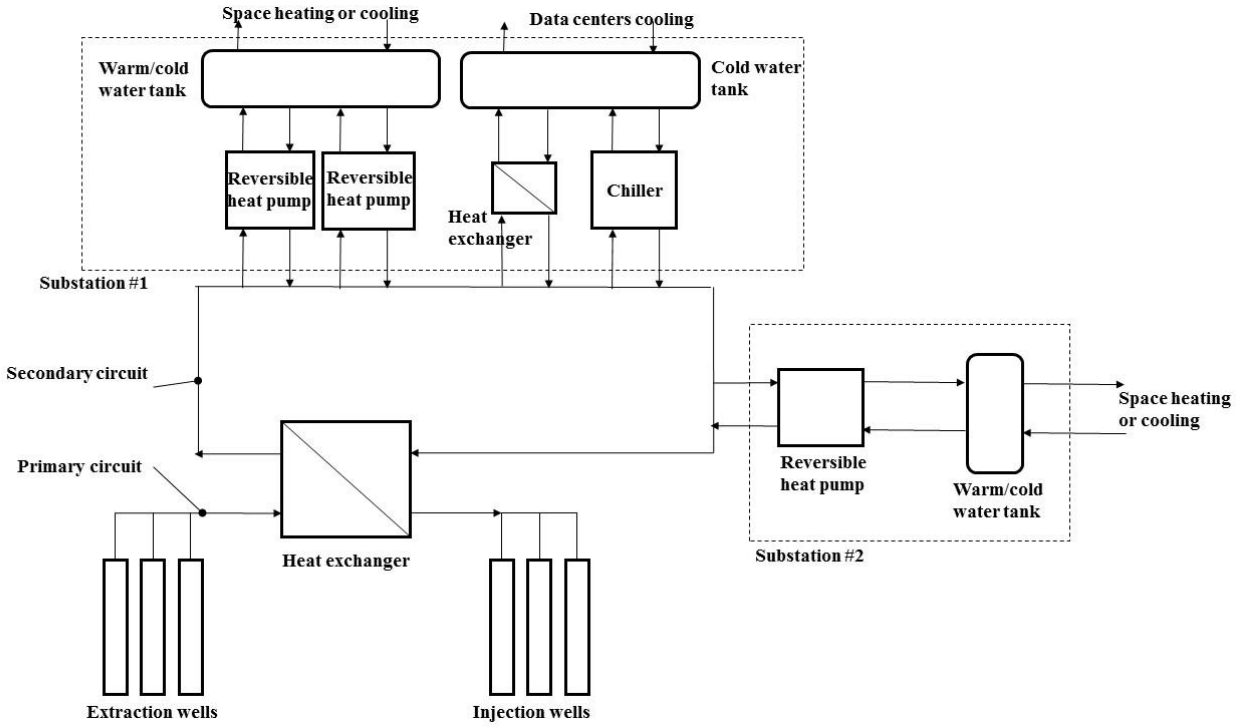


Figure 11. Schematic of the Italian pilot plant.

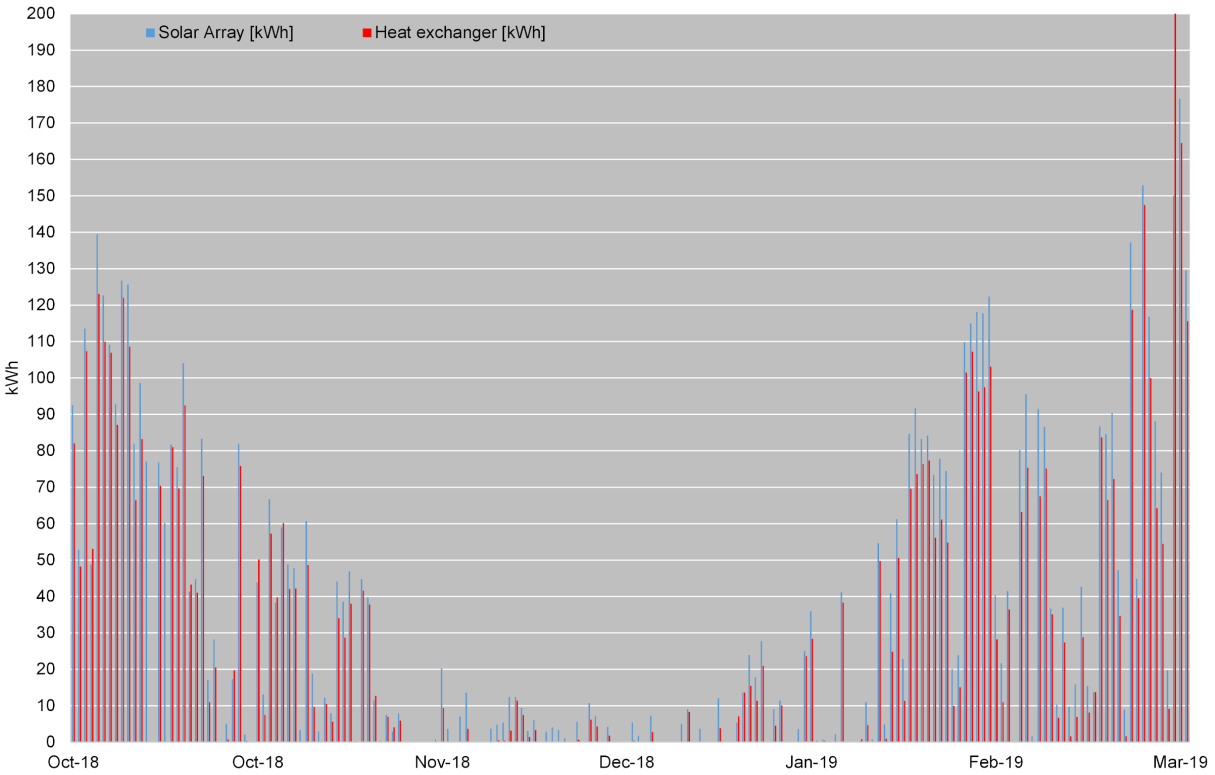
3.3 Combination with solar heat collection and photovoltaic electricity generation

The combination of ATES with solar energy production was tested in both the Belgian pilot and the Dutch pilot in Delft. In Ham in Belgium a state-of-the-art PVT-system was used (35 BLO-260 TripleSolar PVT-panels placed on the roof of the office building, accounting for 119 m² of PVT surface and 18,2 kW of peak power production) that allows for more electrical output at high ambient temperatures than conventional PV-cells, by removing excess heat, thus avoiding the normally observed output decrease with temperature increase. The conveyed heat can be used to generate domestic hot water, but excess summer heat can also be stored in the subsoil via the ATES system and applied usefully in winter. It is also possible to use the PVT-panels to generate additional cooling capacity for use in summertime. The annual energy that can be charged/discharged strongly depends on the entering fluid temperature. Water coming from the Belgian ATES is about 10°C to 13°C. At 10°C entering fluid temperature about 3000 MJ/m²/year heat can be charged or 1100 MJ/m²/year of heat can be discharged according to the technical documentation of the panels. Although relatively small, the PVT-systems provide means to balance the ATES in two directions. Due to an error in the electricity sensor of the PVT panels, data is only available until June 2018. For this reason, the performance of the PVT system is evaluated for the period January 2018- June 2018. In this period the measured electricity production was 9,117 MWh while the warm water production measured 5,831 MWh. Since the yearly design output values are 18,636 MWh electrical and 10,383 MWh thermal, performance was in line with expectations.

In Delft in the Netherlands an innovative Virtu solar system was integrated and tested. This system can generate more thermal output then flat panel PVT collectors in cool climates, since it includes a vacuum tube that reduces thermal losses. Installation was carried out in two phases, firstly a pilot system of just 10 tubes and then, towards the end of the project period, a larger installation of 120 tubes. This new array was operated for six months, generating the data shown in Figure 12 and Figure 13. However, the increased heat generation (combined with cooling loads from the buildings) resulted in the aquifer temperature increasing above planned control limits. Therefore, in April 2019 the Virtu solar array had to be covered, since the heat could not be dissipated within the climate-control system.

Based on the phase 1 data from the small test system of 10 tubes, it was decided to secure frost prevention by connecting the phase 2 array of 120 PVT tubes to the ATES-system via a heat exchanger. The heat exchanger was connected to the cold well output side of the ATES system. A second connection, between the solar array and the warm well is now being considered, as this would allow more flexible use or storage of heat as a function of season. These operational issues provided valuable practical experience of solar array integration with an ATES system, but the delays and over-heating issues have meant that it has not yet been possible to measure temperature distribution effects in the soil following the phase 2 solar array installation.

Figures 12 and 13 show the Virtu solar array production in Autumn 2018 and Winter 2019. Heat production is good in October and February/March with an output of >100 kWh per day on sunny days. Figure 12 shows the daily “positive energy”, excluding heat losses. Excluded from this data are any periods where the measured power was negative, such as on cold cloudy days or frosty nights. Based on this dataset, the total heat energy measured in the period October 2018 to March 2019 was 6.5 MWh of heat generated (measured at the solar array), with 5.7 MWh of this delivered to the heat exchanger. This shows that, on good solar generation days, the efficiency of the pipe-work and heat exchanger system was good in collecting and transferring heat. Figure 13 charts data from the same period, but in this case including the periods of heat loss (i.e. when measured heat is negative). For this “net energy” data set the total heat energies were 4.8 MWh generated and 2.7 MWh delivered.



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479 Figure 12. Measured "positive energy" in Delft: generated heat, with energy losses excluded. The figure includes 2 data sets: the array
480 energy and the heat exchanger energy. The array energy is from temperatures sensors at the array and shows the energy generated by
481 the Virtu collectors. The heat exchanger is from temperature sensors in the plant room and shows how much was delivered to the
482 system. The fact that these 2 data sets match quite closely shows that heat losses from the pipework and system are quite low.

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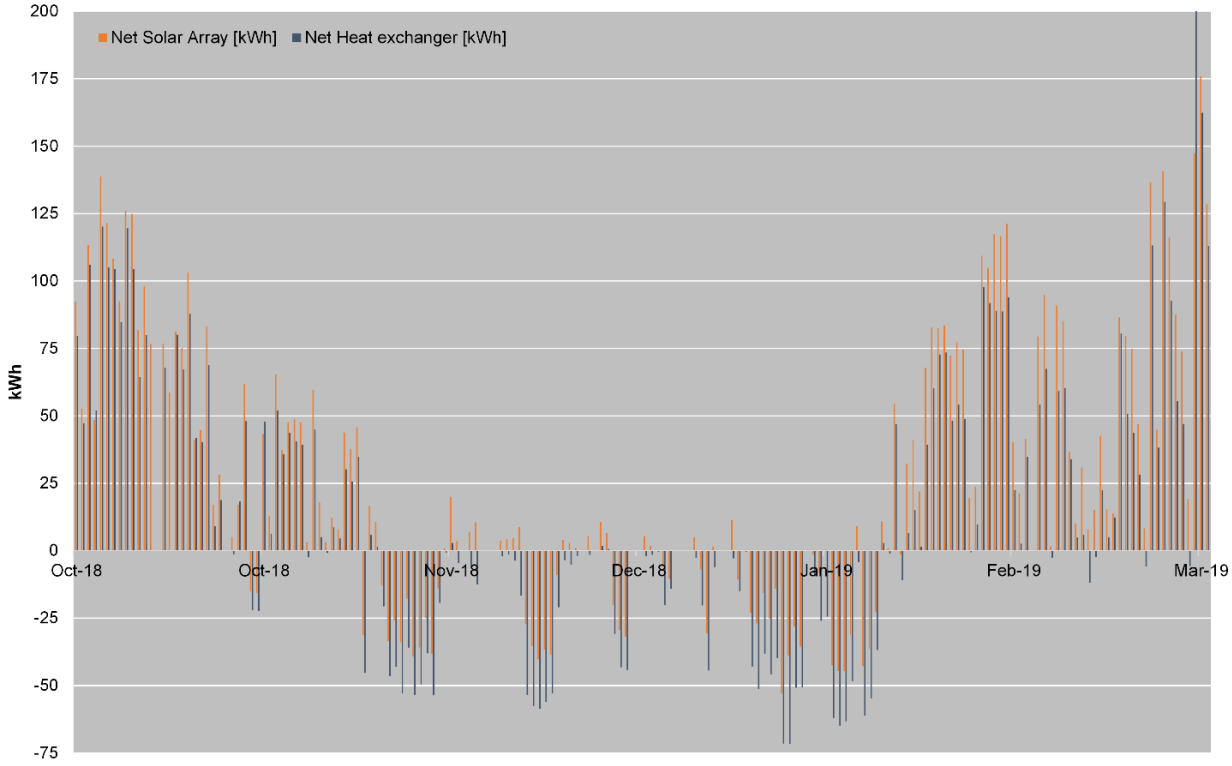

Figure 13. The measured "net energy" in Delft (like in Figure 12, measured at the thermal array and at the heat exchanger) which integrates the power over 24 hours and includes the frost-prevention approach of circulating water at night, so the figure shows the true total energy delivered by the PVT-system to the ATES / climate control system.

The large difference between the "positive energy" and the "net energy" totals is caused by the frost prevention method used in the system, which involved losses due to continuous water circulation through the tubes at night whenever ambient temperature fell below 5 °C (using circulating water temperature of 20 to 30 °C). It is noted that freezing prevention could be realized with much lower power, using water at lower temperature and flow rate, or through use of glycol solution instead of water (in which case no circulation would be required). During this period of the project, heat loss reduction was not a priority. Longer term, energy output will need to be balanced throughout the annual cycle and reduction of this night time loss can form part of the improved integration between the PVT solar array and ATES system. However, this illustrates that the Virtu solar array can also be used in a night-time cooling capacity, which could be applicable to warmer locations, although flat plate PVT systems would be more suitable for that goal.

The thermal power output demonstrated by Virtu in February 2019 shows the advantage of vacuum tube thermal insulation for solar heat production in cool climates. The target temperature for heat production from the array was 40-45 °C and efficient thermal power levels, above 20 kW, were achieved at this temperature on sunny days during

February/March 2019, even when air temperature was below 10 °C. The reduced heat loss to the ambient with the vacuum tube technology (compared to flat panel solar thermal and PVT collectors such as used in the Belgian pilot) also enables higher temperatures and thermal powers during spring and autumn and is therefore of particular relevance to solar thermal ATES installations in cool climates. The Virtu collector is available in two versions: a hybrid PVT version and a thermal-only HOT version. Other field installations of Virtu PVT in the UK have demonstrated similarly effective heat production at low ambient temperature as at the Delft site. Independent testing of Virtu PVT carried out at the TUV Rheinland solar test lab has demonstrated combined heat and power generation of 226 W per tube at 929 W/m2 of solar radiation and a medium water temperature of 32 °C above ambient temperature, which represents a total energy efficiency of 77% based on absorber area or 57% based on aperture area. This is significantly higher efficiency than can be achieved by flat panel PVT collectors operating in this temperature range (Mellor et al., 2018).

3.4 ATES in combination with bioremediation: new experimental results about groundwater quality assessment

At the Dutch pilot site in Utrecht samples were taken on 17 September 2019, more than a year after the last monitoring round, as published in Pellegrini et al., 2019a, in order to test the long-term longevity of the performed bio-augmentation. In soil mesocosms in monitoring wells downstream from the bio-augmentation well still high concentrations of dechlorinating bacteria were found: $2{,}0 \times 10^6$ (in screen 38-42 m bgs) and $6{,}7 \times 10^5$ (in screen 53-57 bgs) and in the groundwater in the $3{,}4 \times 10^4$ *Dehalococcoides bacteria* cells; with about 1/3 of the latter detected to be viable. Concordant with these results, almost no VC was detected in most of these wells anymore. The maximum VC concentration was 0.3 µg/l, found in the upper ATES well (27-32 m bgs), while preceding bio-augmentation these wells contained 2.4 – 4.3 µg/l VC. It appears that both bio-augmentation longevity and radius of influence – enhanced by ATES operation with induced seasonally reversing groundwater flows – is even much larger than expected.

While at the Dutch pilot site in Utrecht only low plume zone concentrations of VC were present in iron to sulfate reducing redex conditions, the Danish pilot site had high concentrations of trichloroethylene (TCE) in an aquifer with oxidative conditions hostile to organisms capable of reductive dichlorination. The deeper part of the aquifer was chemically reduced. Bench testing showed that electron donor injections could not be avoided, with consequently there was an imminent risk of clogging. Since the recirculation system was only used for testing purposes, with no need for utilization of the energy produced, the clogging risk was acceptable. However, clogging was effectively prevented by a filtration unit between the extraction and infiltration filter. A total of 12,000 m^3 of water was extracted, heated from 12°C to 20°C and re-infiltrated, from March 2018 to March 2019. Figure 14 shows that with repeated electron donor (lactate and acetate)

additions, organic matter reached all monitoring wells and consequently electron acceptors were reduced, leading to low concentration of oxygen, nitrate and sulphate and high concentrations of reduced iron that dissolved from the soil.

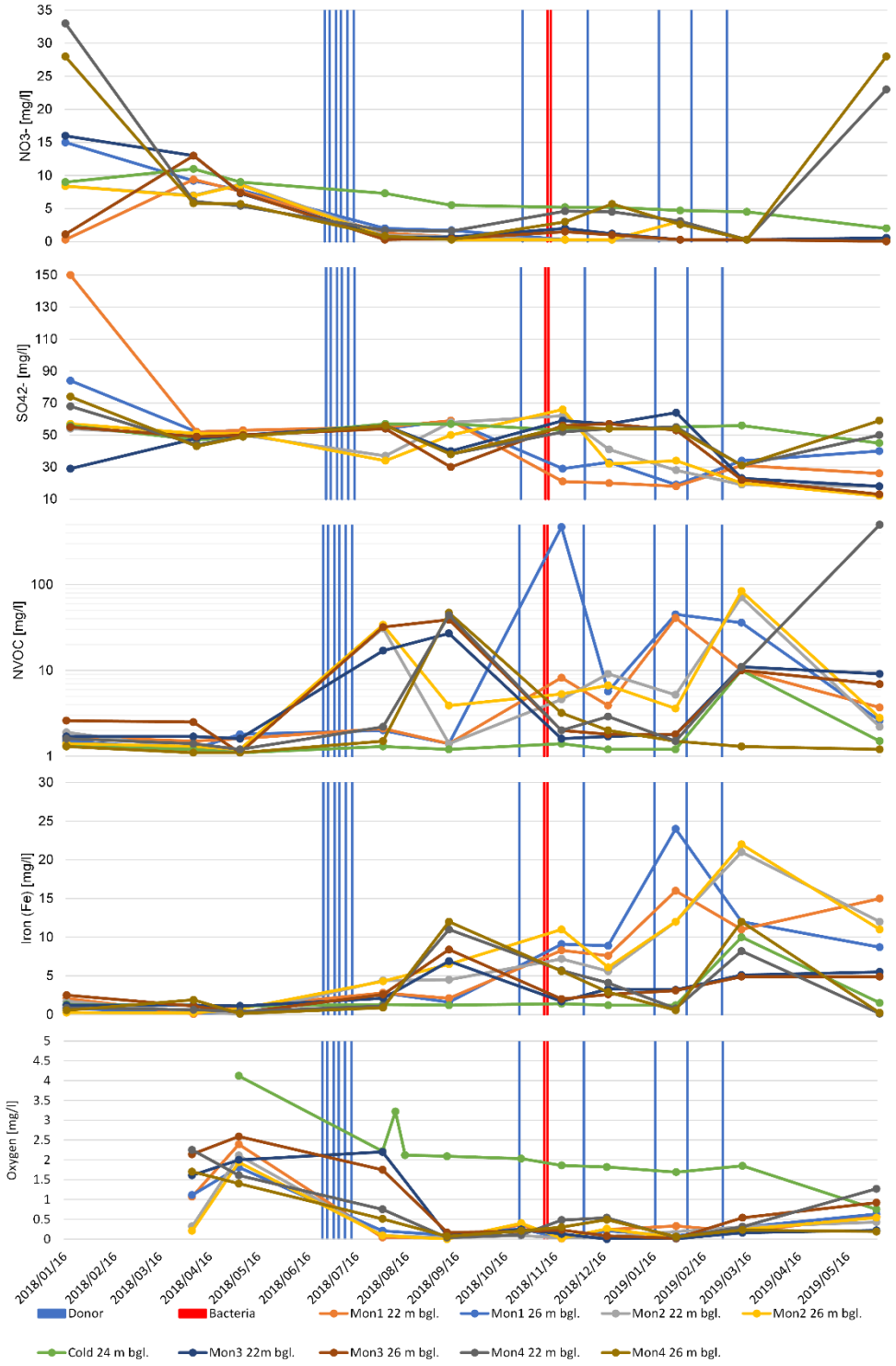

Figure 14. Following electron donor additions into the hot well at the Danish site, organic matter (NVOC) and dissolved iron concentrations increase in all monitoring wells, while electron acceptors oxygen, nitrate and sulphate concentrations decrease. Monitoring wells 1,2, 3 and 4 are situated on a straight line between the hot and the cold well.

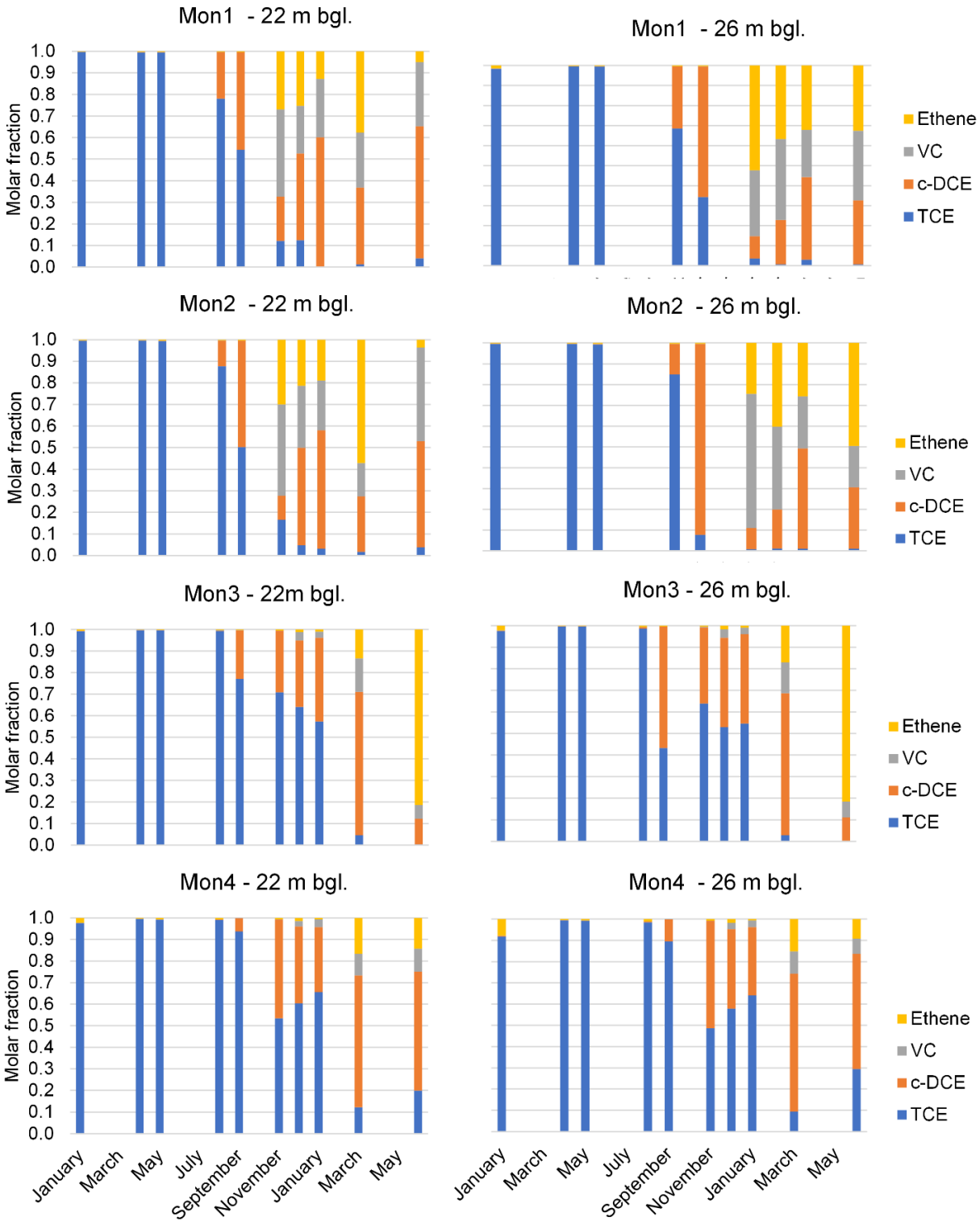

Figure 15. Degradation in monitoring wells at the Danish site as molar fraction of total contamination present.

Figure 15 shows that partial reductive dechlorination, to cis-dichloroethylene (c-DCE), started after the initial electron donor injections in July 2018. Beginning of November 2018, conditions were deemed adequate for the cultivated dehalogenic culture. After bio-augmentation in monitoring well 1 and 2, complete dechlorination to ethene was observed

in most monitoring wells, especially in the ones closest to the hot injection well. In the cold extraction well, only little effect could be observed, owing to dilution by the surrounding groundwater.

From Utrecht and Copenhagen pilots it can be derived that ATES can both enhance soil remediation performance on highly contaminated sites and accommodate groundwater quality improvement, as a tool in groundwater management implementation.

3.5 Economic assessment

3.5.1 Energy savings and related economic benefits

The black circles in Figure 16 show the DPPs calculated for four pilots accordingly to the data presented in Table 2. Since economic conditions can vary widely locally and with time, these numbers only give a rough indication. Nevertheless, the computed DPPs times are in the range from 2 to 12 years that are found on average for state of the art ATES systems in the Netherlands, showing that the system innovations and innovative combinations demonstrated in the E-USE(aq) project, in order to overcome barriers, do not hamper the economic feasibility of ATES. On the contrary, for the Belgian and Spanish case significantly improved DPPs were achieved, reinforcing that ATES represents an economically attractive technology. Nevertheless, in Figure 16 two further DPPs are presented with red triangles, that are the DPPs that may be achieved by Bologna and Delft pilots under certain conditions.

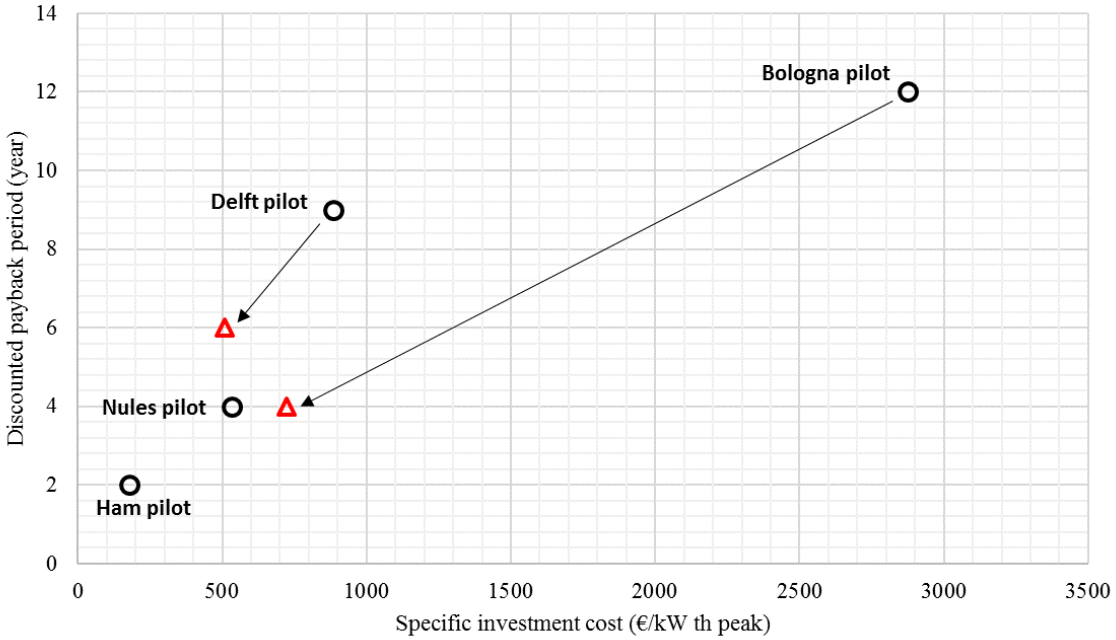

Figure 16. Computed discounted payback periods (DPPs) for the E-USE(aq) project pilot plants.

For the Italian case study, the investment costs stand out as much higher than the other pilots. In fact, the Italian pilot plant is characterized by high redundancy, justified by the type of application (i.e. space heating and cooling of an electric station, wherein a high safety standard has to be satisfied, in particular for the data center rooms). Also, the framework conditions (revamping of the warm and cold water distributing system, realization of a new substation for one building served by the pilot plant, realization of a centralized and automatized control panel for the whole heating/cooling plant), and the monitoring requests made by the regional authority that issued the permits, increased the investment cost compared to the other plants. These elements make the Bologna pilot somewhat unique and not directly scalable (in terms of costs) to other similar applications, i.e. ATES in combination with DHC networks. For a generic commercial scale DHC network, the projected investment required would be 724 €/kWth (peak power), which would result in a DPP of about 4 years.

The DPP for the Delft pilot would also be reduced at scale, taking account of the relatively high cost of the 120 Virtu tubes. For a larger system of 1000 Virtu tubes, it has been projected that the reduced investment costs and increased energy savings would reduce the investment to 508 €/kW th peak, leading to a DPP of 6 years.

3.5.2 Economics of ATES in combination with bioremediation

The specific and discounted cost of groundwater treatment has been computed, starting from the information included in Chapter 2.5.2. The results of the comparison are shown in Figure 17. ATES and bioremediation can be competitive with the existing biological *in situ* treatment options and is much more cost efficient compared to traditional remediation (pump and treat) and chemical oxidation. A wider use of the technology could further increase the competitiveness of ATES with bioremediation compared to bioaugmentation alone.

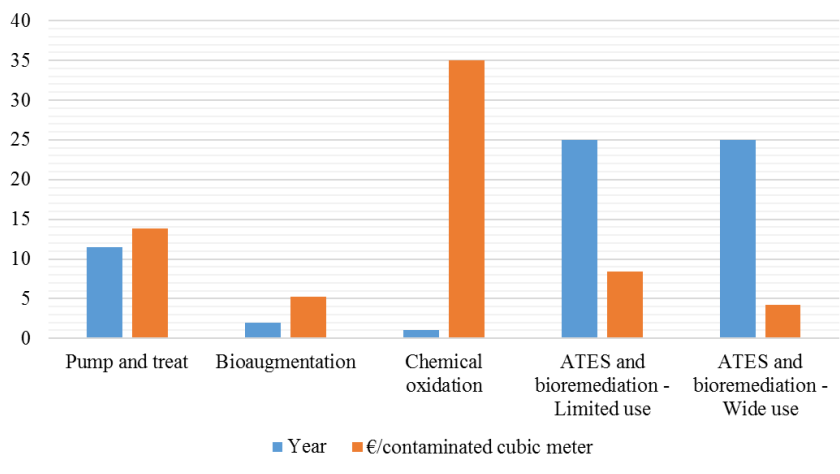

Figure 17. Results of the economic comparison of different groundwater remediation technologies: treatment duration and discounted cost per cubic meter of contaminated groundwater for pump and treat, bioaugmentation, chemical oxidation and ATES+bioremediation.

A further advantage of the ATES with bioremediation approach is that ATES can start operations without the necessity of remediating the groundwater first, which could take many years. In this respect, only chemical oxidation is a relevant alternative technology, because only with this technique could sufficient groundwater remediation be reached within one year, to allow installation of an ATES system into clean groundwater afterwards. However, chemical oxidation is 4-8 times costlier than ATES in combination with bioremediation. Moreover, chemical oxidation influences the groundwater geochemical composition and results in decreased suitability for ATES. So, compatibility of chemical oxidation and ATES, even when subsequently applied, is low.

3.6 Climate impact assessment

In the E-USE(aq) pilots, enough data have been acquired to calculate yearly equivalent CO_2-emission reductions according to the methodology presented above. Table 5 shows the absolute values of yearly equivalent CO_2 reduction for each pilot, and includes also the specific equivalent CO_2 emission reduction, computed on the basis of ATES system size (kW th peak). The Delft and Ham pilots are shown to yield the highest positive environmental impact: this can be explained by the positive contribution given by solar thermal (Delft) and PVT (Ham) in the reduction of fossil fuel consumption for, respectively, heating and heating plus power. Moreover, in both pilots free cooling can be realized. The Nules pilot plant has an intermediate specific CO_2 emission reduction factor, which is produced only by heating. The application of ATES in a swimming pool allows the system to operate at relatively low temperature (35-40 °C), resulting in a high COP for the geothermal heat pump. In contrast, the Bologna pilot has lower performance in heating due to the higher temperature required (50-60 °C), while space cooling is not directly achievable by direct free cooling via groundwater. The combination of lower COP in heating mode and lower Energy Efficiency Ratio (EER) in cooling mode explains the limited climate impact of the Italian pilot.

Table 5. Evaluation of yearly equivalent CO_2 emission reduction for E-USE(aq) pilot plants.

Pilot plant	**Yearly equivalent CO_2 emission reduction (ton/year)**	**Yearly equivalent CO_2 emission reduction per installed kW th peak (ton/year)**
Nules	25	0.23
Bologna	17	0.11
Delft	25	0.36
Ham	205	0.31

The analysis offers an indication of the future avoided emissions which can be achieved by wider ATES application. Taking into account experiences with systems in other countries, an average of 0.2-0.3 ton of equivalent CO_2/year per kW th peak is assumed to be a representative GHG mitigation potential value per ATES systems. The CO_2 emission reduction can be further increased if ATES is combined with PV, PVT or wind turbines plants, or if certified "green power" is consumed, since in that case the power feeding the ATES system can be considered as free from CO_2 emissions.

4. Conclusions and recommendations

This paper confirms the preliminary conclusions (Pellegrini et al., 2019a) obtained by the EIT Climate-KIC project 'Europe-wide Use of Sustainable Energy from aquifers' and adds the following key findings from the six full scale ATES pilots across five European countries:

(1) The use of state-of-the-art soil investigation technology can play a powerful role in ATES implementation. Subsurface characterization is essential both for location and design (with appropriate layers selection and optimal spacing between wells) and for effective operation of ATES systems. With proper site characterization, as demonstrated in the pilots, it is possible to apply ATES in relatively thin water bearing layers.,. This makes ATES applicable in parts of Europe that were formerly not considered suitable, included arid regions.

(2) Use of thermal energy from ATES can be balanced and optimized more cost efficiently by interlinking with different functions, such as housing, office buildings and industrial activities, as illustrated in several of the pilots. Within a smart grid, ATES is especially compatible with solar energy and heat and cooling from surface water, which provides additional energy that can be stored in the subsoil for later use. This makes ATES also applicable in regions with unequal annual demands for cooling and heating.

(3) The presence of soil contamination does not represent an obstacle for ATES application, since ATES can be implemented together with bioremediation. In cases where ATES is economically feasible, groundwater remediation can therefore be made financially more attractive. Thus, soil contamination could even become a driver for the application of ATES.

It can therefore be concluded that ATES technology is widely applicable, and its role can become much more prominent amongst the sustainable energy sources required to transition to a low carbon energy system. These results have provided the technical and economic data which may help in overcoming organizational and social acceptance barriers for future ATES systems, thus paving the way to Europe- and even worldwide application. The 6 ATES pilots have illustrated a range of integration challenges, some technical and some commercial/regional, and demonstrated the combination of fields of expertise required to implement solutions that are both economically viable and environmentally beneficial.

Acknowledgments

The authors acknowledge the EIT Climate-KIC Association of the European Institute of Innovation and Technology (EIT) that co-financed the barrier analysis, part of the site characterization in the pilot sites as well as part of the monitoring work described in the paper via the E-USE(aq) project. EIT Climate-KIC is a European knowledge and innovation community working towards a climate-resilient society founded on a circular and zero-carbon economy. The authors also wish to thank end users and local authorities who made pilot implementation possible: Emilia Romagna Region, Capital Region of Denmark, Municipalities of Nules, Utrecht & Zwolle as well as Nike & Terna SpA.

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