



# D1f E-USE(aq)

## Technical performance & monitoring

### report Dutch pilot Delft

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# 1. Introduction

## a. Barriers to overcome and issues to address

Aquifer Thermal Energy Storage (ATES) has proven to be profitable both economically as well as energetically. However, large scale adoption of the technology is limited by several barriers which were identified in the Climate-KIC E-use(aq) project (Hoekstra et al., 2015). This project report describes activities to address one of those barriers, which is the need to obtain energy balance over a long time period through the addition of renewable heat source and heat sharing between buildings.

To sustain an ATES system, on average the thermal energy stored in the aquifer must be as much as the retrieved amount, so that structural and unlimited growth of either warm or cold well is prevented. Since buildings hardly ever have a heating demand equal to cooling demand, measures need to be taken to optimize system performance by storing extra heat or cooling capacity from other (sustainable) sources. In case of a heat deficit, one way to gain additional heat is from solar radiation. Since ATES systems also need electricity to drive the heat pump, using both solar heat and power would improve the energetic and economic performance of such systems. Also because typically in moderate climates, solar heat is abundant in summer, while demand for heat is largest in winter, temporal storage of heat in an ATES system would utilize the potential heat production during summer.

Naked Energy has developed Virtu, an innovative hybrid solar technology providing combined heat and power. Virtu integrates standard high efficiency silicon photovoltaic cells mounted on an efficient heat exchanger plate and enclosed in a vacuum tube. Since both PV conversion and heat collection are combined in one collector, the result is that higher energy density can be achieved than with separate PV and solar thermal panels. For any given area, more of the sun's energy is converted into useful energy: heat and electricity, compared to existing products with a commensurate positive impact on CO<sub>2</sub> emissions.

The versatile, modular design can be used as a form of distributed energy generation for commercial and industrial applications regardless of climatic or geographic conditions. The horizontal vacuum tube format makes installation on ground or on flat roof particularly easy and flexible, with no need for angled mounting frames. Figure 1 gives a schematic overview of the Virtu modular design. Compared to flat panel PVT panels, the use of a vacuum tube reduces ambient heat losses, potentially enabling higher thermal efficiencies and the ability to deliver higher water temperatures.

Goal of the pilot is to implement and connect PVT panels to an ATES system, overcome practical issues and show-case added value of combination of PVT with ATES for overall energy performance.



Figure 1. Schematic representation of Virtu PVT panel

## b. Partners involved

1. Delft University of Technology, Delft, The Netherlands
2. KWR water research, Nieuwegein, The Netherlands
3. Deltares, Delft, The Netherlands
4. Naked Energy, Crawley, United Kingdom
5. Wageningen University, Wageningen, The Netherlands



### c. Organizational history

A pilot focused on ATES combined with PVT was first discussed with the Jaarbeurs in Utrecht and with the Utrecht University. Both did not have the organizational capacity available to facilitate such a pilot. Therefore it was decided to establish a pilot at the Deltares premises in Delft, for which co-funding could be found.

An ATES system was already in place at the Deltares site, with baseline data collected for operation of the heat pumps and aquifers in which high resolution temperature measurements are performed. Operation showed a requirement for additional heat sharing between buildings and a higher energy flow to increase system stability. The site was therefore a good candidate for the incorporation of solar heat into the system.

Two previous field trials had been carried out of the Virtu PVT system. The first at the Dolmen Hotel in Malta, as part of the EIT funded WE4CCII project (Water and Energy for Climate Change), had tested a prototype design of the product, incorporating 5 inch PV cells on a solder bonded heat exchanger in a 150 mm vacuum tube. Running from 2015-2016, this pilot confirmed the high efficiency performance of the solar collector, while highlighting some reliability issues in the design. A significant modification was made to the design, resolving the absorber reliability failures and also scaling up the PV cell size to 6 inch, which increases the power/cost ratio for the product. A second commercial pilot was then carried out at a supermarket in the UK throughout 2017. This tested the collector performance in a cooler climate and confirmed that water temperatures up to 50-60 C could routinely be achieved, enabling the effective supply of sanitary hot water to the supermarket café and rest rooms. In addition to the Virtu PVT product, an optimized thermal-only version, now named Virtu HOT, was also tested. In the same modular format, this allowed flexible optimization of the PV: thermal ratio to be selected for the required building application. The Virtu HOT demonstrated effective heat collection through a larger proportion of the year and an overall higher thermal efficiency, achieved due to its optimized thermal absorber coating.

During 2017 it was decided that the Virtu solar collectors should be implemented in two phases. The first phase of 10 Virtu thermal tubes were installed on ground mounted rails and the plant room system and ground works installation to connect this into the ATES system was completed in September 2017. The controller was then commissioned in December 2017. Instrumentation included flow and temperature sensors that enabled thermal power output to be quantified. This allowed optimisation of control algorithms (e.g. in response to different weather patterns), in particular the control of flow rate to deliver the desired delivery water temperature.

The second phase of installation was completed in August 2018, this increased the number of Virtu tubes from 10 to 120. This increase in scale improved efficiency of the system and allowed a full demonstration of the seasonal storage concept. This had been delayed from April 2018 to August, due to multiple delays in the manufacture of Virtu PVT tubes, caused mainly by company restructuring by Naked Energy's manufacturing partner Jabil Circuit. The Virtu tubes were finally assembled at Jabil's factory in Marcianise near Naples, Italy and shipped from there to Delft. Commissioning of the larger solar thermal array was completed in September 2018, with adjustments being made to the pump configuration and flow sensors to allow good control and management of the solar heat and more accurate calibration of the data.

## 2. Pilot description

### a. Site Depiction and Pilot Design

The Deltares campus has several buildings, of which two are connected to an ATES system (Tetra). One of the experimental lab buildings (ZZH) was not previously connected to the ATES system but has a very high heat demand, while the buildings with ATES have a heat surplus. In the current pilot the solar heat from the Virtu solar panels and the surplus of heat from Tetra can be stored in the ATES system and transferred to ZZH, which would decrease the overall energy use and would enlarge the available cooling capacity during summer for cooling of Tetra, Figure 2. The projected heat output from the 120 Virtu solar tubes is 25 MWh/year, while the Tetra has an annual heat surplus of 50 MWh/year, which results in a potential energy delivery to ZZH of 75 MWh/year.

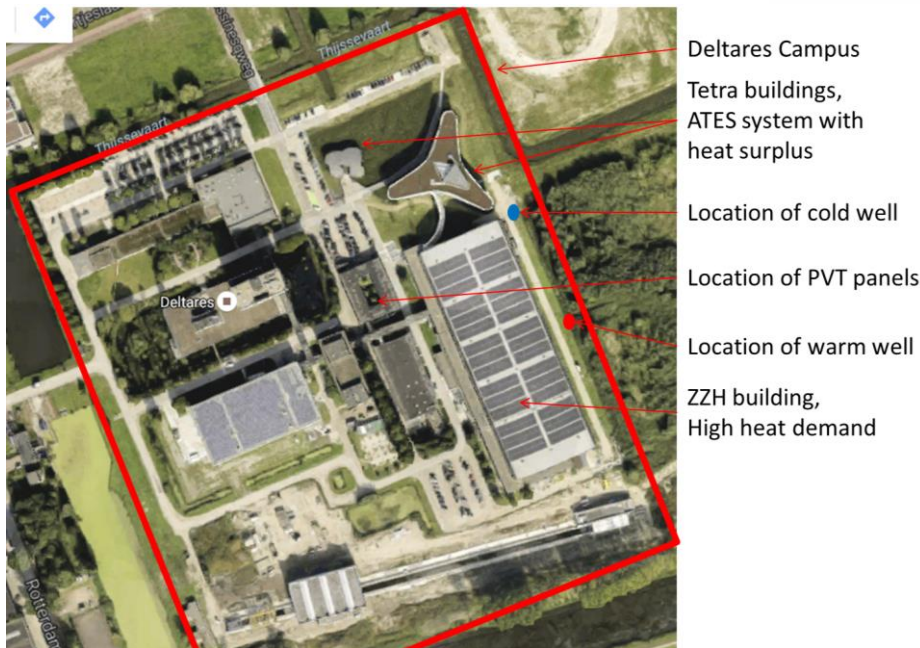


Figure 2. Aerial photo of Deltares campus with the location of different buildings/components indicated

The ZZH-building is heated with conventional gas boilers, no cooling is 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. Deltares has managed the installation of the connection from the plant room of Tetra to the air handling unit of ZZH and the preheating system in it. Energy from Virtu solar array will be used to boost the temperature of the warm well during summer. During winter heating from the array can also be delivered directly to reduce the running of the heat pump. A schematic of the Virtu array connection into the ATES system is shown in figure 3.

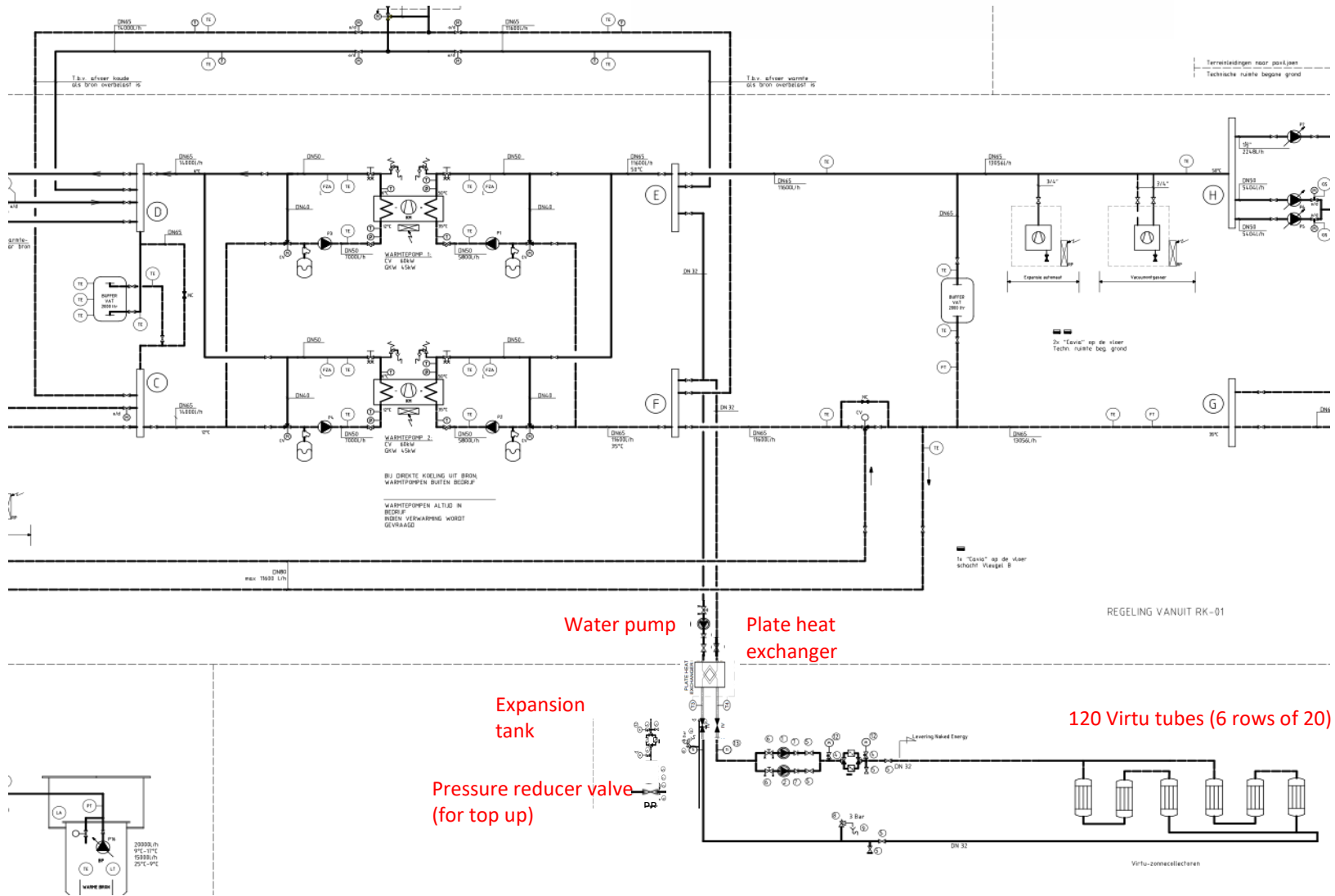


Figure 3, Cut-out of the mechanical scheme of connection of solar array and ZZH to existing plant

To evaluate solar heat generation and energy balance, both temperature and flow of in and outgoing flows are monitored in the new circuits. The required temperature and flow sensors are indicated in Figure 3 and the implemented hydraulic design of the solar array is shown below in Figure 4. Each row of 20 tubes was attached to a common water manifold and 3 rows were connected in series in each half of the array. The benefit of this approach is to reduce pressure loss and flow rate, thereby reducing pumping size and power consumption, and also delivering 3x higher temperature rise than would be achieved from an all-parallel configuration

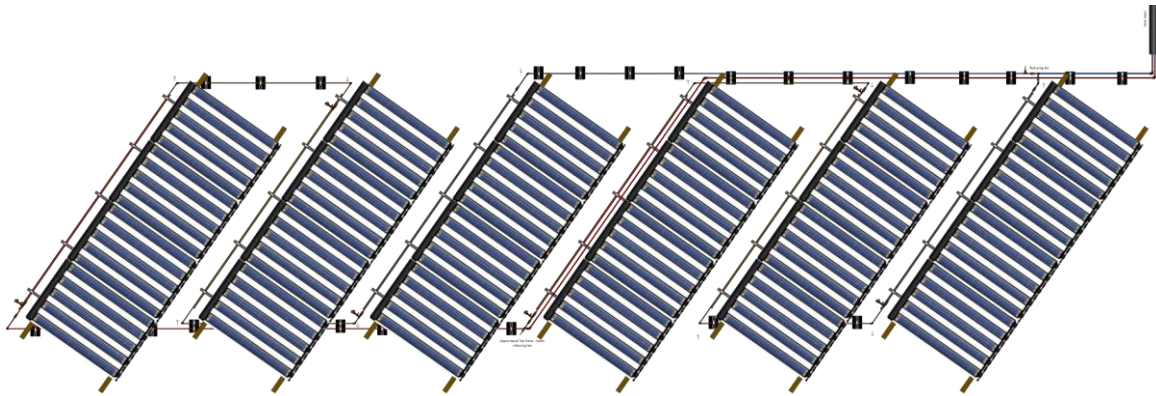


Figure 4, Hydraulic design of Virtu solar thermal array

### b. System installation

The commissioning of the Virtu PVT solar collectors was implemented in two phases. The first phase of 10 Virtu thermal tubes were installed on the ground mounted rails in the location shown in Figure 5, and the plant room system and ground works installation to connect this into the ATEs system was completed in September 2017. The second phase of 120 Virtu thermal tubes was installed in August 2018. Figure 6 shows some images of the installed array and Figure 7 shows the heat exchanger, pump and flow sensors in the plant room.



Figure 5. Placement details of Virtu panels

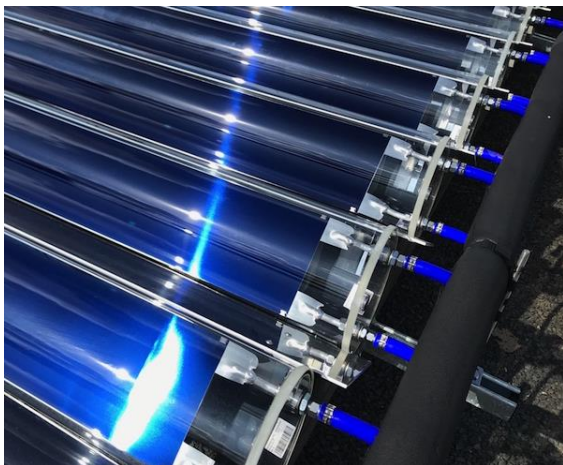


Figure 6. Images of Virtu solar thermal array



Figure 7. Plant room installation for solar thermal array: heat exchanger (left), array pumping station (right).

### c. System operation with specific description of installation activities

The first phase installation of 10 Virtu solar tubes enabled some optimization of the system operation in advance of the larger installation. One key control element is the control of water flow rate. To minimize pump power it is efficient only to flow water when sun intensity is sufficient to generate useful heat. However there are a number of possible control approaches and also some conditions in which flow is required to avoid over-heating or freezing, that require some algorithm optimization at a system level, as follows:

- A number of approaches were considered for determining the trigger for starting or stopping water flow. These included (i) direct monitoring of panel temperature from an in-panel sensor, (ii) monitoring return flow temperature (in combination with pulsing the flow on when idle), (iii) monitoring PV power output from the solar array, (iv) monitoring sun intensity directly from one or more irradiance sensors.
- Once flow is running and a quasi-equilibrium is reached, the flow rate can be controlled accurately based on temperature delta (rise between flow and return water temperature) and an algorithm can be used to maintain this delta T constant by adjusting flow rate. This was implemented in the control system, but required some optimization to avoid unwanted oscillations.
- In the winter, when ambient temperature is below freezing, there is a risk of frost damage to the collectors and pipe-work. A standard approach is to use anti-freeze fluids based on glycol, but in the first phase it was decided to directly flow the main system water to the solar collectors. Therefore in frosty conditions, an algorithm was used to pulse the water flow periodically to prevent water freezing in the pipes.
- The use of the pulse approach for freeze-prevention works in a good combination with the approach (ii) above, of measuring temperature rise during these pulses as a method of deciding when to start water flow, and this approach has previously been successfully used for installations of the Virtu solar product in cold climates. However, at the Deltares site there was also already in place 3 irradiance sensors monitoring a nearby PV array, and the signal from these was therefore used as the primary “switch-on” trigger for starting water flow when sun intensity reached a useful level for extracting thermal power.

In the first phase, system water was flowed directly to the solar array and this gave optimum heat transfer with less system components (compared to having a separate dedicated water circuit). However this direct flow presented some system risks and compromises that became more important when implementing the second phase with a larger array and for a long term operation. Key risk areas related to this direct flow approach are: (i) potential for blocking of the solar collector channels by particles in the main water circuit, (ii) potential for corrosion of the solar collector channels by the water (using water without any corrosion inhibitor). (iii) the need to manage conditions in which water flow stops and the solar collectors over-heat. In the first phase a particle filter was added to the system to address issue (i), a copper tube version of Virtu was used (to address (ii)) and system





control algorithms were implemented to store heat in a 2000 litre water storage cylinder in the case where heat demand was lost to the system (for scenario (iii)).

In the second phase installation a new design of Virtu collectors was used, which reduced the risk of damage during collector over-heating. By implementing a direct flow aluminium absorber plate and high temperature compatible materials, it was possible to make the collector able to withstand over-heating in a stagnation (no water flow) state. This change reduced the system risks associated with over-heating, but however increased the risks from water channel blocking and corrosion, arising from the use of aluminium (instead of copper) for the water channels. Therefore, a decision was made to add a plate heat exchanger between the main system and solar water circuit. With this approach a solar fluid can be used that is kept particle free and avoids corrosion by addition of a chemical corrosion inhibitor. In this case water was used with a corrosion inhibitor rather than glycol, as freeze protection was prevented by using a slow flow rate under freezing conditions. The advantage of water compared to glycol are (i) it is cheaper, (ii) it avoids risks of degradation under over-heating conditions and (iii) it is a superior thermal transfer medium, due to its lower viscosity and higher specific heat capacity.

The control strategy for the array is summarized in Table 1, which shows under which conditions water flow is controlled at different levels.

Table 1. Control strategy for PVT array.

Operation mode	trigger condition	pump (array side)	flow rate (array) l/min	T(flow) C	T(return) C	flow rate (heat ex)	heat transfer in system
<b>Winter</b>							
Standby (night-time)			0			0	
Frost protection	air temperature <0C and light <5%	Magna3	5			0	
Accumulate temp	light intensity > 5% max	Magna3	10		<45	0	
Normal Run	T(return)>45C	CRE3	10-40 (control T(return))	approx 35	50	same as array flow	heat used for building heating
Over-temp	T(return)>65C	CRE3	40		>65	40	heat dump to fan cooler units
<b>Summer</b>							
Standby (night-time)			0			0	
Accumulate temp	light intensity > 5% max	Magna3	10		<25	0	
Normal Run	T(return)>25C	CRE3	10-40 (control T(return))	approx 20	35	2x array flow?	heat stored in aquifer
Over-temp	T(return)>65C	CRE3	40		>50	2x array flow?	heat dump to fan cooler units

In winter (and spring and autumn when building heating is required), the approach is to generate useful heat at up to 50 C, for direct use in heating the building. In summer (and spring or autumn when building cooling is required), a lower temperature is maintained in the array and the heat stored in the aquifer.

#### d. System monitoring

The first phase controller commissioning was completed in December 2017, with the controls being an added module in the ATES management system. The design and software for this controller was carried out by Coneco. Data logging was implemented through the Skyspark web platform and sensor parameters were initially recorded with an 8 min sampling rate, but this was later reduced down to 1 min sampling, to improve power and energy calculation accuracy.

Figure 8 shows the control screen following the phase 2 installation. It shows the temperature, flow and pressure sensors locations and control points for pumps and heat exchanger. The Skyspark platform logged these parameters and enabled thermal power to be calculated and tracked as a function of date, time and weather conditions.

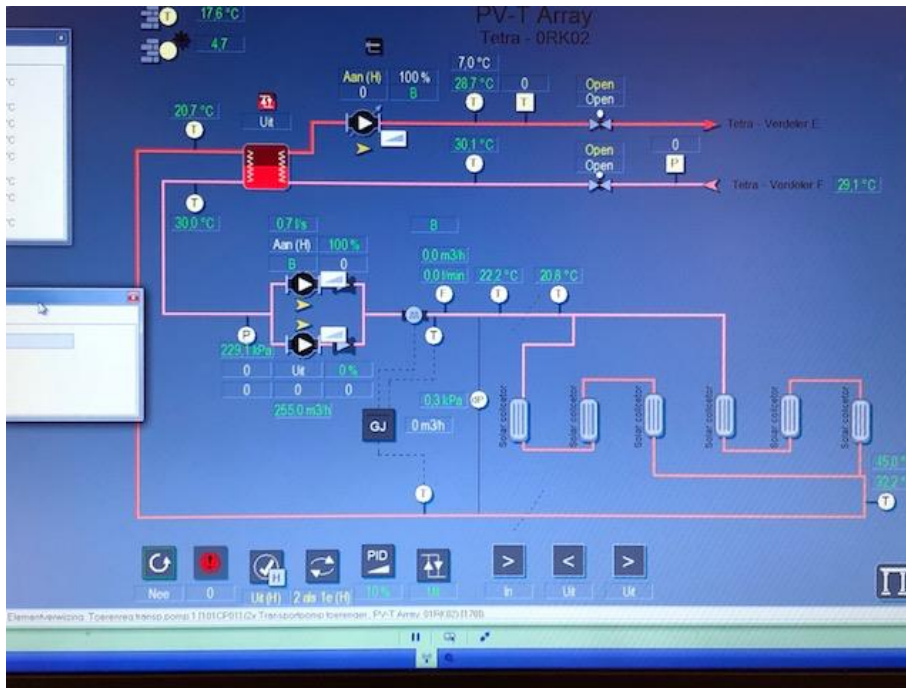


Figure 8. Control screen for solar thermal array

Figure 9 and 10 show examples of the type of data collected for the first phase installation of 10 Virtu collectors, figure 9 showing the thermal power out during a cold winter period in February 2018. Although air temperature was below 0°C, the sunny conditions on this day (peak 700 W/m<sup>2</sup> irradiance) allowed thermal power of approximately 1 kW to be collected for a 4 hour midday period, using an operating water temperature of 30-32°C. Figure 9 shows a second trace recorded in May 2018. As air temperature and sun incidence angle have increased through the spring period the output thermal power and temperatures have also increased. The data in figure 10 shows thermal outputs above 2 kW at water output temperatures up to 50°C. However, the flow rate trace also demonstrates an instability that was observed in the flow rate, arising from the control algorithms described in section c above. At low flows, noise on the flow sensor resulted in poor signal quality, causing the software algorithms to over-compensate and make the flow oscillate. New electronics components and software modification were required to address this problem during the phase 2 installation.



Figure 9. Thermal output data from the phase 1 (10 collector) Virtu solar array – 22-Feb-18



Figure 10. Thermal output data from the phase 1 (10 collector) Virtu solar array: 9-May-18.

In addition to monitoring the solar array thermal output, it is also necessary to monitor to ATEs system storage wells, to track long term temperature trends and energy balance. The wells and observation wells were drilled and installed in 2012. The ATEs system consists of two storage wells; one well to store cold water and one to store warm water. Around each storage well six observation

wells were equipped with fibre optic cables to monitor temperature using the Distributed Temperature Sensing (DTS) technique, with locations shown in Figure 11.

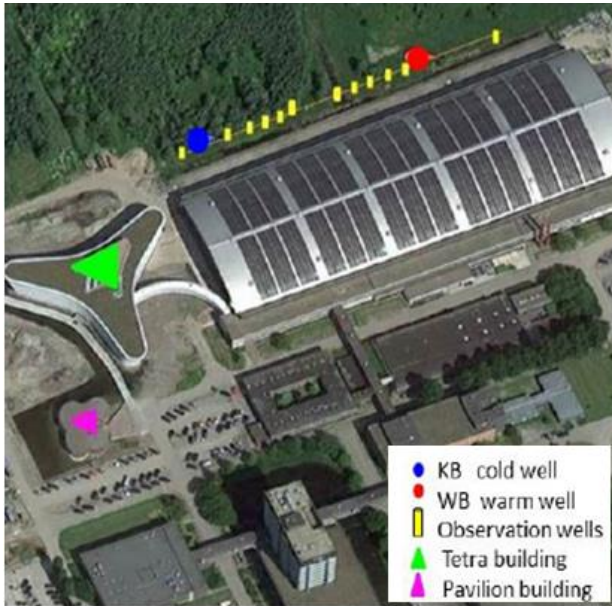


Figure 11. Location of the study area on the site of Deltares. The map indicates the location of the wells (KB and WB) and the observation wells (Pande, 2015)

## 3. Results

### a. System operation

This section reviews the performance data that has been collected so far from the solar thermal array, since the phase 2 installation of 120 Virtu collectors was commissioned in mid September 2018. This initial data confirms the expected level of heat generation during sunny conditions. Figure 12 and 13 show temperature and flow traces for 27-Sep-18, which was a clear sunny day and 30-Sep-18, which had intermittent cloud cover.



Figure 12. Performance data from the Virtu solar array on a clear sunny day



Figure 13. Performance data from the Virtu solar array on a partially cloudy day

In the sunny day data in Figure 12, the flow and return temperature are seen to rise from 12 C in the morning to 31 C and 43 C return at 1:30 pm. Initially in the morning there was some oscillation in temperature as the pump speed was increased and the heat exchanger started to draw heat into the building heating system. From 10 am there was then a rise in temperature and power output, up to the peak solar irradiance at 12 to 1 pm. On the day with intermittent clouds, the array also reached 40 C but power output was more variable.

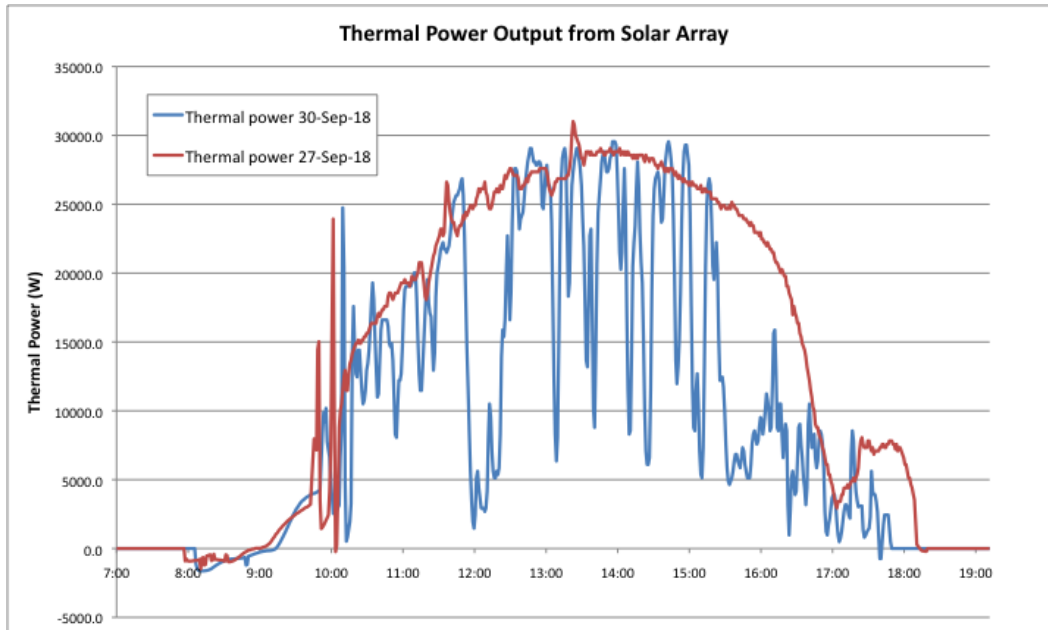


Figure 14 shows the calculated thermal power output during these 2 days.

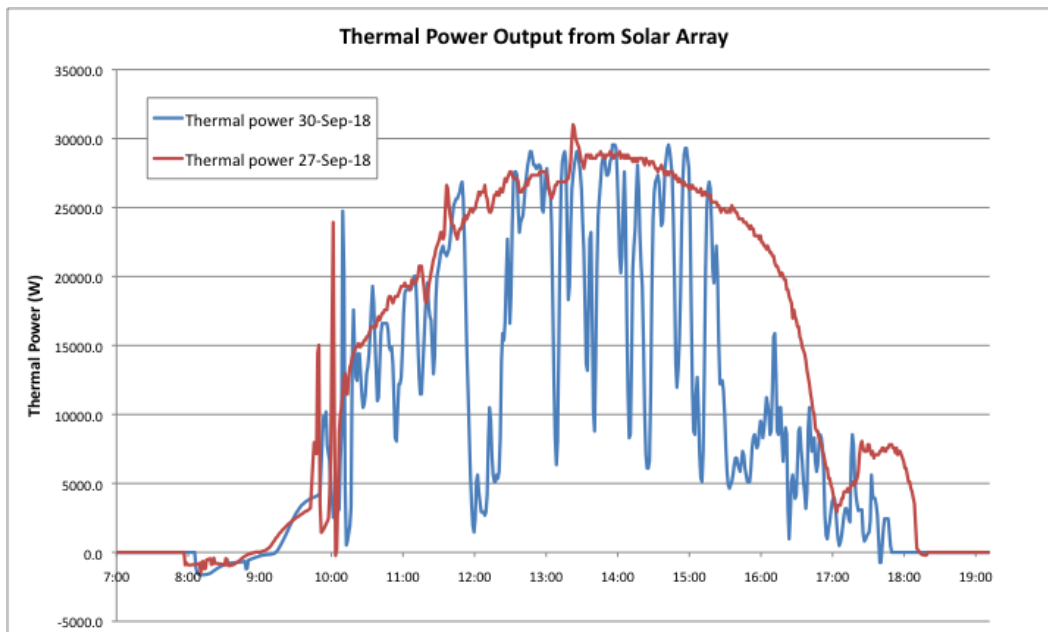


Figure 14. Thermal power output during 27-Sep-18, a sunny day and 30-Sep-18, a partially cloudy day.

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



During the commissioning of the solar array, 3 over-heating events occurred, in which the water flow was interrupted or heat transfer to the system was stopped while the sun was on the array. These resulted in over-heating events in which the array temperature sensors recorded up to 150 C. The root causes of these events all originated in incorrect controller setpoints or algorithms. In the first case the water flow was set to start at an irradiance that was too high, such that flow did not start until 9:00 am. In the other two cases, the pump to the heat exchanger reduced flow mid afternoon, due to a software error. While no significant damage to the solar array or the system resulted from these events, there was some disruption and system downtime. When over-heating occurs the system pressure also rises, due to steam generation in the collectors. In the first over-heating event, the water flow turned on at 9:00 am and this resulted in a large pressure burst as the cold water reached the over-temperature solar collectors. This pressure burst caused some water fittings to come loose, leading to a water leak and the water pressure then fell to a low level at which the pumps could no longer circulate water. The system remained in stagnation (with no water flow) all day and the temperature in the manifolds reached 150 C (which suggests an even higher temperature inside the collectors). The system had then to be covered for a few days while the leaks were repaired and the collectors checked for damage. Fortunately, the system had been filled with water (with a corrosion inhibitor) rather than glycol, since glycol degrades at these high temperatures. Some lessons learned from these events were:

- Do not remove the covers from the solar collectors until commissioning has been completed and the controller functionality and fault mode recovery have all been tested and demonstrated.
- Make sure there is clear ownership of maintenance and controller functions as soon as installation has been completed – this is especially important in collaborative projects with many partners.
- When solar collectors are in a stagnated over-temperature mode, ensure the controller does not turn the water flow back on until the temperature has dropped below 100 C, to avoid thermal shock damage and a pressure burst.
- Ensure all water fittings are tested to higher pressures than the maximum operating pressure, to ensure no fittings can come loose if there is a pressure burst.
- Water (with freeze protection measures) can offer advantages over glycol in robustness against over-heating events.

Figure 15 shows a chart of the maximum operating temperature (water return temperature at the solar array) for the month of October 2018. The typical operating temperatures (on sunny days) were 30 C flow and 40 C return, so a 10 C temperature rise. One of the stagnation events is apparent on 13-14<sup>th</sup> October, with temperature reaching 140 C.

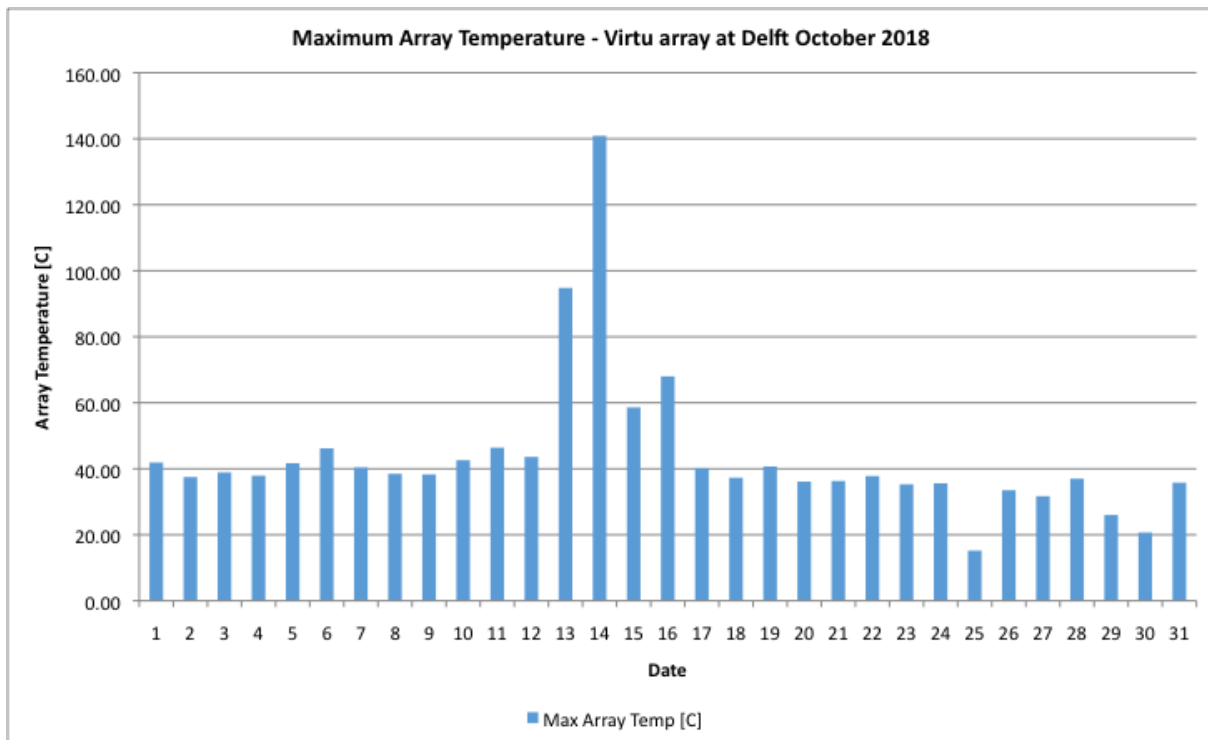


Figure 15. October data from Virtu solar array, showing maximum daily operating temperature.

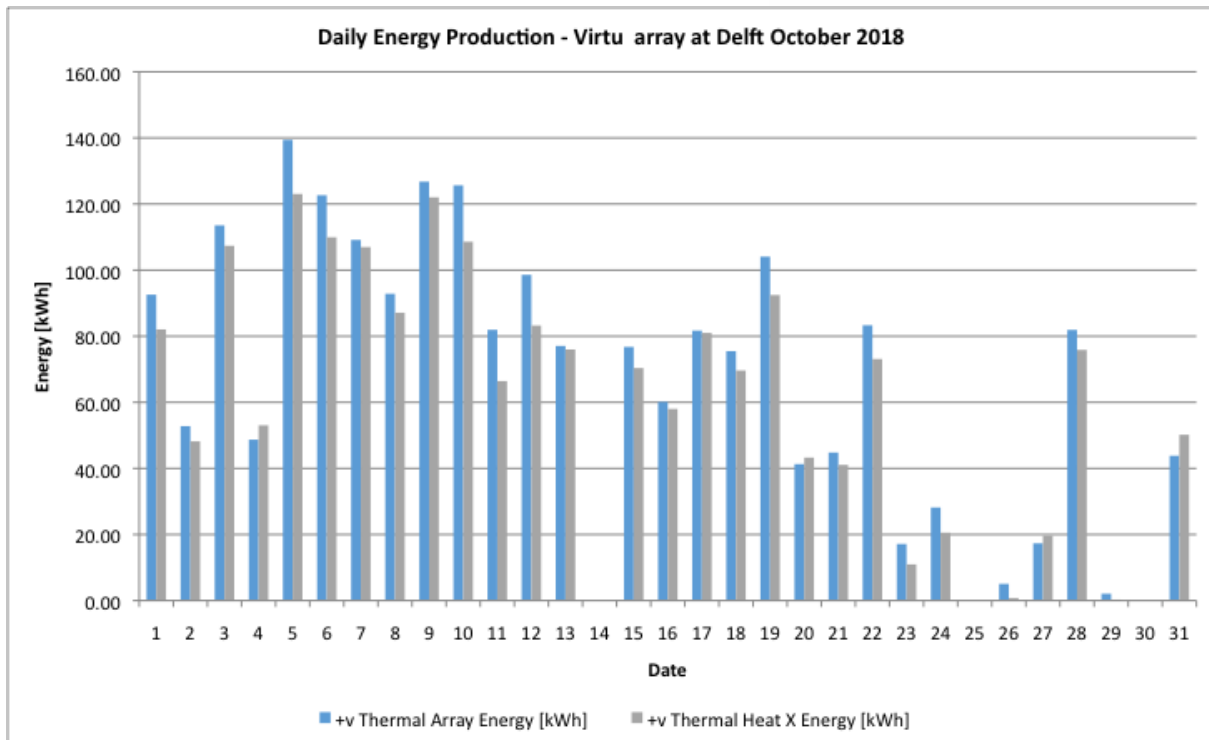


Figure 16. October data from Virtu solar array, showing daily energy output measured at solar array and at heat exchanger.

Figure 16 shows a chart of the average daily solar heat energy production, measured in 2 places: at the solar array and at the heat exchanger. The energy generated by the solar array was approximately 100 kWh per day in the first half of the month, reducing to approximately 50 kWh per day in the second half of the month (due to reducing sun angle and more cloudy weather). The thermal energy that was delivered through the heat exchanger to the ATES system was on average 88% of the thermal energy measured at the solar array. This indicates that there were only 12% system losses, due to heat transfer efficiency and ambient heat loss, which shows that the system was well insulated. It is noted that the solar array was 80 m away from the plant room, but a high quality, well insulated heat main pipe was used to connect these, the initial data confirms that this approach has been effective in minimizing system heat losses.

#### b. ATES well temperature Monitoring

The aquifer temperatures have been monitored over a number of years, to allow heat balance and usage to be tracked. For each location the temperature trend over time has been recorded, to build up 5 years of baseline data, prior to the solar array installation (figure 17). In the cold well the filter screen is split and installed around 58- 65 m and 72 – 82 below mean sea level. Through these well screens cold water is injected and can be tracked at several distances from the cold well, as shown in figure and 18 and 19. Water with cold water does not reach the outer monitoring wells, which is an indication that more cold water can be stored in the subsurface, without the system losing its efficiency. This could be achieved by infiltrating more cold water in the well. It must be stated that the design of the well has a limit in the amount of water which can be stored. Another option could be to add another cold well to the system.



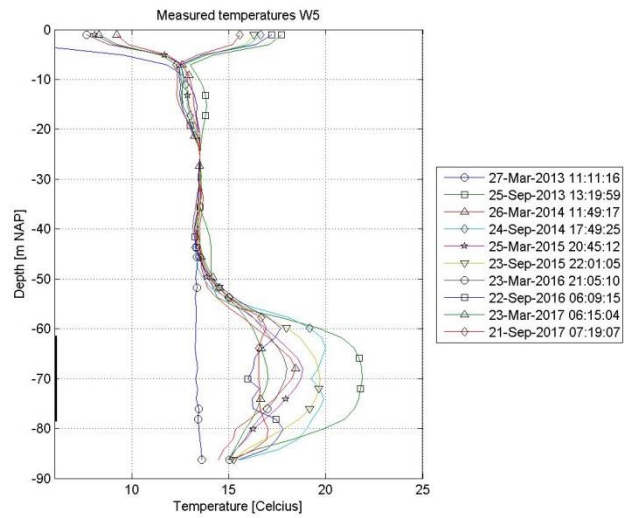


Figure 17. Temperature measurements at observation well W5.

Figure 18 and 19 show charts of this trend between 2014 and 2018 for the temperatures in the cold and warm wells. The annual cycle can be observed, with the September data showing higher temperatures than March. However this cycle alters over the year period. In the cold well, the minimum temperature reduces, with minimum temperatures as low as 9 C observed. While the summer maximum has maintained almost constant at 13-14 C, the annual cycle has become larger resulting in the lower minimum. It can be seen that all cold water is extracted before the summer. A trend that can be observed in the warm well data is that there is a surplus of heat in the subsurface; not all the energy is taken from the reservoir, meaning that the energy balance is not equal on both sides.

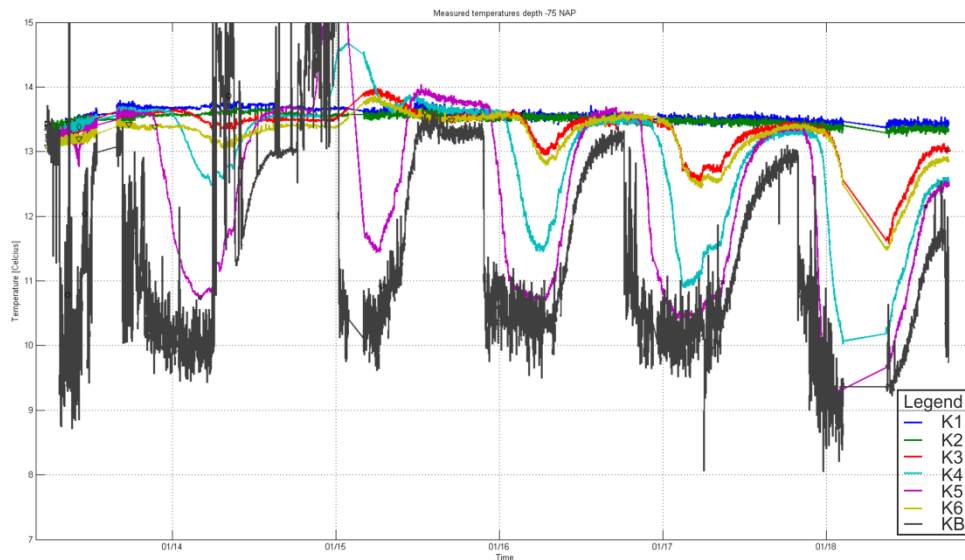


Figure 18. Temperature measurements from monitoring wells, showing trend between 2014 and 2018 in cold well.

Figure 18 shows the temperatures at different monitoring locations from the cold well. The infiltrated cold water does not reach the two monitoring point that are the furthest away (K1 and K2). Almost every summer the cold well is completely depleted. Figure 19 shows the same data for the warm well. This figure shows that heat injection into the warm well has decreased over the past years.

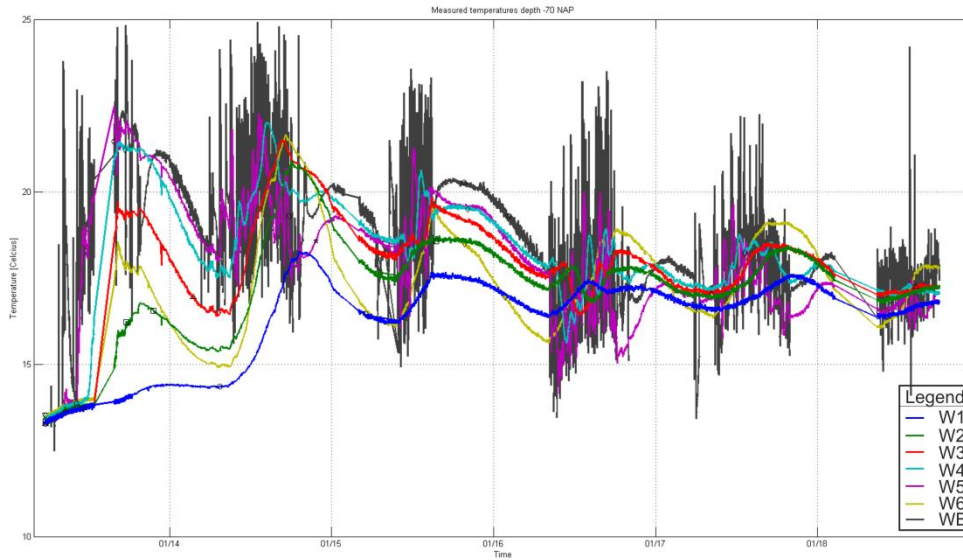


Figure 19. Temperature measurements from monitoring wells, showing trend between 2014 and 2018 in warm well.

By interpolation of the temperature data from the monitoring wells, a temperature distribution has been derived that covers the aquifer space around the (monitoring) wells, shown in Figure 18 and 19. These distribution maps for the cold well in Figure 20 show the temperature distribution around the cold well at the end of winter and the end of summer in 2017 and 2018. Due to the cold winter in 17/18 the cold well is larger in 2018.

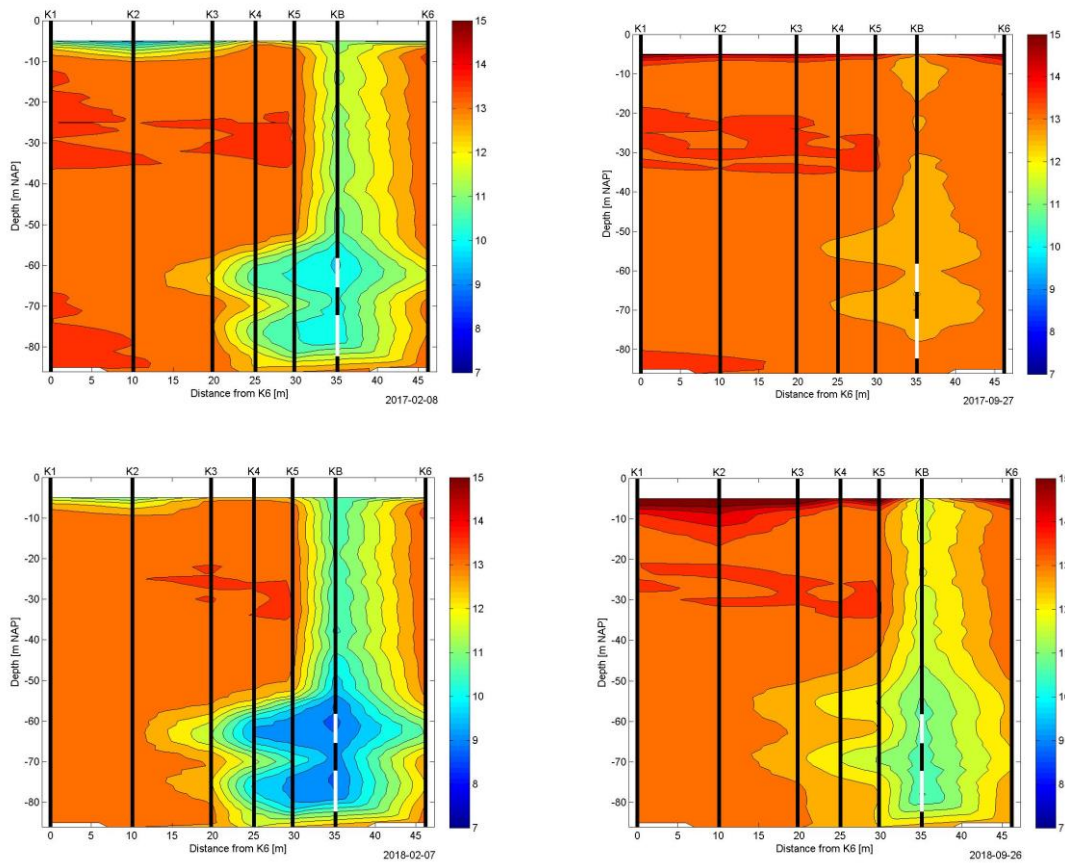




Figure 20. Interpolated temperature data around the cold well showing the change in temperature distribution between 2017 and 2018.

## 4. Conclusion

The Delft ATES pilot at the Deltares site has focused on addressing the key challenge of: improving energy matching over multiple seasons through the addition of renewable heat source and heat sharing between buildings. The economic benefits of an ATES system can only be analysed when an annual cycle is created.

This balance can be partly achieved on a site-wide basis by balancing the heating and cooling demands of different buildings, as shown in this case with the Tetra and ZZH buildings, i.e. where one building has a higher cooling demand and the other a higher heating demand. This is a key learning for future ATES projects, that it is beneficial to include within a project multiple buildings with differing energy requirements, which thereby leverage the benefit of inter-seasonal storage while maintaining long term storage temperature balance.

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 optimisation (e.g. temperature control, freeze protection); in the second 120 tubes were installed, to give a 30 kW heat production capability, which was also demonstrated during the last months of the project. 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. 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.

## References

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