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Near-autarkic heating and cooling of buildings using a triple well aquifer thermal energy storage concept: Identifying suitable demand conditions

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ABSTRACT

The energy transition relies on electrification and due to the increased use of heat pumps this is especially true for the heating and cooling of buildings, causing congestion on the electricity grid. The Aquifer Thermal Energy Storage (ATES) Triplet can decrease the reliance of low-emission heating and cooling on electricity by utilizing on-site energy generation, two heating and cooling supply wells and one well to prevent thermal pollution of the other wells. With this setup the system provides heating and cooling without the use of a heat pump, only by circulating groundwater for the energy supply and asynchronous energy generation. A simulation study is conducted to identify when the ATES Triplet is a more viable option than a standard ATES doublet. Five building energy variables are systematically assessed with a subsurface thermohydraulic dynamics model, i.e. heating demand, cooling demand, injection temperature levels, cutoff temperature levels, and return temperature levels. These scenarios are evaluated based on the calculated electricity requirements, pumping volume, and on-site energy generation requirements. The results show that the Triplet outperforms an average low-temperature ATES doublet in most of the considered cases, especially cases with low sub-surface losses, a high heating ΔT, a low cutoff temperature and a low return temperature after heating. This requires building HVAC (Heating, Ventilation and Air Conditioning) systems to accept as wide a range of supply temperature as possible. Systems with a low heating demand ($<$ 1 TJ) in combination with a high required temperature for heating ($>$ 80 °C) are unfavourable.

1. Introduction

Heating and cooling of buildings accounts for approximately half of the global final energy consumption, emitting 40% of the energy related CO_2 emissions in 2023 [1]. Furthermore, the demand for cooling is steadily growing with the global demand expected to double before 2050 [2]. Therefore, it is imperative to decarbonize space heating and cooling of buildings in order to decarbonize the overall energy supply and meet legal agreements such as the Paris agreement [3].

To decarbonise heating and cooling, a significant portion of the built environment switch from fossil-based heating to systems which use energy obtained from the local environment, with the temperatures upgraded or downgraded to match the demand temperature using heat pumps [4], which use a significant amount of electrical energy to run. The closer the source is to the required demand temperature, the less electricity is required. To exploit this, systems such as Aquifer Thermal Energy Storage (ATES) which store thermal energy in groundwater, overcoming the seasonal mismatch between thermal supply and demand [5] and allowing for more stable supply temperatures, and thus require less electricity. ATES systems are utilising open wells and therefore allow large thermal powers that can provide larger buildings with heating and cooling.

The use of ATES and other heat pump systems for space heating and cooling is growing, as well as the research into potential adaptation of systems in different countries/regions [6–9]. Since ATES systems depend on a heat pump, a major challenge of ATES adaptation remains in areas where transition from fossil fuel derived heating drives increased demands for (significant amounts of) external electricity, especially at times when heating demand is high. Meanwhile, also other sectors, such as transport and industry, are decarbonizing by

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electrification. This widespread electrification is a key challenge in the energy transition, increasing overall electricity demand and creating grid congestion due to synchronous demand which is asynchronous to supply by wind and solar [10].

By storing the required thermal energy (for heating and cooling) at the desired temperature level, thermal energy can be delivered in a so-called "passive" manner, i.e. without using a heat pump to concentrate the thermal energy. With passive heating or cooling only circulation of water is needed, considerably decreasing the requirements for electricity, and in particular decreasing electricity use at the moment of demand. For example, high temperature (HT-) ATES systems can partially facilitate passive heating by increasing the temperature of the thermal energy stored. Research into the applications, efficiency and mitigating/understanding risks of high temperature systems is increasing [11–14] with the first novel system in the Netherlands becoming operational recently [15].

Although HT-ATES systems reduce or remove the need for a heat pump for heating supply, cooling cannot be provided. Therefore, a combination of an HT-ATES system with an additional cold well for cooling has been proposed that could accommodate both heating and cooling supply as well as disconnecting heating and cooling supply from major electricity use [16,17]. This idea constitutes the concept of a three-well system, which has been called the ATES Triplet, or the Triplet (illustrated in Fig. 1).

The Triplet concept [16] is proposed to have two wells at temperatures that are directly used for heating and cooling provision, and a third well with an intermediate temperature, which is used as the return well for both the heating and cooling wells when the return temperature is not suitable for injection into the other well, i.e. is not at a temperature which can be directly used. An integrated system including sources for harvesting thermal energy at the temperature which can be directly used for heating and cooling is proposed, such that the hot and cold wells can be recharged without the use of a heat pump and asynchronously from demand. Any locally available sources can be used as long as they provide thermal energy at the desired temperatures for passive heating and cooling. This system could then be nearly autarkic and will therefore limit the stress on the power grid, while also considerably reducing primary energy use and associated GHG emissions. Another three-well ATES systems has been proposed [18], yet these use the third well to stop groundwater flow from decreasing the efficiency of the ATES system, by placing an extraction well upstream of a doublet, which is a different use for the third well as proposed in this study.

The proposed Triplet system has a straightforward basic working principle (as shown in Fig. 1). It consists of three circuits, the sub-surface wells, the building supply system, and the thermal energy generation system, in this case dry coolers and solar heat collectors. These circuits transfer thermal energy to each other using heat exchangers. In the summer, the 'cold' from the cold well is used to cool the building, causing the groundwater that is extracted to heat up. If sufficient solar capacity is available, the water is then heated further and injected into the hot well. If not, all or part of the return flow will be directed towards the buffer well. Water can also be extracted from the buffer well and heated if there is an overcapacity to generate thermal energy. In the winter, the thermal energy from the hot well is used to heat the building, cooling down the groundwater that is extracted. If sufficient dry cooler capacity is available, the water is cooled down further to meet the cooling supply temperature and is injected into the cold well. If not, the return flow after heating will be (partially) injected into the buffer well.

Initial studies indicate that such a system is feasible [16,17,19]. In these previous feasibility studies, a range of relevant operational and subsurface conditions were varied but they did not analyse the interplay between the parameters assessed. Though the study showed that the Triplet was feasible, it remains unclear for which combination of demand conditions the Triplet is a suitable choice. A follow-up case study showed the system operations to be complex [20–22] as passive heating and cooling can result in strict temperature requirements for the hot and cold wells, requiring many modes of operations to maintain these temperatures. The case study investigated by Boro [20], Chalga [21] and Wasman et al. [22] utilised a building heat transfer model for one specific building with all relevant heat transfer dynamics but did not assess the feasibility for different building types and utilised a simplified approach for the subsurface behaviour. A follow up study [23], considered the sub-surface behaviour for different well placements, and specifically how to decrease the energy requirements for regeneration of the wells. However, it also focussed on specific cases, and did not test the applicability of the Triplet for different building types Since elevated temperatures will cause heat losses to contribute significantly to the produced temperatures [11] the sub-surface behaviour is likely to be critical for performance. This is likely to be exacerbated by the significant influence of the building-driven temperature requirements.

The analysis of ATES system performance has mostly focused on the subsurface system and the subsurface losses [11,13,24], despite it being clear that the dynamic demands play a key role in performance [25]. Initial work on investigating the impact of building behaviour on ATES system performance [26] indicated that the subsurface ground temperature and the resulting system coefficient of performance can be both improved by balancing thermal loads. In a city with a large ATES penetration (Utrecht, the Netherlands), it has been shown that most systems have a substantial (>10%) thermal imbalance [27] and that heat losses and poor performance could come from either the subsurface or the building energy system, and in particular the interplay between the two [28]. Dynamic balancing of ATES systems, with control on the

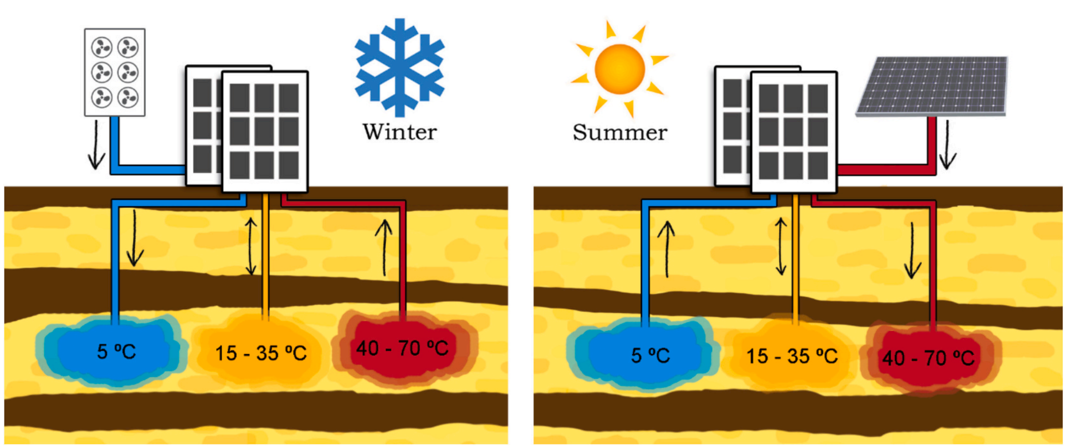

Fig. 1. Concept image of the Triplet including operation in winter (left) and summer (right), in this case using dry coolers for harvesting thermal energy for cooling and solar collectors for harvesting heat.

building, network and subsurface flows, has been seen via monitoring and data analysis to enable enhanced performance over a multi-year period [29]. Therefore, especially in a system where the heat pump and therefore flexibility is removed, dynamic balancing, building control and sub-surface design and layout are critically important. However, since the ATES Triplet is a new system, it is unclear for which building conditions the system is applicable. Before the design can be tested for different sub-surface designs, with different control schemes and other technologies incorporated it is needed to analyse the building conditions under which a system can perform well.

This study, therefore, aims to identify the viable building demand conditions and temperature levels for the ATES Triplet concept. This is done by assessing and quantifying the interplay between the subsurface behaviour and the energy and flow requirements for the storage system for a wide range of building demand conditions and temperature levels. This is tackled with a simulation study, focussing on the subsurface thermohydraulic dynamics. Different heating and cooling demand profiles and supply temperature settings are applied to assess how combinations of such conditions affect the required of the electricity needs for well pumps and building operations, as well as the required capacity for heating and cooling generators to operate an ATES Triplet. Such insights are not only relevant for ATES Triplet development, but for any heating and cooling system.

2. Methods

A numerical simulation study of the ATES Triplet is carried out, whereby a fixed subsurface is considered and a sensitivity analysis is conducted by varying the building demand and operational parameters that affect the functioning of an ATES Triplet system. Firstly, an overview of the simulation is given, after which all the steps are explained in more detail. The model is available for download [30].

2.1. Simulation

2.1.1. Overall simulation set-up

The simulation workflow is presented in Fig. 2, which consists of a heating and cooling demand profile based on a building scenario, a thermohydraulic dynamic model of subsurface based on pre-selected parameters and an iterative evaluation step where it is ensured that the heating demand is met followed by a performance assessment. The building scenarios define the yearly thermal energy demands, the temperatures injected into the wells as well as the operational temperature levels. For each scenario, the required flows to and from the wells are calculated based on a series of assumptions. The simplifying assumptions are intended to balance maintaining realism, while allowing the results to be straightforward to interpret. These are:

- A year consists of a single heating season and a single cooling season.
- The heating demand and cooling demand, and the injected and extracted energies follow a simplified sinusoidal profiles per half year, illustrated in Fig. 3.
- External heat is always and only available in the cooling season and cold is available in the heating season.
- Heat and cold are always available for charging in the opposing season.
- The background temperature of the groundwater is sufficient for cooling, but the cooling demand must be met in the regeneration of the wells.
- Wells do not influence each other in the aquifer.

As a result of these simplifications, the system can be considered to have two modes of operation: one with heating from the hot well, whilst regenerating the cold well, and the second with cooling from the cold well whilst regeneration the hot well. In both cases, where there is any mismatch from needed flows into or out of the hot and cold wells, the buffer well is used to compensate.

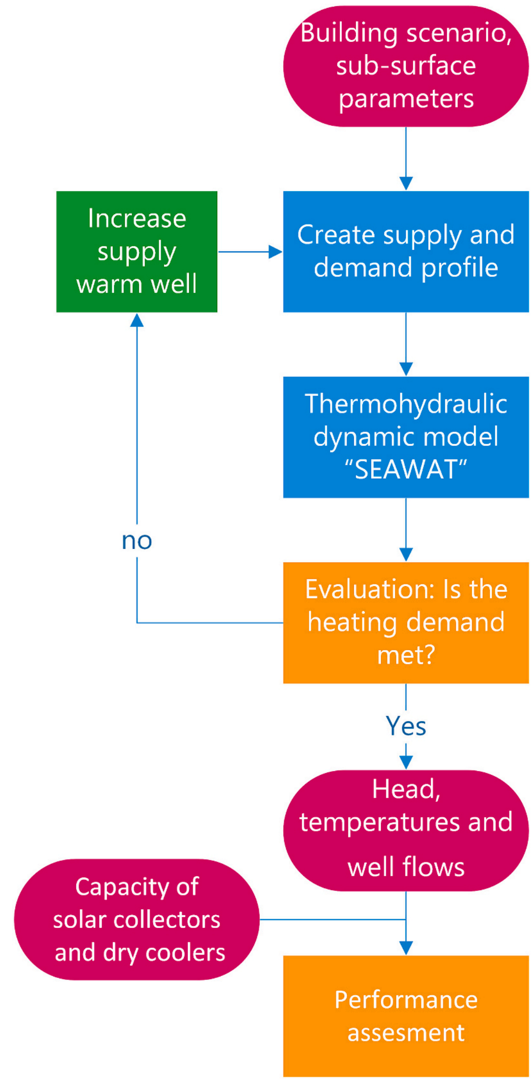

Fig. 2. Flow chart of the model workflow [30]. The workflow is carried out for different scenarios, allowing for a comparison between these scenarios.

Initially, the amount of heat that needs to be stored is estimated based on the heat demand, then the required daily flows are estimated and input into a thermohydraulic dynamic groundwater model [30] which is used to evaluate the temperature level retrieved from the wells and keeps track of storage in the wells. The model is run with a daily timestep for eight years, of which the first 3 years are considered model startup years, and the remaining 5 years are considered operational years. After the full runtime, it is assessed whether the heating demand has been met every day in the five operational years by evaluating if the production temperature on the last day after the heating season is higher than the required temperature (the cutoff temperature). If this is not the case, the amount of heat stored is increased (quantified by a sizing factor, such that the sizing factor is the ratio between the heat stored and the heat demand), and the model is run again, until the value is found for which the model can supply the heating demand, or the sizing factor is higher than 10. Note that the inverse of the sizing factor is the recovery efficiency for the hot well which is the produced energy divided by the injected energy. If the factor is higher than 10, the system is not considered feasible, since a high number of solar collectors is needed as well as high pumping volumes. The system is not further assessed.

After the end of the simulation, the resulting flows, pressure head and amount of energy stored are extracted from the model and used to

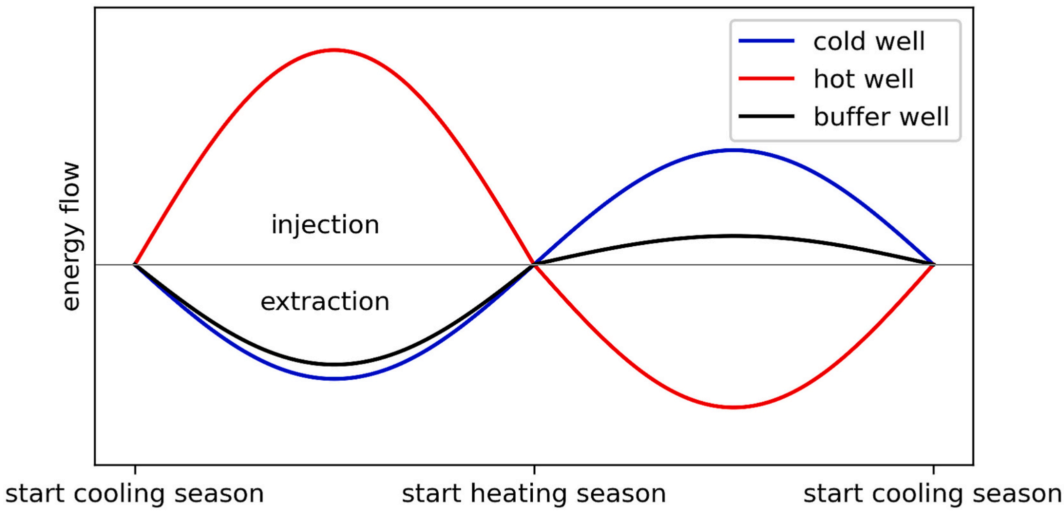

Fig. 3. Example of an injection/extraction profile based on the demand. The energy injected into the hot well is equal to the demand multiplied with a sizing factor, and extraction from the hot well is the heating demand. The cooling demand is both injected and extracted.

evaluate the performance of the system.

2.1.2. Building scenarios

There are a wide range of building types and building behaviour (energy performance), which results in significantly different demand conditions. The key parameters which are considered are: (i) the annual heating demand, (ii) the annual cooling demand, (iii) the injection temperature into the hot well, defined by the heat production system (e.g. solar collectors), regulations and system operation, (iv) the minimum temperature required for the building heating system to function (i.e. the cutoff temperature), and (v) the return temperature after heating. All scenarios considered are representative for the Netherlands, have both a heating and a cooling demand, with an indoor temperature targeting 20 °C, Domestic hot water use is not considered.

Cooling is evaluated across different scenarios, assuming constant injection, operating, and return temperatures. This assumption is based on the relatively narrow temperature range (5–8 °C) observed in cooling using LT-ATES systems [31]. Given the target indoor temperature of 20 °C, these variations are considered negligible and have been seen to not affect the outcomes of this analysis. The injection temperature is fixed at 5 °C, and the cutoff temperature is 12 °C. As the conditions in the Netherlands are used, a background subsurface temperature of 12 °C is considered, therefore no cutoff temperature needs to be defined as a limit for the groundwater extraction for cooling.

The cutoff and return temperatures are defined as a factor of the storage injection temperature and supply temperature, respectively. This approach prevents impossible temperature values, e.g. a return temperature under the room temperature. The cutoff temperature and return temperature are defined respectively as:

$$T_{h,cutoff} = T_r + \left(T_{h,inj} - T_r\right) \times f_c \quad (1)$$

$$T_{rh} = T_r + \left(T_{h,cutoff} - T_r\right) \times f_r \quad (2)$$

where $T_{h,cutoff}$ is the cutoff temperature, T_r is the required temperature, i.e. the room temperature + losses in circuit = 22°, $T_{h,inj}$ is the injection temperature in the hot well, f_c is the hot well cutoff factor, T_{rh} is the return temperature after heating and f_r is the return factor. For example, if the injection temperature is 80 °C, the required temperature is set to 22 °C, and the hot well cutoff factor is 0.9, the cutoff temperature is thus 22 + (80–22) × 0.9 = 74.2 °C, i.e. this is the lowest temperature whereby it is possible for the building to be heated. At this minimum production temperature, if the return factor is then 0.5, then the return temperature will be 22 + (74.2–22) × 0.5 = 48.1 °C, i.e. the lowest return flow temperature.

The values for the sensitivity analysis (Table 1) are chosen such that the scenarios represent a range of buildings, varying in size from roughly 500 to 25,000 m^{2,} depending on insulation level and supply temperatures for heating and cooling [32]. A well-insulated small office building might for instance have a small heating demand, a larger cooling demand, have a low injection temperature for the hot well, a small ΔT (high return factor) and little margin for error (high hot well cutoff factor). The chosen values are not one-to-one related to specific case-studies but rather give a spread of different scenarios. Not all combinations will be as realistic as others. Nonetheless, all combinations are considered as scenarios for consistent comparison of results, resulting in a total of 1620 scenarios.

2.1.3. Subsurface parameters and thermohydraulic dynamic model

The subsurface model is made using SEAWAT [33], a MODFLOW based model used for groundwater flow modelling with a heat flow component, including the impacts of buoyancy. The code is based on PySeawATES [34], a simulation environment made for ATES research that has been used in several studies [11,35–37]. For this research, 3 wells are simulated simultaneously, but do not interfere with each other, and a control system is added to translate energy demand into the well flows for the 3 wells.

The location and orientation, and interactions between wells are not considered in this study, therefore, the chosen model setup is axisymmetric [38]. The model consists of 5 axisymmetric domains Three domains (see Fig. 4) are made with wells (at the central domain boundary) and the two in between are boundary rows-set to be inactive, to prevent interactions between the domains. This causes each domain with a well to behave as if it is in a separate axisymmetric model. The approach is similar to the model used by Bloemendal and Olsthoorn [36] and Bloemendal and Hartog [24], but adapted for three wells. An example of the subsurface layout is shown in Fig. 4 for one domain. Each row consists of cells of 2 m high and initially 1 m wide. The width of the cells

Table 1
Building parameter variations.

Parameter (unit)	Value
Heating Demand (TJ/y)	0.5, 1, 2, 5, 10
Cooling Demand (TJ/y)	0.5, 1, 2, 5, 10
Injection temperature hot well (°C)	50, 60, 70, 80, 90
Hot well cutoff factor (−)	0.5, 0.7, 0.9
Return factor (−)	0.5, 0.7, 0.9

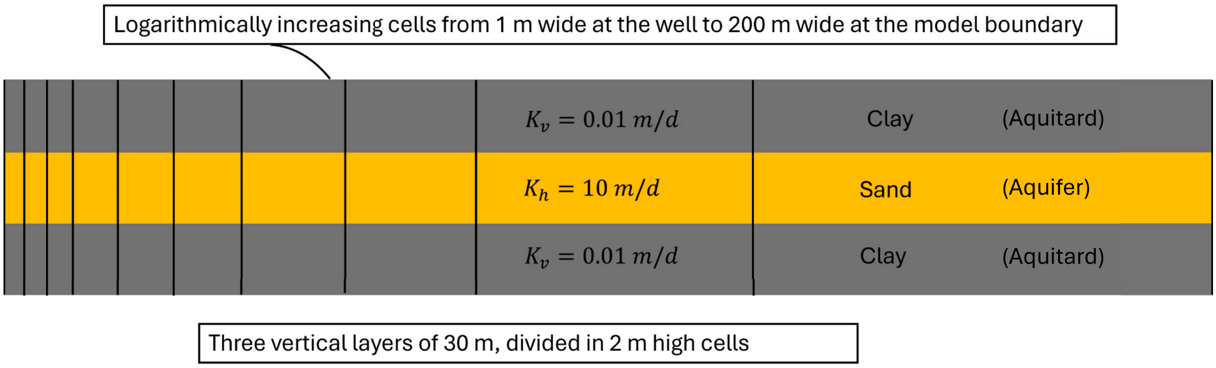

Fig. 4. Schematic of the subsurface domain and model setup for one axisymmetric model. K_h is the horizontal hydraulic conductivity and K_v is the vertical hydraulic conductivity.

increases logarithmically to 200-m-wide cells at the model boundary at 1000 m. These values are chosen such that there is convergence of the results.

The subsurface parameters are presented in Table 2. They have been selected to be representative of conditions in the Netherlands suitable for ATES [24] and are fixed for all simulations. The conditions are fixed to facilitate a comparison of the impact of the building scenarios. The subsurface is considered to have two thick aquitards with a 30 m thick aquifer in between. Twenty meters of the total thickness of the aquifer is utilised for the well screens.

The energy demand and recharge determine to the injection and extraction for the different wells. The flows are calculated based on the type of well and all the different set point temperatures. For the hot well the cutoff temperature determines if there is discharge that timestep or not. All flow calculations, and the decision tree to determine the different flows are shown in Fig. 5, with the explanation of the parameters in Table 3.

2.2. Model verification

The thermodynamic model is adapted from an existing model used for various ATES studies [11,35–37]and has been extensively verified for its hydrogeological and heat transport behaviour, as well as for use as an ATES simulator. The changes made to the model are such that the subsurface workings are the same, to ensure the veracity of the model. The only adaptations have been in the use of the simulator to be able to run with three wells of different temperatures, enable the multiprocessing of several scenarios simultaneously, and make the script running

Table 2
Subsurface characteristics applied in this study.

Parameter	Value	Unit
Ambient Groundwater temperature	12	°C
Well Screen length	20	m
Thickness aquifer	30	m
Horizontal hydraulic conductivity aquifer	10	m/d
Vertical hydraulic conductivity aquifer	2	m/d
Horizontal hydraulic conductivity aquitard	0.05	m/d
Vertical hydraulic conductivity aquitard	0.01	m/d
Thermal conductivity sand	2	W/m/K
Thermal conductivity clay	1.7	W/m/K
Thermal conductivity fluids	0.58	W/m/K
Porosity	0.3	–
Density fluids	1000	kg/m3
Density sand and clay	2640	kg/m3
Dispersivity	0.5	m
Vertical Transverse Dispersivity	0.005	m
Horizontal Transverse Dispersivity	0.05	m
Specific heat capacity fluids	4183	J/kg/K
Specific heat capacity sand and clay	710	J/kg/K

the simulator more readable and open-source friendly. The grid-size and timesteps were chosen such that the results showed convergence. Mass balance was checked to ensure that the total flows to the three wells balanced in all time steps and cumulatively. As no Triplet system has been construction, no validation against experimental data specific to the Triplet is possible.

2.3. Performance assessment

To assess and quantify the interplay between the subsurface behaviour and building energy transfer, different metrics are used. These metrics are:

- the pumping volume, since it shows the effect of subsurface losses on the required design of the triplet, as well as the required electrical demand.

- the bridging energy, i.e. energy used to heat/cool water used for regeneration up/down to the minimal usable temperature, before bringing it up/down to the required injection temperature and then storing in either the hot or cold well, which partially determines the overcapacity required for the energy generation.

- the total electricity requirements compared to a doublet since it shows when an ATES triplet system can be a reasonable alternative to a doublet.

2.3.1. Pumping volume required

The pumped volume is the total volume of extracted water from the three wells (which is exactly equal to the total volume injected). This metric is a proxy for (i) the amount of subsurface space that is needed to be used, and (ii) the amount of energy needed to be used to operate the system. This factor is influenced by the energy demands, the injection temperature and cutoff temperature, i.e. the operating window coming from the building, and the subsurface heat losses. The subsurface heat losses (quantified by the size factor) dictate the volume that is injected into the hot well and thus extracted from the other wells. As the demand differences of the scenarios implicitly require different total pumped volumes, a relative pumping volume is also used, i.e. the average yearly pumped volume per energy supplied.

2.3.2. Bridging energy

The amount of energy injected into the wells (recharge energy, $E_{recharge}$) is calculated using the difference between injection temperature and return temperature after heating or cooling. However, this does not translate to energy that needs to be generated ($E_{generated}$) since when generating the heat, the input temperature is defined by a mixture of the cooling return temperature and the buffer well production temperature at that time. (Re)heating the groundwater used as the input into the heat/cold generating system (e.g. solar collectors or dry coolers) has then two components, (i) an amount of energy that is added to the

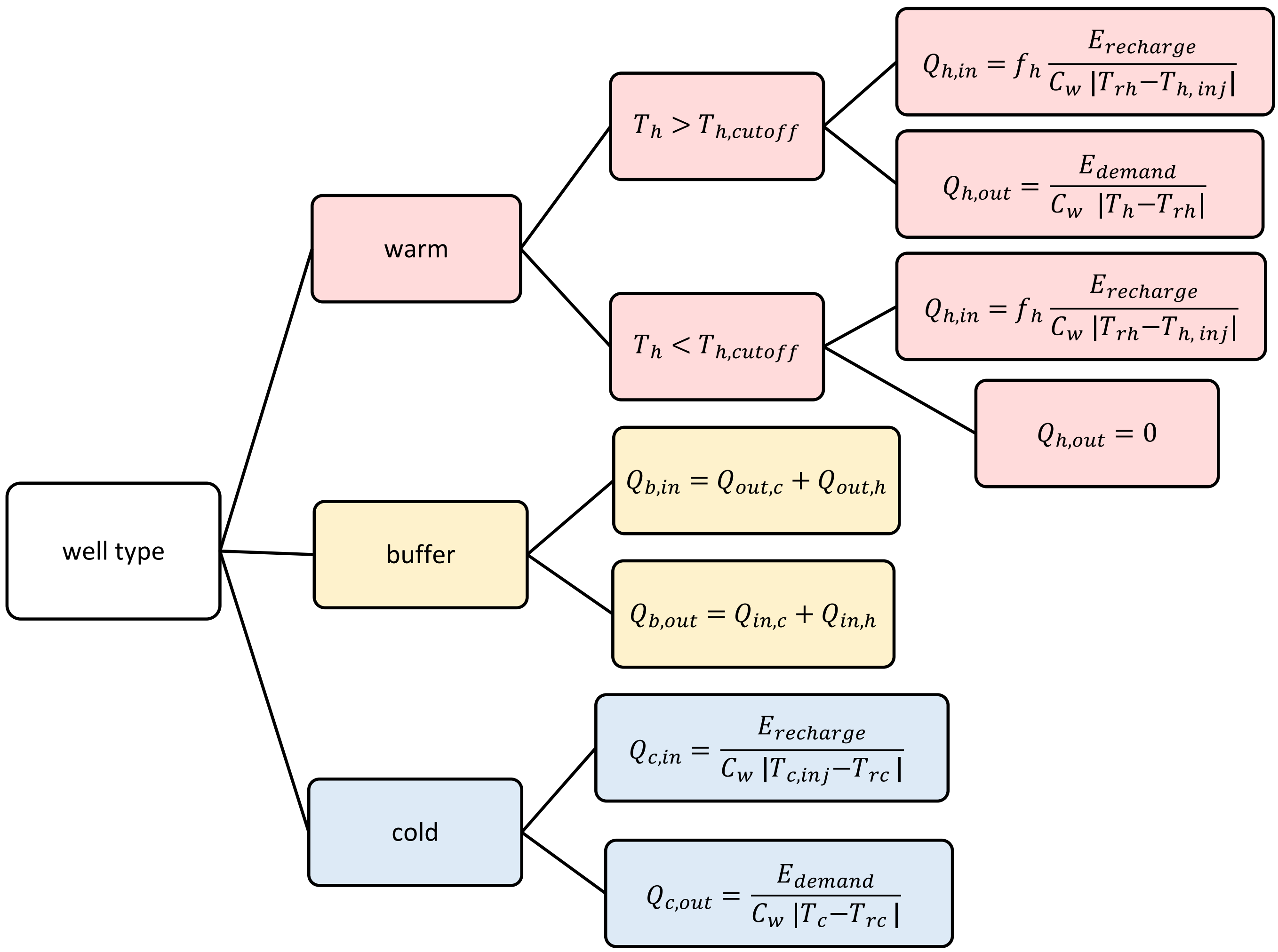

Fig. 5. Flow chart for calculating flows. In the model the buffer flows are aggregated into one in/outflow, and the temperature is calculated using the volume weighted averages of the inflows.

Table 3
Explanation of parameters in Fig. 5.

Parameter	Symbol	Unit
Well temperature (hot / buffer / cold)	$T_h/T_b/T_c$	°C
Cutoff temperature	$T_{h,cutoff}$	°C
Return temperature after heating / cooling	T_{rh}/T_{rc}	°C
Injection temperature (hot / cold)	$T_{h,inj}/T_{c,\ inj}$	°C
Discharge well (hot / buffer /cold)	$Q_{h,out}/Q_{b,out}/Q_{c,out}$	m^3/day
Recharge well (hot / buffer /cold)	$Q_{h,in}/Q_{b,in}/Q_{c,in}$	m^3/day
Energy demand	E_{demand}	TJ
Recharge demand	$E_{recharge}$	TJ
Sizing factor	f_h	–
Volumetric heat capacity	C_w	J/K/m^3

groundwater to bring the water up to the return temperature, i.e. the energy used to bridge the gap between the input water temperature and a useful temperature, this energy is further referred to as 'bridging energy' (E_{bridge}), and (ii) the energy needed to recharge the wells, i.e.:

$$E_{generated} = E_{bridge} + E_{recharge} \tag{3}$$

where the bridging energy can be calculated for the hot and cold wells, respectively, as either:

$$E_{bridge} = Q_{h,in} * C_w * |T_a - T_{rh}| \text{ or } \quad E_{bridge} = Q_{c,in} * C_w * |T_a - T_{rc}| \tag{4}$$

where T_a is the temperature of the water used for regeneration. This is either the return temperature after cooling, when regenerating the hot well or the return temperature after heating when regenerating the cold well, combined as a volume weighted average with the buffer well temperature if used.

To decrease the required capacity for solar collectors and dry coolers, this bridging energy should be kept at a minimum. As with the pumping volumes, relative bridging energy, bridging energy divided by demand, is used to compare scenarios with different sizes.

2.3.3. Electricity use

Electricity is used for a Triplet system by the submersible well pumps, circulation pumps and dry cooler fans. In this study, a wide range of buildings are assessed that in practice will have different components, and thus different electricity uses per volume pumped or energy generated. In order to compare different systems, simple rules of thumb are used to evaluate electricity use. As such it is assumed that the electricity required to pump one cubic meter is 0.15 kWh, which is 540 kJ/m^3 [39]. It is assumed that the volume pumped in the building is equal to the volume pumped by the wells, and that the building pumps require 240 kJ/m^3, which is estimated based on several industrial applications [40]. One circuit pump is assumed to be used for the energy supply to the building, and two are used in the regeneration circuits, one to circulate the generators, and one to pump from the generators to the heat exchanger with the wells. Lastly, dry coolers require electricity to run their fan which is used to provide the cooling. There are no clear rules of thumb for the electrical requirements of the dry cooler fan, but based on several industrial applications, 0.025 J/J is used to calculate the electricity required [41,42]. To make the comparison between systems and with low temperature ATES systems easier, the relative electricity use is adopted, which is the ratio of the electricity use to the thermal energy delivered.

2.3.4. Comparison with low temperature ATES system

To see when the Triplet can achieve a reduction in electricity use compared to regular LT-ATES, the Triplet and LT-ATES are compared via the electricity use. Using the ΔT and an average seasonal coefficient of performance (SCOP) of a LT-ATES, the electricity requirements can be estimated in a simple manner based on the heating and cooling demand. The LT-ATES is considered to have a ΔT of 6 [43] and a SCOP of 5. When the cooling demand is more than heating, it is assumed that dry coolers are used to generate cold with the same electricity use as described for the Triplet. The doublet is considered to have a volumetric balance, and the pumping volume thus consists of twice the volume needed for the maximum of the heating or cooling load. One internal circuit pump is considered to be running during heating or cooling to provide the energy to the building.

3. Results

3.1. Electricity use

Since the system has no heat pump, electricity in the Triplet is used for the well pumps, the internal circulation pumps and the dry cooler fans. For the cases selected, the relative electricity use can be as low as 2% of the delivered thermal energy, but also as high as 23% (as seen in Fig. 6A). In comparison, an LT-ATES doublet has a range of 9% to 23%. Though the range in relative energy use is similar, it is seen that in 89% of cases the Triplet uses less electricity than an LT-ATES doublet.

In addition, Fig. 6 shows that systems using a large amount of electricity for a doublet (relative or absolute), would use less with a Triplet system, and as the systems uses less (relative) energy the doublet system is more frequently better.

Fig. 7A shows the relative Triplet electricity use relative to the hot well efficiency and the ΔT for the building heating system, against also the hot well injection temperature. A lower hot well recovery efficiency is seen to increase the relative electricity use for two reasons. Firstly, as more volume is required to be pumped, the pumping power required increases. Secondly, fewer losses result in less energy that needs to be generated, so also less electricity is consumed by the circulation pumps when regenerating the wells. The colouration of the of the points in Fig. 7A indicates that generally the hot well efficiency is highest when the injection temperature is lowest, likely due to the reduction of heat losses driven by a lower temperature gradient in the aquifer, albeit with a spread of results. Indirectly, increasing the injection temperature in the hot well is likely to increase the temperature in the buffer well and therefore increase the amount of energy needed for bridging energy to regenerate the cold well (meaning further use of dry coolers), further increasing the electricity use. The Triplet would benefit from a low return temperature after heating to keep the relative electricity use at bay.

Furthermore, as shown in Fig. 7B, a smaller ΔT in the heating system is shown to result in an increase in relative electricity use. This is because a larger volume of water is required to be pumped in order to deliver the same energy and therefore increases the pumping electricity. A small ΔT causes the cutoff to be reached sooner due to the losses in the subsurface. To prevent hitting the cutoff temperature, more hot water needs to be injected, increasing the electricity use of the circulation pump as well as the well pump.

Fig. 7 shows, therefore, that increasing the hot well injection temperature has two contrasting effects: (i) it enables buildings to have a higher temperature difference in the heating system, which increases efficiency and reduces the amount of electricity used, yet at the same time (ii) increases heat losses in the subsurface, which increases the amount of electricity used. These results show that for the design of a Triplet system, the hot well injection temperature must be chosen such that a balance is found between a large ΔT and keeping losses in the subsurface low enough.

The balance between heating and cooling demand is of importance, as is shown in Fig. 8A, which reproduces the comparison between the Triplet and LT-ATES systems shown in Fig. 6A, colouring the points by the percentage of heating demand (Fig. 8A) and the return temperature after heating the building (Fig. 8B). Due to the high electrical requirement to generate cold (by the dry coolers used in this case), systems dominated by cooling are more likely to have an increased electrical requirement. For cooling dominated systems (shown on the left hand side of both sub-figures), the return temperature after heating (Fig. 8B) is a big factor in the increased electricity use, since more cold bridging energy needs to be generated. In Fig. 8B, only the cold dominated systems are seen to have a very clear relationship between the return temperature and relative energy use. For the Triplet to be a decent option in cooling dominated systems, the return temperature after heating should be kept as low as possible. In general, the Triplet seems to be most viable for the balanced to heating dominated systems.

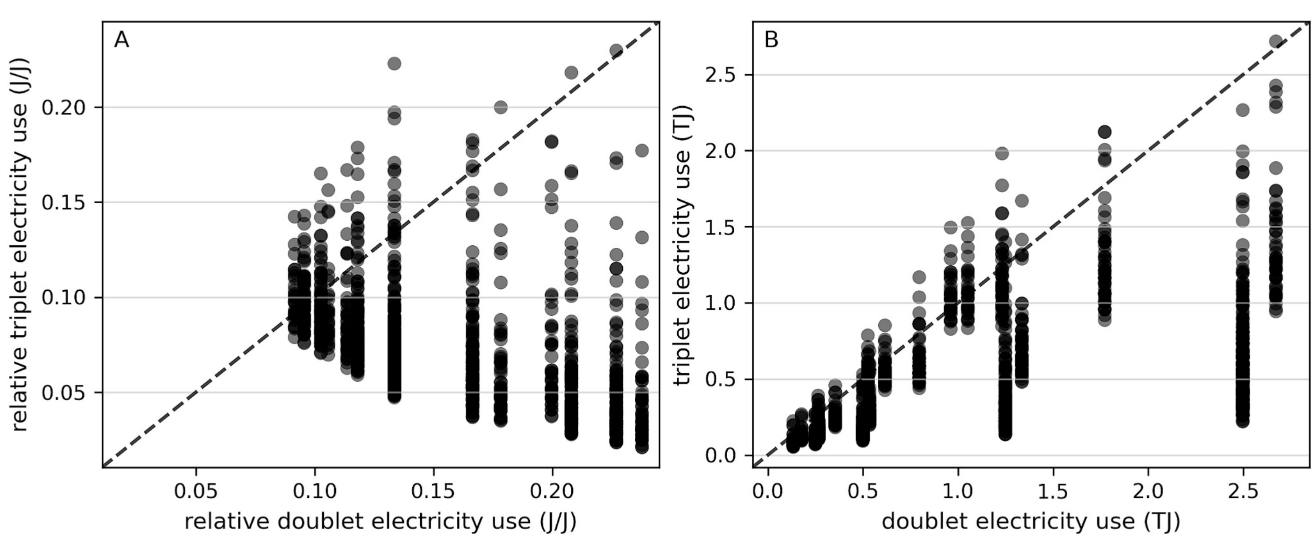

Fig. 6. Comparison between the electricity requirements for a doublet or a triplet for all simulation realisations. A darker colour indicates a larger density of dots.

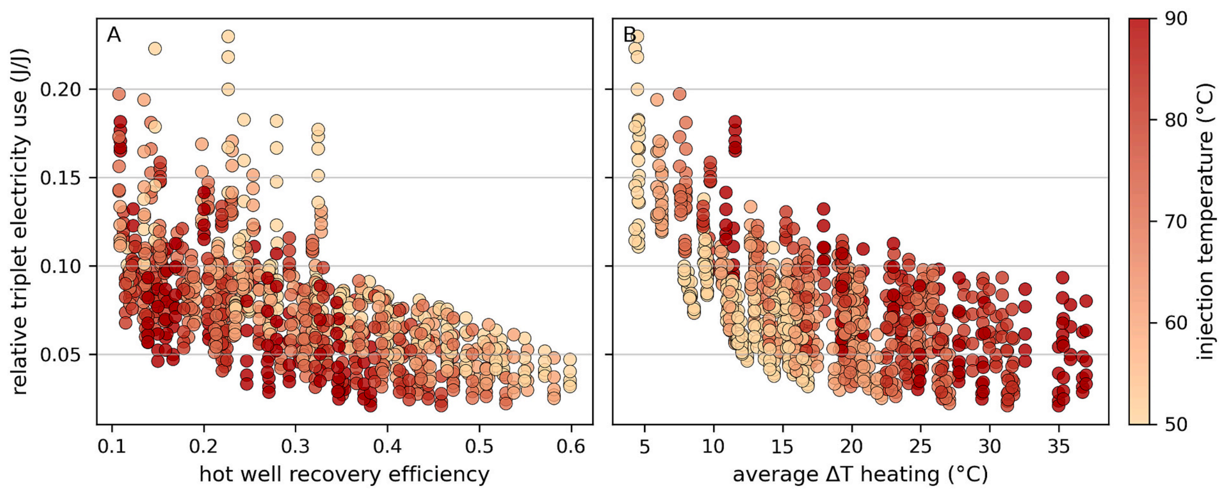

Fig. 7. A: Electricity use comparison for different hot well efficiency values, B: Average ΔT for heating. The vertical axis shows the electricity required to run a year by the triplet divided by the electricity that would be required for a doublet.

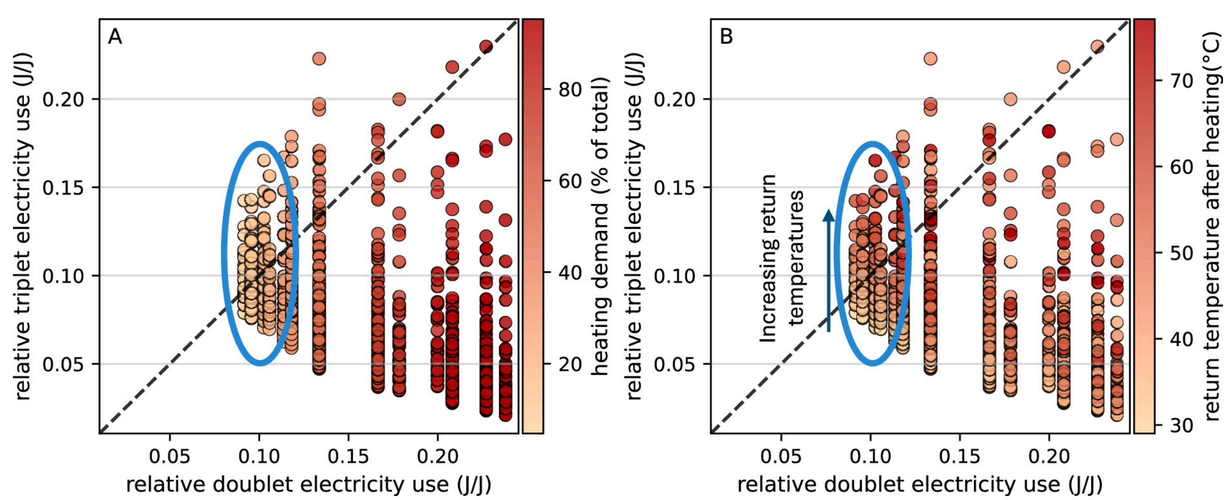

Fig. 8. Relative electricity use of the different scenarios. Everything below the dotted line would use more electricity when a doublet would be used, and everything above would use more electricity when a triplet would be used. The circle highlights cooling dominated systems.

3.2. Effect of bridging energy

The bridging energy for heating is the energy required to bridge the energy gap between the return flow after heating, and the water used for the regeneration of heat., The water used for regeneration is a combination of water from the buffer well and the returning water after

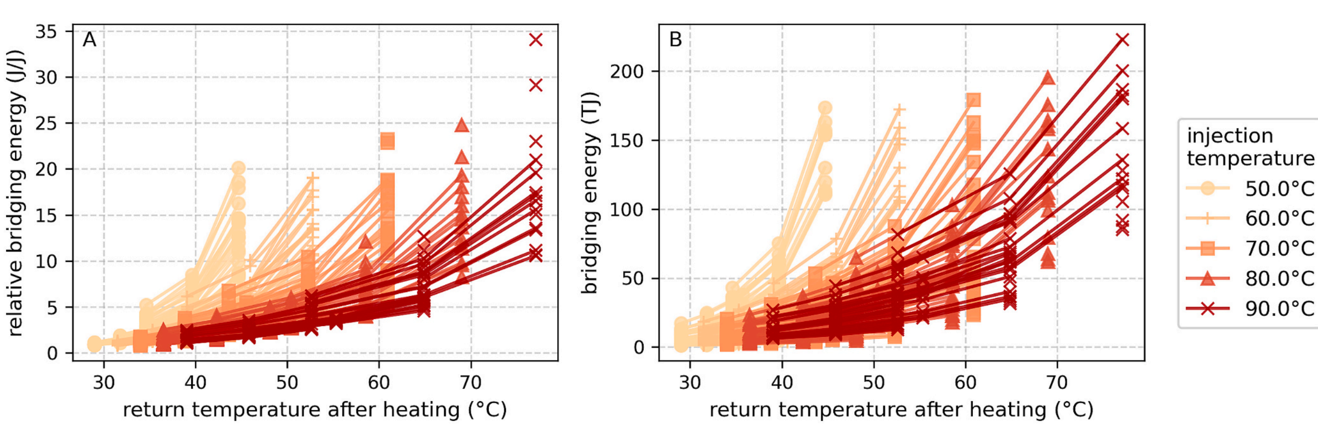

Fig. 9. The effect of the heating return temperature on the bridging energy. Image A shows relative bridging energy, which is bridging energy over the thermal energy provided. Image B shows the absolute bridging energy for all the different scenarios. Scenarios with the same other variables (heating and cooling demand, injection temperature and cutoff factor) are connected by lines.

cooling, and the temperature of that water is the weighted average of the two. For cooling it is naturally opposite.

The combination of hot well temperature variables is presented for both the relative and the absolute bridging energy in Fig. 9 where relative bridging energy is the amount of bridging energy per supplied thermal energy. It illustrates the amount of bridging energy for the different scenarios and that the required bridging energy is strongly influenced by the return temperature after heating. The total relatively bridging energy is always above 0.8 J/J, but mostly above 1 J/J, meaning that more energy is used to bridge the gaps between the operating windows of heating and cooling rather than being used for heating or cooling directly. This energy is generated from the environment in this case example, i.e. from solar collectors and dry coolers, and therefore cannot be directly used to determine the externally provided electricity. It is however important for the amount of generation capacity required to operate the Triplet, and the number of solar collectors and dry coolers that need to be installed and maintained. Fig. 9 shows that keeping the return temperature as low as possible in the design of the system is essential to keep the bridging energy low. This is especially true for cooling dominated systems as shown in Fig. 8B and highlighted in Section 3.1, where cooling dominated systems require more electricity to operate for a higher return temperature after heating.

These results shows that the bridging energy is an important factor to account for when designing an ATES Triplet, as it is a greater amount of energy than the energy delivered for heating or cooling. It increases the required generation capacity and may increase the dependency on grid electricity considerably. Since the bridging energy is a unique aspect that stems from a system without a heat pump and increases complexity for the building heat transfer system, it is identified as the main challenge to the design and operation of a Triplet system.

3.3. Effect of pumping volumes

The pumping volume is influenced by multiple design parameters as well as subsurface effect. The demand in combination with temperature levels determine the volume that would be needed if losses were neglected, the subsurface losses will add to that required pumping volume. Higher hot well injection temperatures typically reduce the amount of water pumped since higher storage temperatures typically show a higher ΔT in the building. In those cases, the energy density is higher directly reducing pumping volumes and generally dominating additional subsurface losses (occurring due to a higher temperature in the subsurface). Larger heating demands increase the volume in the subsurface, typically decreasing the surface area to volume ratio, meaning that the relative losses are lower [11].

3.3.1. Effect of subsurface losses on triplet performance

Fig. 10A shows that the amount of water pumped per useful energy delivered reduces with increasing heating demand, which is attributed to a smaller sensitivity to losses. As for all HT-ATES systems, increasing temperature losses in the subsurface impact the performance of the entire system, which would reduce the recovery efficiency. For the Triplet, losses result in more than just a decreasing recovery efficiency of the wells (Fig. 10B), since the volume of groundwater that needs to be pumped around increases too. Since no heat pump is available, the hot well is required to have a sufficient energy content to supply heat throughout the season. Therefore, losses must be compensated for, and more heat is injected, increasing the extraction of the buffer well during regeneration of heat, increasing the total pumped volume.

The systems with small volumes are more sensitive to losses due to the higher hot well temperatures, as is the case with all ATES systems [11]. Fig. 10, illustrates this with the decreasing efficiency for both smaller heating demands and higher temperatures. Higher temperatures require a lower volume but are more sensitive to losses due to buoyancy driven flow losses. Since these losses must be compensated, pumped volume relative to the demand goes up, as Fig. 10A shows. Even though the energy content per cubic meter is larger with higher temperatures (in this study ΔT's scale with injection temperature), this is not enough to compensate the losses, especially at small demands. The result is that for larger heating demands, for the shown scenarios, increasing the injection temperature above 60 °C, and thus increasing the ΔT (ΔT is determined by a factor that is dependent on injection temperature) does not yield lower pumping volumes per TJ of heat delivered, since the increased losses require more injection as well.

3.3.2. Accepting temperature degradation

Though minimizing thermal dissipation (losses) is of importance, losses cannot be eliminated entirely, and temperature degradation in the hot well will always happen. Temperature losses in LT- ATES doublet systems reduce performance but is it corrected by using a heat pump incorporated in systems. Traditionally, boiler and heat pump-based systems are operated with a set temperature output, since the burning

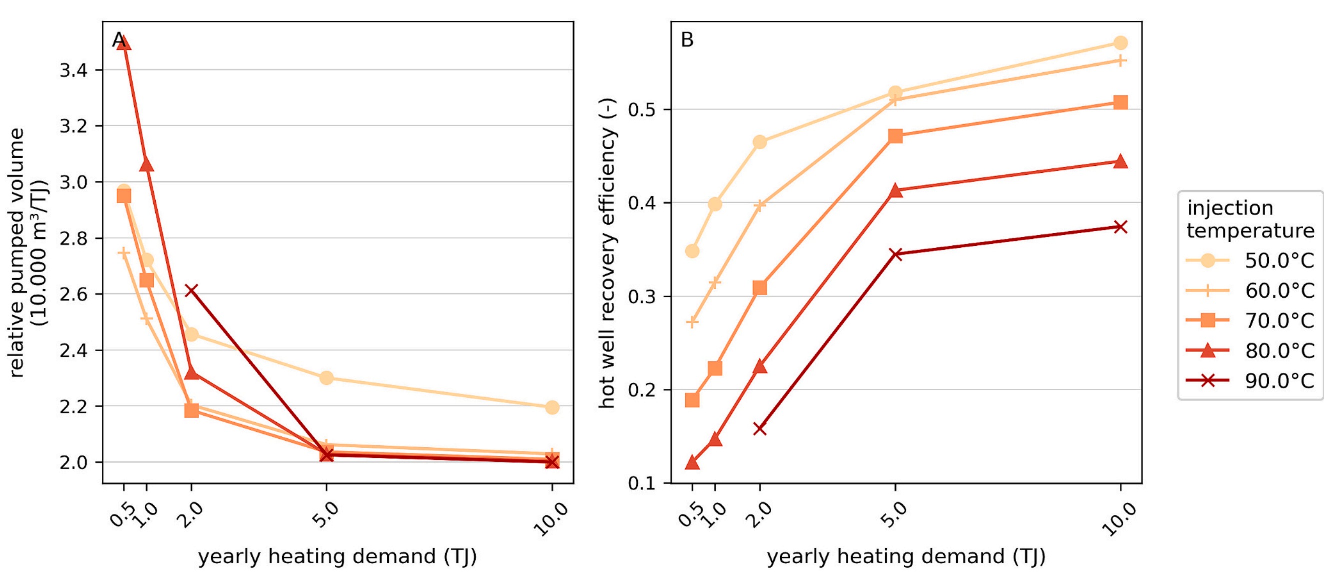

Fig. 10. A: Relative pumped volume for different temperatures and heating demands. B: Hot well recovery efficiency for different temperatures and heating demands. Missing datapoints indicate an efficiency lower then 0.1, after which they were no longer evaluated by the model, and results in both figures are for balanced scenarios with a return temperature factor of 0.7 and a cutoff temperature factor of 0.5.

of fuel or addition of electricity can be used to control the heating temperature.

In an ATES Triplet, this is cannot be done since there is no heat pump at the demand side. The heat transfer system in the building using the Triplet must thus be able to handle a range of input temperatures. If this range is kept small, which supports using standard building setups, a low level of temperature degradation in the subsurface quickly leads to a temperature in the well that is not suitable for heating. Therefore, it is beneficial to increase the range of acceptable input temperatures. Though more heat will be lost in the subsurface, the hot well can be used with lower temperatures, and more total energy can be recovered. Fig. 11 shows the effect of decreasing the cutoff temperature, i.e. accepting more low temperature energy, i.e. accepting more low quality energy. Both the efficiency (B) and relative pumped volume (A) benefit from a greater range of acceptable input temperatures, but for larger volumes, increasing the cutoff factor greatly does not seem to make a big difference anymore, indicating that the system is less sensitive to losses.

3.3.3. *Tuning the building heat transfer system characteristics*

The results on electricity use and bridging energy have shown that ΔT is an important design parameter of the heat transfer system. Maximizing the ΔT will decrease both the electricity use and the bridging energy, but it will also decrease the pumping volume which is illustrated by *Fig. 12*A. In this study the ΔT is dependent on the injection temperature for the hot well, the cutoff temperature and the return temperature, and it is not constant over a heating season. In the design of a system, these three parameters should be chosen such that they result in the highest average ΔT possible with a return temperature that is as low as possible to ensure small pumping volumes, low bridging energy and thus low electricity use. In Fig. 12, the lines are connecting scenarios with the same energy demands, injection temperature and cutoff temperature. A higher ΔT is thus caused by a lower return temperature. The downward trends in the increasing return temperature direction thus indicates that decreasing the return temperature always leads to lower bridging energy and smaller pumping volumes.

4. Discussion

4.1. *Optimal demand conditions*

The ATES Triplet system has the same requirements to be suitable as a regular ATES system. These are climatic conditions that result in both a heating and a cooling demand, as well as a suitable aquifer. Though this study uses a simulated aquifer similar to those found in the Netherlands, in many places in the world other types of aquifers are suitable for ATES [44]. Therefore, it is anticipated that the ATES Triplet should be applicable in those cases too, and more care should be taken in design in areas where ATES is more difficult to implement, due to for instance varying groundwater tables, and overextraction of groundwater [45]. For the Triplet system however, the demand conditions of a building directly impact the subsurface behaviour and vice-versa, in a more significant way than has been observed in ATES systems [43]. The numerical simulations in this study show that the combination of demand parameters affect the electricity use and volume pumped significantly. Specifically, Triplet systems can significantly outperform other heating and cooling systems such as an ATES doublet, as long as the bridging energy (especially when generating cooling) and storage volumes are controlled.

Hence, it is important to keep return temperatures after heating as low as possible to limit the bridging energy required for cold generation. This is more important than having higher return temperatures for cooling, since in this study heat harvesting is done with solar collectors that do not require external electricity other than circulation pumps, however this will change if heating and cooling sources with other characteristics are considered.

Since the Triplet system has no heat pump, temperature degradation (which controls what are considered energy losses) in the subsurface can have a large effect. The influence of heat losses in the subsurface is not a unique problem to the Triplet, since the performance of all ATES systems is affected by losses [24,46,47]. Especially HT-ATES systems are sensitive to the design of the wells, and to a small storage volume [11]. However, the system performance of the Triplet is more sensitive to losses since there is no way to increase the temperature of the incoming water. As a result, a cutoff close to the injection temperature will result in large injection volumes to counteract these losses and a high electricity use due to more well pumping and more required regeneration. To ensure that this does not happen, it is needed to developing HVAC systems that can handle a larger deviation in incoming temperatures. Whilst this is a necessity for systems such as the Triplet, allowing for a larger spread in incoming temperatures for heating can reduce the required pumping volumes for all ATES systems and make heating systems more robust. In this work, larger systems are seen to outperform a

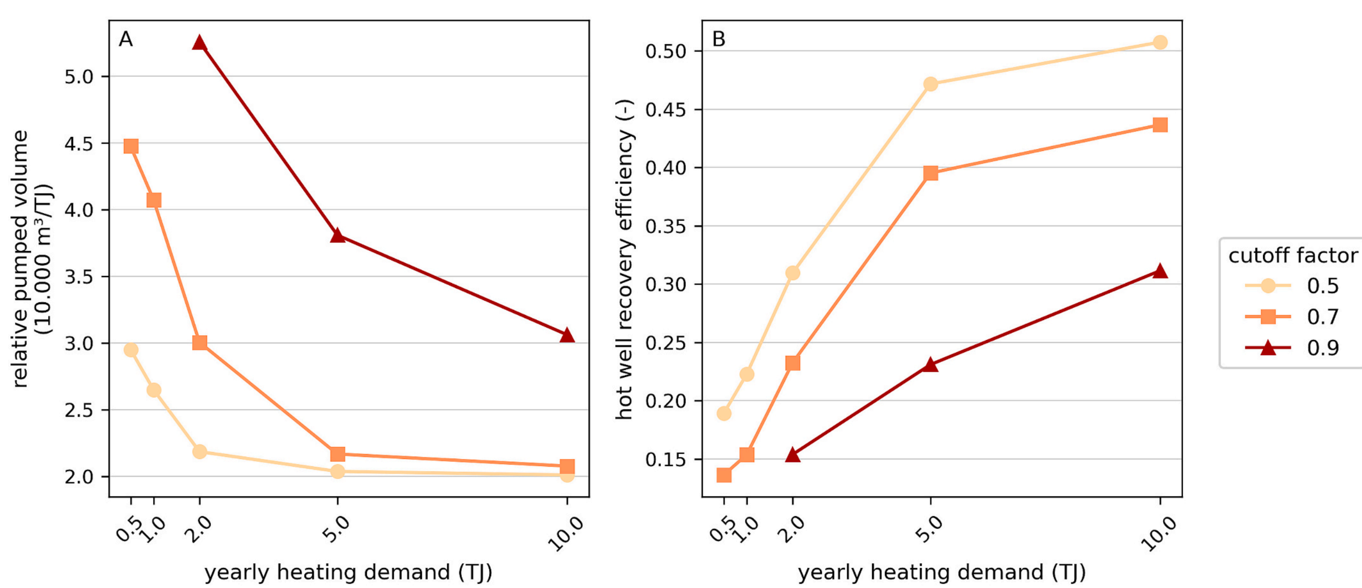

Fig. 11. A: Relative pumped volume for different cutoff factors and heating demands. B: Hot well recovery efficiency for different cutoff factors and heating demands. Results in both figures are for balanced scenarios with a return factor of 0.7 and an injection temperature of 70 °C.

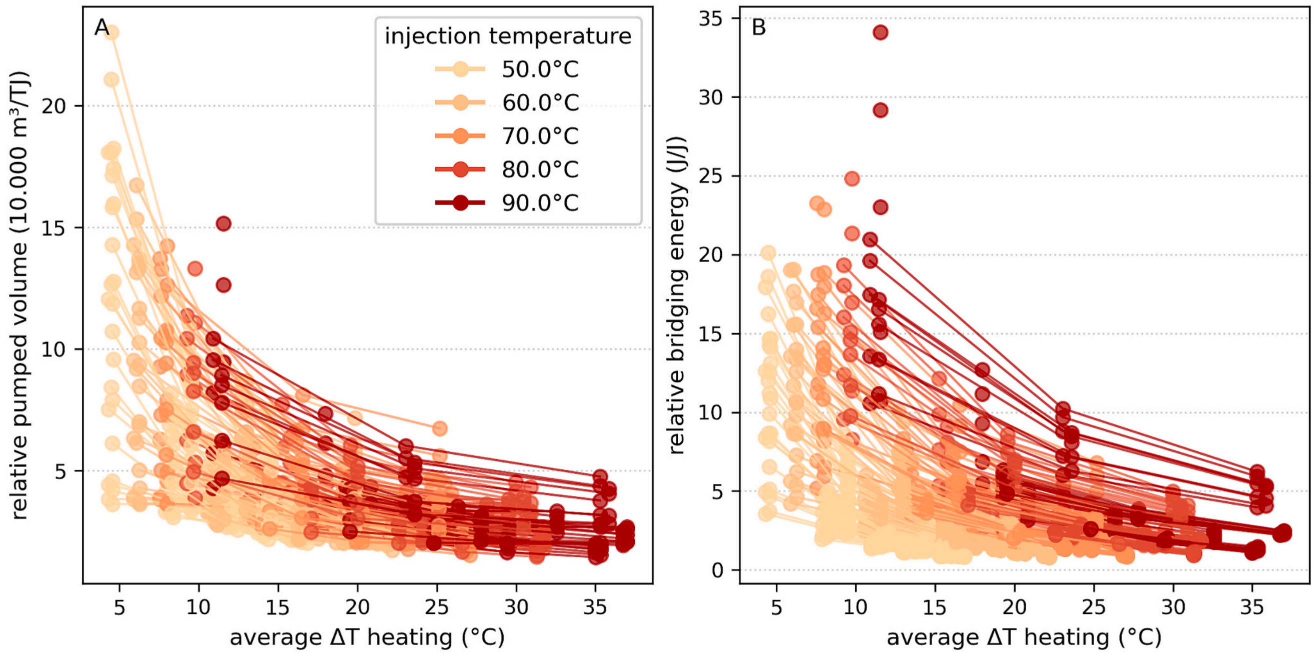

Fig. 12. The effect of the ΔT on the pumped volume and bridging energy. A: Relative pumped volume, which is the pumped volume needed to deliver a certain amount of thermal energy. B: Relative bridging energy, which is the bridging energy required to deliver a certain amount of thermal energy. Scenarios with the same heating and cooling demand, injection temperature and cutoff factor are connected by lines.

doublet more often than smaller systems. However, Triplet systems do not necessarily need to be large.

For a Triplet to have optimal demand conditions, the total electricity use, the pumped volume and the bridging energy need to be kept as low as possible. These results show that this is the case for systems that have a higher heating demand then cooling demand (Fig. 8A), have a high density of energy with a large enough storage volume to reduce losses, which is achieved by a combination of larger heating demands (>5TJ) whilst also having higher storage temperatures (60 °C). It is important to keep the cutoff temperature sufficiently low, which requires a heat exchanger that can handle a large range of input temperatures, whilst simultaneously keeping the return temperature after heating as low as possible. For the buildings that fit that description, a Triplet would be an ideal system. This would most likely be large scale apartment buildings or large office buildings, in regions where heating demand is dominant, and that are already suitable for regular HT-ATES systems.

When cooling is dominant, the cold regeneration is likely to require large amounts of electricity, causing some of the systems to be less favourable. A Triplet could, however, still be a viable option if the bridging energy is kept small by controlling the operating well temperatures, or if the Triplet is combined with other cooling methods as auxiliary systems, e.g. utilizing solar electricity for cooling when it is

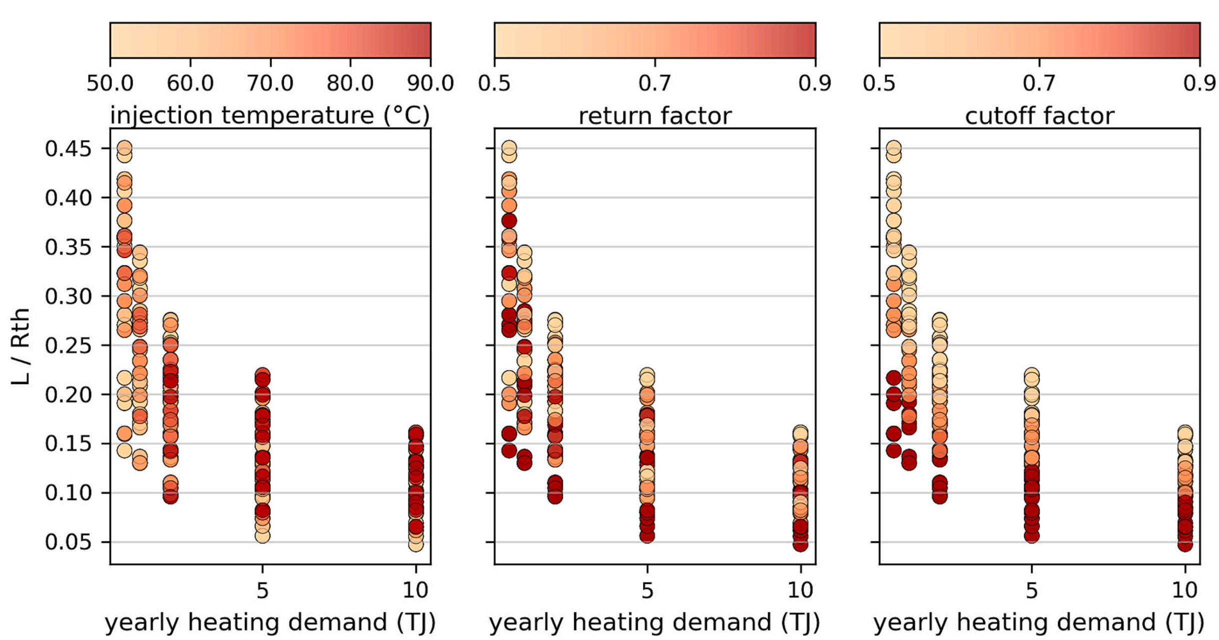

Fig. 13. Screen length / thermal radius (L/Rth) against yearly heating demand for all the scenarios, coloured by the three operational temperature variables in each sub-plot.

available, and using the cold well otherwise.

4.2. Uncertainty of subsurface condition and no interactions on outcomes

Since the storage volumes of the wells were not known before the simulations, a fixed value for the screen length (L) was used for all scenarios. This made it easier to compare scenarios, since they all have the same subsurface layout. However, as the shape of the storage volume differs across the scenarios applied in this study, and thus the losses [11]. Beernink et al. stated that the lower the L/ R_{th} ratio (where R_{th} is the thermal radius), dispersion and conduction are the more dominant processes causing energy losses, whereas for higher L/R_{th} buoyancy plays a larger role. Fig. 13 shows that the low demand systems were more susceptible to density driven flow. High cutoff factors (Fig. 13 C), i. e. a small amount of usable energy, combined with a high return temperature (Fig. 13B), i.e. a small ΔT, would lower the L/R_{th} and make the buoyancy losses less dominant. However, these measures would simultaneously increase the bridging energy for the system (Fig. 9 and Fig. 12). Thus, to make smaller systems work, a smaller L/R_{th} is required.

Other variables that can be different in the subsurface, such as the thermal conductivity, groundwater flow and aquifer heterogeneity, will mostly increase or decrease the sensitivity to losses. If the sub-surface has a composition where HT-ATES would be feasible [11], a Triplet should be feasible as well. On the other hand, concerns relating to HT-ATES such as heat pollution of groundwater will also be a concern for the Triplet. Well design and well spacing will need to be studied to identify if the Triplet configuration can lessen these effects.

4.3. Building heat transfer system

The rule-based control with only two modes of operation used in this study causes an overestimation of subsurface losses as well. The strictly seasonal switching between charging and discharging the wells increases the timespan where the hot well has no inflow of warm water. The on-site energy generation of a Triplet enables use and the charging of the wells to be any time when there is generation, also outside the main heating and cooling seasons. Allowing such operations, would reduce the losses in the wells, as storage times reduce and the thermal extent of the warm/cold plume reduce since part of the thermal energy is stored at shorter cycle length.

The direct use of energy from the generation facilities is expected to be useful mainly for heating, since cooling is often not required on cold days, and dry coolers do not function if it is too warm outside. In buildings with high insulation, a glazed façade, where the radiative heating of the sun heats up the building on a very cold day is an exception, as well as server rooms that need constant cooling.

Even if the operation of the system would include many modes, the results would still have sensitivities to ATES losses, bridging energy and temperature settings. The system operation could be used to mitigate these sensitivities, but to analyse this a true co-simulation model would be required, where an energy management system and the sub-surface model are linked together, which is outside of the scope for this study.

4.4. Practical implementation/considerations

The results show that not all energy requirements are equal in costs. Cold requires more electricity to generate then heat does in our example. However, electricity use is likely not the only limiting factor in the design of a heating and cooling system. The availability of space for dry coolers and solar collectors, as well as financial means and maintenance, is to be considered in the further development of the Triplet. Dry coolers and solar collectors are considered the best options for on-site thermal energy harvesting, but other sources of heat/cold can be used, since the Triplet simply facilitates the disconnect between energy generation and usage. Using a heat pump and solar panels (PV) to generate heat or use it at times when the electricity prices are low would, for instance, also be an option.

For large systems, especially for buildings with large plots sizes, bridging energy could also be decreased by adding additional buffer wells of different temperatures, creating a separate HT-ATES system for heating and a LT-system for cooling. The plot sizes required for the ATES Triplet systems will be dependent on the well temperatures, demand and interactions in the subsurface. As the hot well temperature is elevated substantially above standard ATES well temperatures, the energy density is higher, and the pumped volumes are likely to be smaller. Therefore, the required plot sizes are not expected to be much larger than for regular ATES systems. Fig. 10A indicates for the balanced 10TJ scenario (20TJ heating and cooling demand in total), a pumping volume of 200,000–220,000 would be required, which is in the same magnitude as for a large LT-ATES system, and typical of large systems currently installed. An initial study on the aspect of well spacing (and therefore the needed plot size) is found in [23]. These practical considerations change depending on the limiting factors for the required building. Nonetheless, these results have shown that in many cases a disconnect between on-site thermal energy generation and usage with the use of a multiple well ATES system can considerably reduce electricity use and with those GHG emissions.

4.5. Flexible electricity use

The disconnect between generation and usage also means a disconnect in timing of electricity use. This could mean that triplet systems that will have similar total electricity use when compared to doublet systems, are a lower burden for the electricity grid and benefit more from low energy prices. Still, this disconnect is to be evaluated in more detail for different systems, since the harvesting of cold might still occur at times when the availability of green electrical generation is minimal. Since the results have shown that dry cooler electricity is a major component in the dependency on grid electricity for the Triplet, design and future studies should include storage losses for cooling as well, despite the lower temperature difference in the subsurface.

5. Conclusion

The ATES Triplet concept, i.e. an ATES with a hot well, a cold well and a buffer well, is shown to be often a feasible and efficient system, with potentially significantly lower external electricity use than an ATES doublet. The energy use of the Triplet can be as low as 2% of the provided energy and 9% of the used energy of the comparable LT-ATES system due to the removal of the heat pump from the system. However, in poorly designed and operated systems this can be up to 23% of the provided energy and 67% more energy than a comparable LT-ATES system. To make an efficient system which significantly outperforms an ATES doublet, it is imperative to design a system where heat losses in the subsurface are low since losses increase the regeneration requirements, and therefore also the electricity required to run the system. Larger systems are less susceptible to subsurface temperature degradation, so the Triplet should be applied in cases where the heating demand and injection temperature result in a large enough storage volume. To have an optimal system a Triplet should accommodate a larger heating demand compared to cooling demand, have a large heating demand (>5TJ) whilst having an injection temperature for the hot well that is not too low (> 60 °C). The cutoff temperature for heating should be at least 10 °C lower than injection temperature, and the return temperature should be as close to room temperature as possible.

The system has limited applicability for buildings with a low heating demand (< 1 TJ) in combination with a high injection temperature (> 80 °C). A large cooling demand disproportionately affects the electricity requirements for the Triplet, since in this case the regeneration of the cold well is done using dry coolers, which require electricity to provide cold. The Triplet will require a redesign of the HVAC system, since there will be no fixed supply temperature. The HVAC system will directly determine the requirements for the energy generation facilities, grid capacity, supply temperature, and the bridging energy. A building will also require enough space for heating and cooling generation systems, whether they are solar collectors and dry coolers on-site or external energy systems.

With the sensitivities shown in this work, concepts for an ATES Triplet can be further developed. Future work includes more detailed investigation of interaction effects between wells. The interaction between building systems and wells under future climate and more extreme weather will be explored with a co-simulation study, using hourly heating and cooling demand data based on weather data and possibly experimental case studies. Gains in performance that are seen in co-simulation studies for standard ATES doublets are likely to be even higher for ATES Triplets, given the performance sensitivity to building parameters.

CRediT authorship contribution statement

Matthijs S. van Esch: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Martin Bloemendal:** Writing – review & editing, Validation, Supervision, Software, Project administration, Funding acquisition, Conceptualization. **Niels Hartog:** Writing – review & editing, Validation, Supervision, Conceptualization. **Philip J. Vardon:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used GitHub Copilot, with the Chat-GPT4.0 model in order to speed up the programming and generation of data analyses code. All the code has been reviewed by the authors and edited as needed. The authors take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: M.S. van Esch reports financial support was provided by Dutch Research Council. M.S. van Esch reports equipment, drugs, or supplies was provided by SURF Coöperative. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

I have provided a link to the data in the references of the journal

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