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Novel ATES triplet system for autarkic space heating and cooling

M. Bloemendal[1,2,*], M.S. van Esch[1], P.J. Vardon[1], J.J. Pape[2], N. Hartog[2]
[1]Delft university of Technology
[2]KWR Water Research Institute

*j.m.bloemendal@tudelft.nl

Abstract. Governments and companies have set high targets in avoiding CO_2 emissions and reducing energy. Aquifer Thermal Energy Storage (ATES) systems can contribute by overcoming the temporal mismatch between the availability of sustainable heat (during summer) and the demand for heat (during winter). Therefore, ATES is an increasingly popular technique; currently over 3000 low temperature ATES systems are operational in the Netherlands. Low-temperature ATES systems use heat pumps to allow the stored heat to be supplied at the required temperature for heating (usually around 40-50°C) and for cooling in summer. Although on average a conventional low-temperature ATES system produces 3-4 times lower CO_2 emissions when compared to gas heating, the heat pumps still require substantial amounts of external electricity, causing over 60% of the remaining primary energy use. In the ATES triplet system, the temperatures in the hot and cold wells of an ATES system are increased and decreased respectively to match the required delivery temperatures and a third well is added at an intermediate temperature. With this strategy, other sources of sustainable heat and cooling capacity can supply the subsurface close to the temperatures required in the hot and the cold well. However, the return temperatures from the building systems do not conform with either of the hot or cold wells and an additional well is used to store water at the return temperature. Additional components are then required to supply the hot and cold wells (from the third well) by increasing the temperature in summer (e.g. solar collectors) and decreasing it in winter (e.g. dry coolers). In this study the feasibility of this concept is evaluated. Simulations and an economical evaluation show significant potential for triplet ATES with economic performance better than conventional ATES while the CO_2 emissions are reduced by a factor of ten. As the temperature differences are larger, the volume of groundwater required to be pumped is considerably lowered, causing an additional energy saving. Ongoing research focusses on analysing the energy balance and energy loss in the subsurface, well design requirements, working/operational conditions of each well, as well as the integration of building system components, such as the influence of weather conditions on performance of system components.

1. Introduction

About 25% of the final energy use in The Netherlands is needed for heating and cooling of buildings [1]. Hence, a considerable amount of emission reduction can be achieved should this energy use be decarbonized. Agreements on carbon emission reduction state that by 2050 no natural gas can be used for heating buildings, resulting in attention for decarbonizing heating and cooling supply [2,3,4]. One technology for sustainable heating and cooling is Aquifer Thermal Energy Storage (ATES) [5]. In combination with a heat pump, ATES systems provide sustainable heating and cooling to buildings, a drawback is however, that the heat pump still requires a substantial amount of electricity to run [6], typically about 60% of the total energy use of an ATES system. In a future situation where all buildings need a heat pump instead of a gas fired boiler, this would also require a considerable increase in sustainable electricity production and large adaptions to the electricity grid infrastructure and control. Therefore, in this work, an ATES system without a heat pump is proposed by using three wells (a triplet), solar heat collectors and a dry cooler, see Figure 1 [7]. The solar heat collectors are used to inject water at >40°C in the warm well when there is sufficient incoming solar radiation, the 40°C water can be used for heating directly in the next winter. Similarly, the dry cooler is used to inject water at about 5°C in the cold well when the air temperature is below 4°C. During heating and cooling, the building returns water around 20°C , which is not suitable for either well, therefore a third well is needed to prevent "thermal pollution" of the warm and cold wells. Water from the third well is used as an input to the dry cooler and solar heat collectors at a later time when they can produce water at the right temperature. The solar heat collectors could also be photo-voltaic-thermal (PVT) panels to generate electricity at the same time.

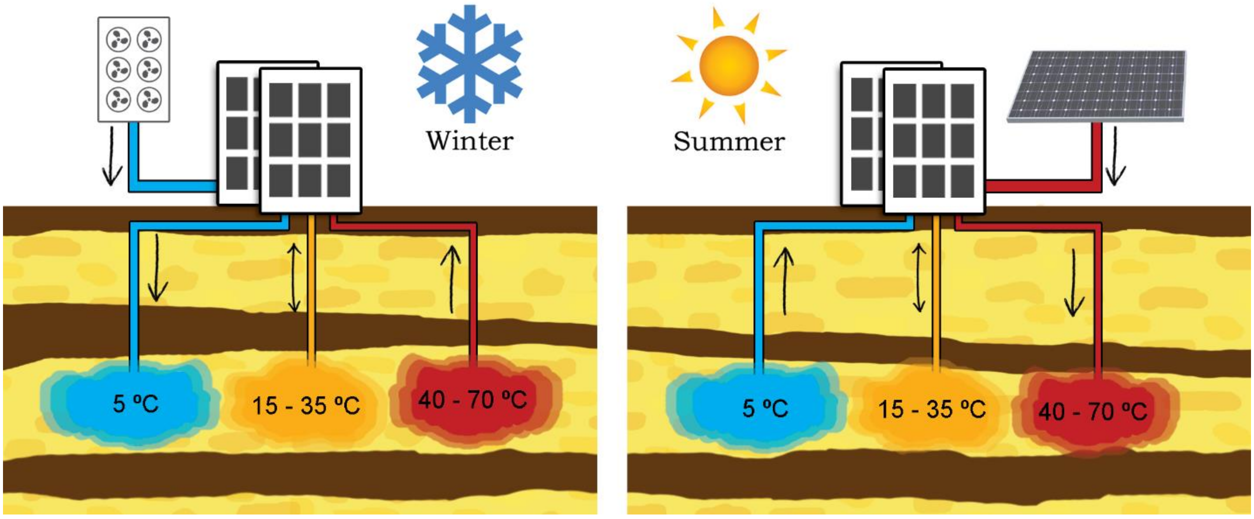

Figure 1. Schematic representation of the basic working principle of ATES triplet system [7]

An ATES triplet system can be utilised for various building types, and as no heat pump is needed, the heating and cooling demand are disconnected, allowing efficient use of aquifer storage resources. Due to the relatively high temperatures used, this concept is suitable for new and retrofitted buildings. In this paper the results of a preliminary feasibility study of the triplet concept are presented.

2. Benefits and downsides of regular/low temperature ATES systems

When operating a conventional (Low Temperature, LT) ATES, cooling is the most efficient: direct or free cooling from the cold well can be delivered. The coefficient of performance (COP, i.e. delivered cooling over used electricity) of free cooling with ATES varies between 20-40, depending on the exact temperature levels. This is a considerable better performance than the COP of ~3 cooling machines regularly achieve. However, during cooling the temperature increase of the groundwater is limited, theoretically it can never be higher than about 18°C, as the objective temperature in buildings is usually around 20°C. But 18°C groundwater cannot be used for direct heating of the building, hence LT-ATES systems require a heat pump to increase the temperature level to 40-45°C, and at the same time provide low temperatures at the evaporator to achieve required cooling capacity for summer. These processes of heating and cooling are already more efficient than conventional gas fired boilers and cooling machines, and result in about a 50% reduction in emission. Nonetheless, ATES systems still require considerable amounts of power to run the heat pump in winter. About 60% of the primary energy use of an ATES system is attributed to the heat pump [8].

3. Heating and cooling operation with the ATES-triplet system

Winter
In heating mode, passive heating is used from the triplet hot well. Because the target temperature of building space heating is usually around 20°C, the return flow of the water circulating in the building cannot be lower than 20°C, and will usually be >25°C. Groundwater with this temperature cannot be used for passive cooling. Hence, prior to injection into the cold well, the temperature should be further reduced to <10°c to allow for passive cooling in summer. If outside air temperature is low enough, the return flow from the building can be diverted to a dry cooler to further reduce its temperature and obtain the required temperature for injection into the cold well. However, there will be times that heating is needed, but outside air temperature is not low enough to reduce groundwater temperature to the desired passive cooling temperature level. In such conditions, a third buffer well is needed to prevent thermal pollution of the cold well. During cold periods, groundwater from the buffer well can yet be pumped and diverted to the dry cooler and stored in the cold well, to ensure sufficient cooling capacity in the cold well for next summer.

Summer
In summer the mode of operation is more or less similar, only now groundwater is extracted from the cold well and injected in the warm or buffer well. Also in summer, the target temperature of buildings is usually around 20°C, hence return flow from the building is usually <15°C, which is not high enough for heating in winter. When there is sufficient incoming solar radiation, the return water from the building is directly diverted to solar collectors, to increase the temperature level to the desired temperature for passive heating and subsequently injected into the hot well. When it is not possible to obtain high enough temperature for the hot well, the return water from the building after passive cooling is again stored in the third buffer well of the triplet system to prevent thermal pollution of the hot well. Also in summer, groundwater from the buffer well can be extracted and increased in temperature via the solar collectors to ensure sufficient heating capacity availability in the hot well for the next winter.

Flexibility
Under partial load heating or cooling conditions groundwater can be extracted simultaneously from the buffer well. This allows for storing extra heat in the hot well in cooling mode, or extra cooling capacity in the cold well in heating mode, if dry cooler/solar collector conditions allow. Also a partial flow can be sent to the buffer well, if dry cooler/solar collector capacity can only meet required temperature for a part of the return flow from the building. The occurrence of these conditions depend on climatic conditions and capacity of dry coolers/solar collectors. To allow for the above mentioned flexibility, various hydraulic connections between wells and components are needed. Control valves control the contribution of various components to actual mode of operation, which depends on current heating/cooling demand, weather conditions and desire/need for storing extra heating/cooling capacity.

By using solar collectors and dry coolers instead of a heat pump the thermal energy storage in the wells is disconnected from the heating/cooling demand of previous season, as is the case in normal ATES systems. In the ATES triplet system, it is only needed to ensure storage of sufficient heating/cooling capacity (expected to be) required for the next season. Any differences in heating and cooling demand settle in the buffer well. Hence, depending on climatic conditions and building characteristics and use, a heat surplus or shortage will arise in the buffer well.

4. Feasibility and benefits of ATES triplet

4.1. Design considerations for autarkic heating and cooling

The heat stored in, or extracted from ATES wells is directly linked to building demand for heating and cooling; when cooling, heat is stored for next season and while heating, cooling capacity is stored. In a normal ATES system, when using a heat pump while heating, the warm well temperature level is not that important, because the heat pump ensures the required temperature level provided to the building. However, when heating directly from a hot well (free or passive heating) in the triplet system, the quality (temperature level) of the heat coming from the well is of great importance. In both normal and triplet ATES systems, the cold well temperature is important for passive cooling. In a normal ATES system, the cold well temperature is ensured by the heat pump evaporator exit temperature in heating mode. In the triplet system, another source of cooling capacity is needed. Hence, instead of a heat pump, several other facilities are needed to sustainably and with low external energy use supply heating and cooling to the building: a third well to prevent thermal pollution, sufficient dry cooler capacity (or other sink of heat), sufficient solar collector capacity (or other source of heat), all of which increase the capital costs.

Two elements are of key importance for all ATES systems. Firstly, the yearly storage capacity of both the total heating and cooling demand (J) which determine the total storage volume and extent of the hot/cold zones around the wells. Secondly, the required capacity for the warmest/coldest day of the year (J/s), which determines the required flow rate and hence the required number of wells for a given geohydrological condition. Of course the required building feed-in and return temperatures and ensuing hot and cold well temperatures have great impact on both elements as well. Hence, ensuring as high as possible hot well temperature, and as low as possible cold well temperature is of great importance. However, at larger temperature differences with ambient groundwater temperature, losses also increase. Especially in the hot well this may affect recovery efficiency considerably. Since losses occur at the boundaries of the stored volume, the larger the storage volume is, the smaller the relative losses are [5]. Recent insights in storing heat at higher temperatures at large scale indicate recovery efficiencies of about 60-90% depending on local conditions, storage temperature and volume [9,10].

4.2. Approach

For a realistic but fictitious renovated office building of 50 000 m^2 it is identified what would be the Total Cost of Ownership (TCO) and total emissions when heating and cooling would be delivered by 1) a conventional boiler and cooling machine, 2) a regular ATES and 3) an ATES triplet. The energy demand of the building is derived from specific annual heating and cooling demand numbers [11], but varied across the simulation period of 5 years proportionally to the relative temperature difference of the outside air temperature in De Bilt (2011-2015) [12]. For each of the 3 systems, the required heat flow and primary energy flows are calculated and tracked at temporal resolution of 1 week. The required size of the components (needed for the cost calculation) are derived from the required peak heating and cooling loads. Next to the investment costs and primary energy use, also yearly operational and maintenance costs of 5% of CAPEX are included for each system. The key parameters used for the analysis are provided in Table 1 [13].

Table 1. Key parameters used in the feasibility study [13].

	description	value	unit	description	value	unit
Heating demand	annual energy	57	kWh/m²	max. rate	57	W/m²
Cooling demand	annual energy	35	kWh/m²	max. rate	45	W/m²
CO_2 emission	gas	1.8	kg CO_2/m^3	electricity	0.46	kg CO_2/kWh
Costs	heat pump	200	€/kW	dry cooler	80	€/kW
Costs	boiler	60	€/kW	solar collectors	0.2	€/kWh
Costs	electricity	0.2	€/KWh	gas	0.65	€/m3
Temperature heating	supply	40	°C	return	20	°C
Temperature cooling	supply	5	°C	return	20	°C

Following the approach of Pape [13], a groundwater simulation model, a dry cooler, solar collector and building model are connected following the hydraulic connections described above. The model is used to co-simulate the building heating/cooling demand and, harvesting heating and cooling capacity from dry coolers and solar collectors and ATES triplet well performance, for the indicated period.

4.3. Results

Figure 2 shows that it is needed to structurally extract more groundwater from the buffer well in summer in order to provide sufficient heat in the winter, because the heating demand is larger than the cooling of the building. As a result, the dynamics of the heat stored in the buffer well strongly follows the inverse dynamics of the cold well. When the cold well is utilised for cooling, also (extra) heat needs to be stored in the hot well. To be able to deal with (in practice unknown) seasonal variations in heating and cooling demand, the solar collectors and dry coolers store up to 20% more in the hot and cold well respectively. The capacity of the solar collectors and dry coolers is chosen such that the thermal energy stored in the hot and cold wells is never smaller than 0 during the 5 year simulation period. Because the average outside air temperature increases over the simulation period, an imbalance is created in the hot well. More heat is stored than is recovered, nevertheless in the 5th year the required 20% over capacity is reached. To provide the required heating and cooling capacity, a total of 2 000 m^2 of solar collectors is needed and 1 MW dry cooler capacity.

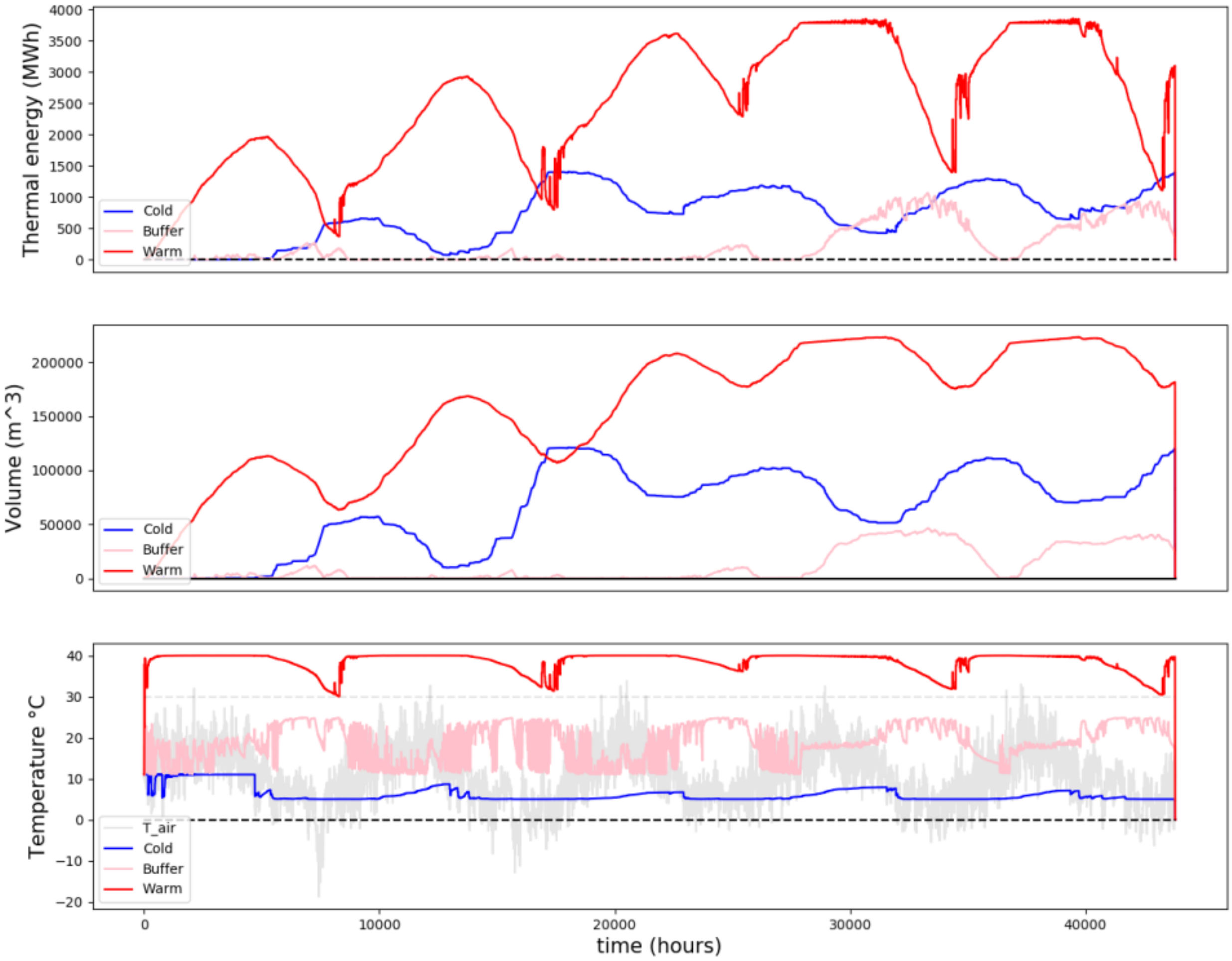

Figure 2. Results of the ATES triplet simulation of a 50 000m^2 office. Top: thermal energy in wells, Middle: groundwater volume stored in wells, Bottom: well extraction and outside air temperature [13].

During winter the buffer well is frequently used. During the day, the outside air temperature is often not low enough to provide cold enough temperature to the cold well. However, during cold nights dry coolers can efficiently store cooling capacity in the cold well from the buffer well. Hence, in winter the buffer well is charged during the day and discharged during the night. In summer this is less so, when there is cooling demand, there usually is also high incoming radiation. Hence, return circulation water from the building can directly be diverted to the solar collectors, without temporarily storage in the buffer well.

Next to the triplet co-simulation model, similar co-simulation models are built and utilized for conventional system (boiler and cooling machine) and regular ATES system (groundwater model and heat pump). The results of the simulations of these 3 models are aggregated for costs, energy use and emissions. Figure 3 shows that ATES triplet and regular ATES systems have comparable business cases, as the 20 year TCO's are almost the same. However, the triplet system has much lower emissions by a factor of around 5.

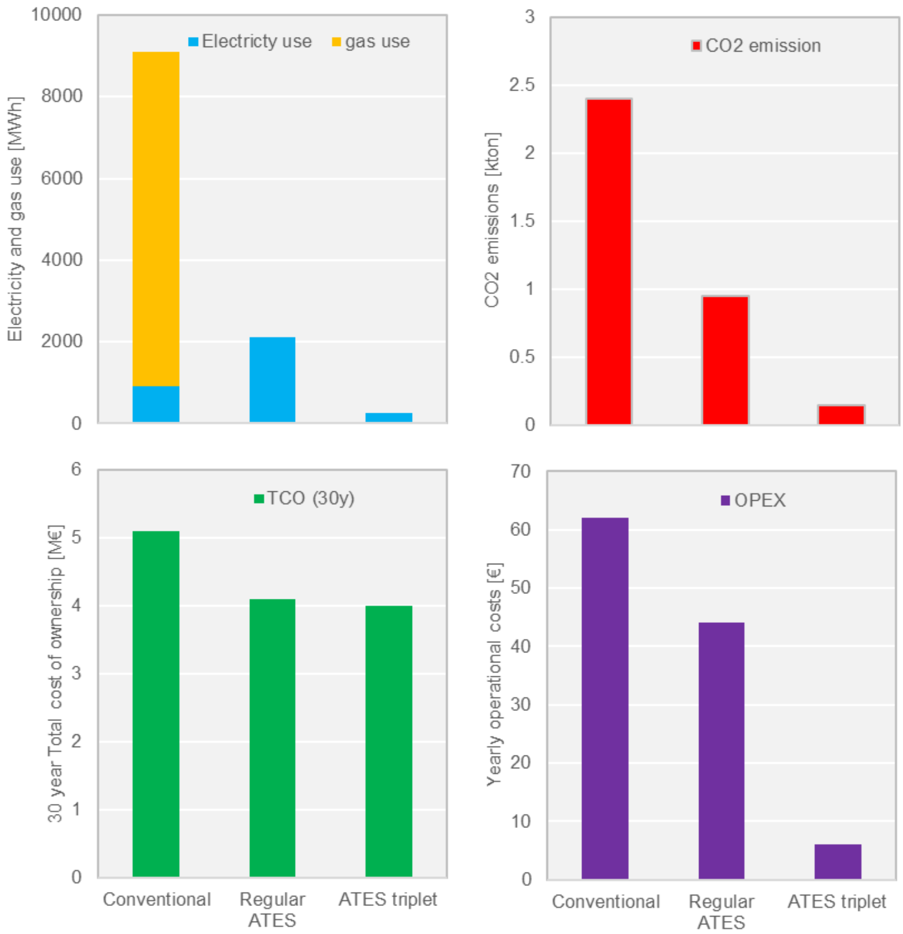

Figure 3. Aggregated simulation results for primary energy use, emissions, TCO and yearly operational expenses (OPEX) [13].

5. Discussion and conclusions

Discussion

Instead of solar collectors and dry coolers, also alternative sources and sinks of heat can be used, e.g. aquathermal for cooling, waste heat from industry for heat. In that case, the building cannot be considered to be autarkic because thermal energy is imported from external sources. However, if the thermal sources are readily available, they may additionally reduce costs and emissions. In the ATES triplet concept, dry coolers and solar collectors are chosen, because those can be placed on top or in the close vicinity of the building it is supplying. Furthermore, PVT solar panels could be used to also produce the little amount of electricity needed on the building location. This is not (yet) included in the analysis to allow for clear comparison of changes in primary energy use and associated emissions. Using PVT panels, could change the triplet TCO, but reduce emissions.

The higher the temperature of the water in the hot well, the larger the potential of the ATES triplet for existing, poorly insulated buildings. By increasing storage temperatures to >60°C, older buildings where it is not possible to insulate sufficiently to allow for 45°C supply temperature can potentially be sustainably heated and cooled with an ATES triplet. This may prevent or delay the need for radical renovations in existing buildings, where the largest challenge lies in decarbonisation of the built environment. In the Netherlands, the existing buildings stock consists of >8 million buildings.

Due to the popularity of LT-ATES systems, there is currently in some locations subsurface congestion, so that there is not sufficient space for additional projects. While the ATES triplet concept adds an additional well, it also increases the heat density by elevating the temperature in the hot well and decreasing it in the shallow well. The result is a likely improvement in the spatial efficiency of systems.

In the Netherlands as well as in many other countries, it is not currently straightforward to get a permit for heat storage at temperatures >25°C. [14, 15]. Given the required energy transition, Dutch local governments have currently a positive attitude towards such systems, however, permits are not easily issued and require extensive monitoring of impact on water quality changes.

Conclusions

This paper provides a first analysis of the possible feasibility and operation of an autarkic ATES triplet system. The concept is promising as it seems feasible to do passive heating and cooling and the required wells, solar collectors and dry collectors, stay within the ranges of what is commonly applied in current practice. The ATES triplet is shown to have comparable costs as a regular ATES, but much lower primary energy use and emissions.

Next steps

Successful implementation and operation of the ATES triplet well concept requires key developments on the following aspects, which are currently being investigated in the ATES triplet NWO project:

- Building hydraulics and predictive process control: Ensuring reliable energy delivery within a wide range of operating conditions and time scales (everything ranging from minutes for building climate control to multiple seasons for well performance). Developments of new types of control algorithms and (simplified) models for such controllers are required.
- Heat storage in porous media and control: Optimising recovery efficiency, understanding and predicting chemical aspects of the groundwater, i.e. preventing reservoir or well clogging.
- Technology development of triplet projects: rules/guidelines for well spacing (efficient use of the subsurface), well design and well operation and rules for optimal interaction with the building system and the interplay between, and control of, three wells and building energy management system.
- Assessment of alternative sources of heating and cooling capacity, including also renewable power production.

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