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Fjell 2020 High Temperature Borehole Energy Storage - System Control for Various Operation Modes

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ABSTRACT

Energy storage is defined as one of the most promising solutions for cutting peak demands. It enables for smaller installed power to cover the same demand and allows larger flexibility. Among the solutions of storages, borehole thermal energy storage (BTES) is gaining interest. Most existing BTES systems use ground source heat pump (GSHP) with storage temperatures in the range of 3 – 30°C. However, recent solutions have encouraged the development towards high-temperature BTES (HT-BTES) with storage temperature in the range 60 - 100 °C, which enables optimizing the seasonal use of excess heat or other sources.

In Norway, the research project RockStore, focus its interest towards this topic. GeoTermos - Fjell2020 in Drammen, Norway is one of the pilot installations in this project. GeoTermos - Fjell2020 will supply the heating demand to the new primary school at Fjell and is designed to use higher-temperature borehole thermal energy storage (50 – 60 °C). The system attempts to cover the space heating needs of this school via direct heat extraction from the BTES (without using heat pump). The BTES stores heat from solar thermal panels and excess heat from a CO_2 heat pump. The 100 boreholes are ca. 50 meters deep each and are placed concentrically in rings relatively close to each other with a maximum 4 m between them. Eleven boreholes are monitored by means of Distributed Temperature Sensing (DTS).

The space heating (low temperature floor heating) and the ventilation heating demands are covered with heat extracted from the innermost wells. By using heat from the core ring, the temperature should be high enough so that the heating can be used directly without the need of after heating via the heat pump or the electric boiler. However, for some periods with larger demands during the winter these two are installed in case of need for back up. The outermost rings have a lower temperature and can be used indirectly via heat pump. And the ring furthest out will be used as a “blocking” ring to control and minimize the heat loss at the border of the storage. The domestic hot water demand to the school is covered via a devoted CO_2 heat pump.

The goal of this publication is to analyze the control strategies and to discuss the functioning of the solution in Norway and how the control of the systems can be optimized in order to be the most energy-efficient.

1. INTRODUCTION

The increased awareness on the need for decarbonizing the energy systems has drawn attention to the needs to have more available storages.

Heating and cooling of buildings represents 40 % of the energy use in Norway (Sartori et al. 2009) and a big share of this energy is covered via electricity from the grid. This share can to a large extent be replaced by renewable energies. Then the electricity otherwise used for heating would be available, e.g. for charging electric cars or being sold abroad.

New buildings are highly efficient and have low energy demands. However, their peak power demand remains high, or has even increased. In addition, electric cars are becoming a general commodity and even though the building envelopes are better, energy demands are not decreasing. In the evening people come from work or gyms and charge the cars incurring in large electrical peak demands. To cover these peaks, the systems would need to be over dimensioned unless flexibility is introduced. Heat loads are probably the easiest ones to shift and for this storage should be introduced. Single buildings per today lack possibilities for thermal energy storage (Brange et al. 2017) that would enable the integration of more renewable energy sources (Winterscheid & H. 2017). The flexibility and potential for using large BTES for coping with periods of peak demand is only to a limited extent proved. Using BTES to store the available heat produced when accessible and using it during peak demand, contributes to a more continuous operation of the equipment within the area close to maximum efficiency (Lanahan et al. 2017). Renewable energy sources can also be better exploited with better storage systems. If solar collectors were not having accumulation tanks for short term heat storage, they would need to be under dimensioned for winter as otherwise they would be too large for the summer. Short term storage would avoid this problem. Additionally, for seasonal variations BTES are expected to be a good solution. Many renewables, especially solar, fluctuate largely and do not always match with demand profiles. BTES systems can contribute to increased energy efficiency and are seen as an answer to cope with the seasonal mismatch. However, borehole thermal energy storage in moderate to medium depth is a relatively unproven concept (Bär et al. 2017). Challenges related to increased heat losses compared to other storage solutions, drilling costs, slow response to fast changes in production and demand (Lanahan et al. 2017) and the effect of geology and groundwater, prove that more knowledge is needed.

Emmaboda in Sweden is a good example on how BTES can cope with storing waste heat seasonally (Andersson et al. 2009). The extraction of heat from the storage was started this winter and more results will be available (Nilsson & Rohdin 2019).

Drake Landing in Canada has been in operation for more than ten years now and the results for the first five and ten years evaluation are available (Mesquita et al. 2018; Sibbitt et al. 2012) and their conclusion is “ The system has successfully demonstrated the reliable operation of a high solar fraction solar district heating system with seasonal thermal storage in a very cold climate.” However this has lower storage performance (36-41%) due to groundwater flow (Lanahan et al. 2017). The project GeoTermos - Fjell 2020 is highly inspired on this project with the difference that in this case, a CO_2 heat pump is introduced in the system, the possible groundwater flow and borehole temperatures will be also followed up with distributed thermal sensing, and the storage media consists of crystalline bedrock.

2. FJELL 2020 DESCRIPTION

The Fjell 2020-project is a large and important city development in the city of Drammen, Norway. Within the Fjell2020 neighborhood, the old school is going to be replaced by a new school building of 6500 m^2. Additionally, an activity house of 1500 m^2 and a multisport hall of 2000 m^2 will be built.

The new school targets the Norwegian Passive house level (Standard Norge 2013). Owing to this, windows have a U-value of 0.8 W/m^2 K and additional 5 cm insulation is installed in the building envelope. The energy distribution of these buildings is built so that there is a good interaction with the GeoTermos. Thus, water borne is used as heat carrier, and the way of laying the piping is tight enough so that 25 °C supply can maintain comfort temperatures according to simulations in Ida Ice (Drammen_Eiendom KF 2018). Ventilation, heating and lighting are demand controlled.

Fjell2020 is one of the pilot installations on the Norwegian research project Rockstore. With the “GeoTermos project”, Drammen Eiendom (the real state division of Drammen municipality) intends to demonstrate the feasibility to use borehole thermal energy storage provided with solar energy in the school Fjell2020 in Drammen, Norway. One of the major goals of this project is to demonstrate the possibilities for efficient energy use and integration of different energy carriers besides the normal Norwegian practice of using electrical energy by deployment of thermal energy storage with several heat sources as Figure 1 shows. This project is highly inspired on Drake Landing (*Drake Landing Solar Community* 2019). Additionally two CO_2 heat pump are installed. One will supply the demands of domestic hot water needs and CO_2 heat pumps are specially efficient for this purpose as long as the return of the CO_2 is cooled down sufficiently (Justo-Alonso & Stene 2013; Stene et al. 2018). A second CO_2 heat pump is installed to charging of the GeoTermos. CO_2 is chosen as refrigerant due to the low global warming potential as an environmentally friendly refrigerant. The use of CO_2 requires that the system is built so that the return temperature of the CO_2 is as low as possible so that the heat pump performs more efficiently. Finally, the system has installed many sensors (temperature, energy, flows…) so that the monitoring can be done in a reliable way and most of the pumps are frequency controlled.

A borehole thermal energy storage is an underground structure where heat is stored (*Drake Landing Solar Community* 2019). In this project, the heat from the sun is harvested mainly during summer time to be used in winter time to reduce peak power demands. The GeoTermos BTES is basically a heat store with 100 boreholes at 50 m deep and with a maximum distance of 4 meter. The wells are placed so close to improve the storage efficiency and reduce the heat losses. Additionally, a layer of insulation is placed on the top of the BTES to reduce heat losses.

The electrical supply to the CO_2 heat pumps (2 units: one of 20 kW to supply domestic hot water and one of 250 kW for charging of the GeoTermos) happens directly with PV electricity (1000 m^2) installed in the roof and the required complementary electricity from the grid. In addition, for thermal purposes, solar collectors (125 m^2) are mounted in the roof and façade. Moreover, the system has two accumulation tanks at 7500 liters each to assist in the short-term accumulation and to balance temperatures as it is further explained afterwards and 400 kW electrical boiler to be only used as back up. Figure 1illustrates the interaction between systems.

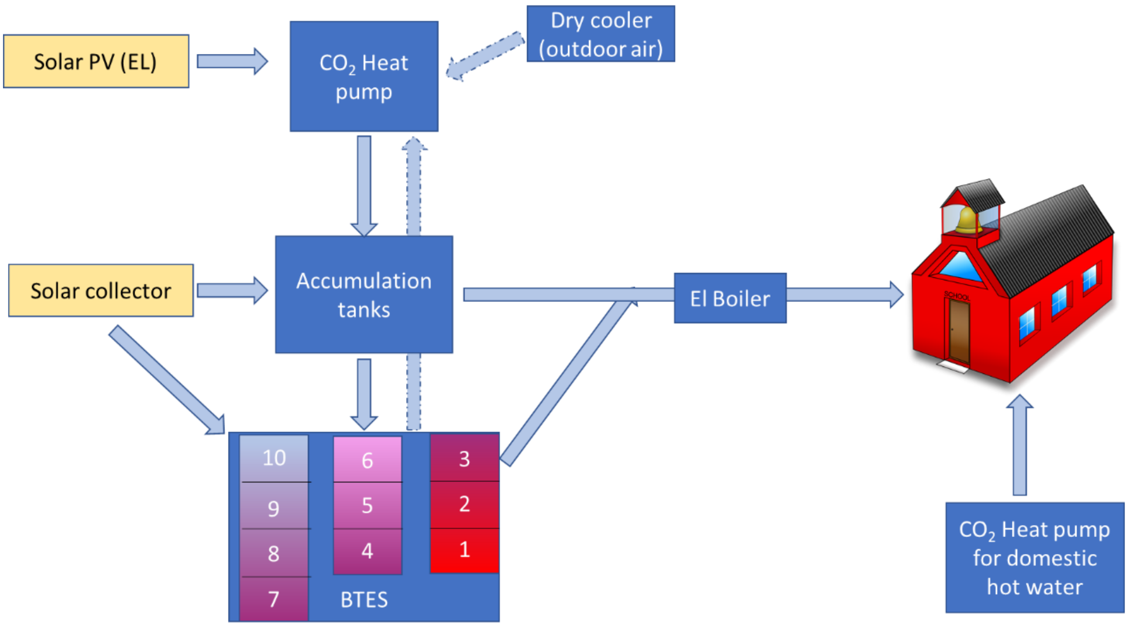

Figure 1: Principle of the interactions between energy systems in GeoTermos. The PV provides electricity to run the heat pumps, the solar collectors and the CO_2 heat pump provide heat to the BTES that covers the building’s base loads. A devoted CO_2 heat pump covers the domestic hot water demands.

All in all, the available loading capacity is 7-800 000 kWh/year and it is expected to extract ca. 350 000 kWh/year in the form of heat at different temperatures. It is expected that the GeoTermos delivers about 80 kW (in base load) and up to 300 kW during much shorter periods to cover peak demands.

2.1 The BTES- GeoTermos

The Borehole Thermal Energy Storage (BTES) is a thermal energy storage in the ground consisting on 100 boreholes at 50 m placed relatively close to each other, with maximum 4 m between them. It is a cylindrical BTES where the boreholes in the center are expected to have a temperature oscillating between 50 and 60 degrees centigrade and lower temperatures in the subsequent rings.

The system is expected to be able to deliver heat at the right temperature to supply space heating and ventilation mainly without the use of the heat pump. In fact, the control is done in a way that the right temperature to each demand is extracted based on the thermal gradient of the concentrically placed rings. Radially outwards the temperature decreases till the outermost ring that is called the blocking ring which has the lowest temperature and can be directly used for cooling. These last 36 boreholes have the goal of limiting heat losses. They have the lowest temperature difference with the ground and in addition, by being used for cooling, the temperature of this ring increases and thus these boreholes are thermally charged "for free". The blocking ring has a lower temperature than in the BTES and thus the difference with the undisturbed ground is smaller. Even when the area of contact is the largest, the heat losses are reduced due to the limited temperature difference. With this configuration, and the insulation in the top, the GeoTermos has the largest possible ratio storage volume / heat transfer area that minimizes heat losses.

The boreholes are connected by groups of four always from the center outwards as

Figure 2 shows. The idea behind investing in so much piping is the possibility to control where to charge heat so that it is possible to store heat at highest temperatures in the center. The heat extraction can be done in the boreholes closest to the temperature requested.

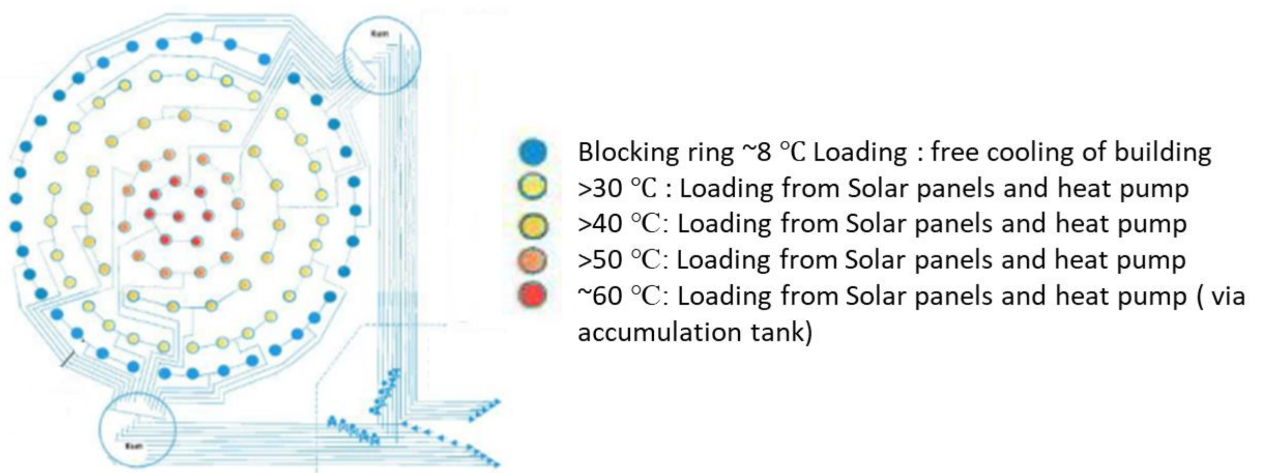

Figure 2: Layout of BTES's connections and and expected ground temperatures

The heat is harvested either directly from the solar panels when the temperature is high enough, and otherwise, the PV electricity is used to run the CO_2 heat pump that harvest heat from the outdoor air via the dry cooler, the cooling activities or the wells. When the GeoTermos is loaded with heat from the CO_2 heat pump, the outermost ring can be used to fully cool the return water so that the efficiency of the CO_2 heat pump is maximized.

The boreholes in the BTES are done with standard collector technology, i.e. U -pipe and it is an important supposition that the PE-RT material of the boreholes in the center will stand the possible 80 °C that may happen during normal operation of the system. To ensure that the temperature in the collector fluid is not surpassing the 80 °C, the accumulation tanks are used. With them it is possible to regulate the temperature that is supplied from the solar collector so that it does not melt the U pipes. The use of alternative materials or collector types that tolerate higher temperatures was considered. However, in order to keep cost low, traditional solutions were preferred.

2.2 The DTS in the BTES

In order to have better control of the boreholes, distributed temperature sensing (DTS or fiber) is used in eleven of the boreholes. The use of DTS is thought to control and monitor every change in the borehole, and not only the circulating collector fluid that is measured in and out of the evaporator in the heat pump as it is normally done. The use of DTS gives a very high resolution in time and throughout the well (Acuña 2013), as the temperature can be measured as often as every 5 seconds and by every 25 centimeters. This knowledge in combination with the geological details of the site will unveil details like water-carrying fractures and possibly groundwater movement.

The temperature measurements with fiber can verify other conditions such as zones with other temperatures either caused by changes in the thermal conductivity (for instance in the transition between loads and rock) and / or others radioactive rocks such as alum shale (Ramstad et al. 2014).

In this project we are expecting to use the measurements to study the heat exchange in the wells at various operating conditions such as charging and heat output with high heat output per meter borehole. When studying the whole borehole in detail, energy and heat extraction can be studied simultaneously, and development of new knowledge is expected. By using data analysis such as machine learning, improved control strategies will probably be developed and tested soon.

Figure 3 shows the eleven boreholes where the fiber has been installed marked with the red line. A whole diameter of the storage is followed up so that the measurement hopefully will be representative for the whole GeoTermos storage volume. The fiber is already installed, and data collecting will start from the heat charging phase in August 2019.

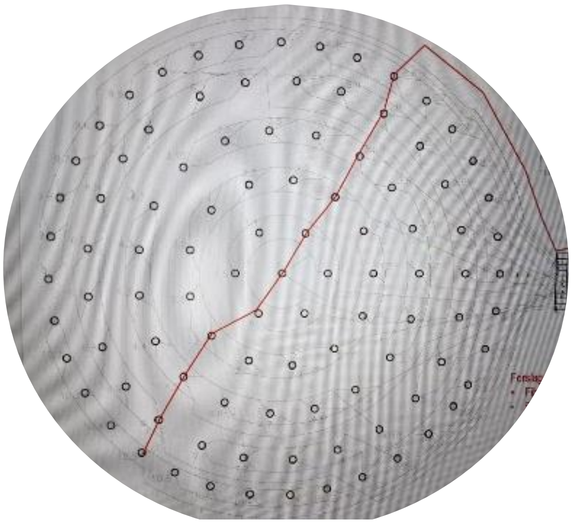

Figure 3: The eleven boreholes monitored with distributed temperature sensing.

2.2 Geology and possible challenges for the BTES

The bedrock geology at the GeoTermos site is mapped by the Geological Survey of Norway as granite. The area has clay on the top with varying depths from a few meters to a maximum of about 13 meters. The clay covering the BTES has to some extent an insulating function. Earlier geotechnical investigations observed a mix of clay and silt, and moraine covering the rock surface.

Prior to the construction of the BTES, three thermal response tests were performed to evaluate the suitability for a BTES. A further description of a thermal response test can be seen in (Gehlin 1998). The temperature profiles in the 60-meter-deep test boreholes were also measured before and after the tests. The main purpose of the tests was to see if there was any sign of groundwater movement in the fracture system at the site. A regional groundwater flow can flush away the stored heat and can be present if there is a hydraulic gradient in the fracture system.

The results of the effective thermal conductivity from the thermal response tests are within the expected range based on the mineralogical composition of the bedrock (Ramstad et al. 2014). A significantly higher value for the effective thermal conductivity measured by the thermal response test would have implied that the tests were influenced by groundwater flow, either locally within the borehole, or regionally. The temperature measurements in borehole 1 and 2 after the response tests indicate permeable fractures at 15- and 12-meters depth, respectively, but these have minor influence on the value of the effective thermal conductivity. The remaining temperature profiles have no sign of groundwater movement. The overall conclusion from the thermal response tests, is that the site is well suited for BTES. This assertion may be complemented by the analysis from the DTS results.

3. THE CONTROL STRATEGIES

A building monitoring system will control the whole energy system in such a way that the heating and cooling demands are always covered and that the heat charging of the BTES is optimal. The hierarchy of the energy system and its controls is to 1- cover demands and 2 charge the BTES.

Whenever outdoor air temperature is below 14 °C for more than 30 minutes, heating is supplied until the outdoor temperature is 17 °C for more than 30 minutes and there are no other heat demands. Additionally, a schedule will avoid unnecessary start/stops during summer or winter seasons. All the supply systems (BTES, accumulation tank, heat pump and electric boiler) are controlled so that the supply setpoint temperature (outdoors temperature compensated): main setpoint is obtained. If the supply setpoint is not obtained, either dampers are regulated, or the main supply temperature is modified by extracting heat from another ring or by adding heating systems (as detained in the control strategies in Table 1).

The hierarchy of the four supply systems (BTES, CO_2 heat pumps, accumulator tank and El-Boiler) can be altered. It may be modified and further developed owing to the initial testing phase being undergone for the time being (based on measurement results). Initially, the GeoTermos BTES has the priority as it harvests “free” energy from the sun, and it is designed to be the base load during heating season. The control strategies have been developed in collaboration between Thermo Consult AS and Drammen Eiendom and for the time being 11 strategies have been developed.

Table 1: Control strategies (ThermoConsult 2019).

Mode	Heat source	Steering strategy
1	Heat extraction from GeoTermos	The return flow is circulated by the first ring that is warm enough to cover heat demands, from the coldest to the warmest (inwards) The supply water is directed from the first ring where it is warm enough
2	Heat extracted from the accumulation tank	The accumulation tank warms up a share of the return water after this has circulated through the BTES. When there is no further accumulated heat, the accumulation tank is short cut and an alternative heat source may be used if needed.
3	Heat extracted from the heat pump	The heat pump warms up a share of the return water and a pump and a valve steers the effect to achieve the main supply setpoint. When the heat pump is run together with the GeoTermos, the heat pump's set point is risen to cover the difference between the GeoTermos supply and the main supply setpoint. When the heat pump is run alone, the heat pump's setpoint is the same as the main setpoint.
4	Heat extracted from the electric boiler (El boiler)	The electric boiler warms up the main stream from the other three heat sources. The whole flow of the return water pass through the boiler. Supply temperature is controlled according to main set point. This system is only foreseen as backup.
5	Charging GeoTermos with solar panels	The heat from the collector is harvested as soon as the return temperature from the collector is 5K over the desired set point. When the short-term accumulator can be loaded this has the priority, and it is loaded. Otherwise, if the accumulation tank is full of unavailable, the GeoTermos is loaded directly, but this is not the best solution to avoid having more than 80 °C supply temperature from the solar collector. The outlet temperature from the solar collector is controlled via the circulation pumps, on in this last case, the flow has to be increased if temperatures are close to 80 °C.
6	Charging GeoTermos with CO_2 heat pump	The supply temperature from the heat pump to the GeoTermos is controlled according to the desired supply temperature. The heat pump pressure is controlled according to the available power from the solar collectors, or at a fixed speed of the GeoTermos' circulation pump. The heat source is chosen between the dry cooler or borehole depending on which gives the largest temperature on the evaporator's cold side and thus the largest heat pump efficiency.
7	Charging the accumulation tanks with solar collectors	The heat from the collector is harvested as soon as the return temperature from the collector is 5K over the desired set point. When the short-term accumulator can be loaded this has the loading priority.
8	Charging the accumulation tanks with heat pump	The use of the heat pump is especially interesting to use the cheap nighttime electricity to cover the morning's power peak. The heat pump is controlled according to the desired temperature in the accumulator. Heat pump pressure is controlled according to the available power or the return temperature from the accumulator. The heat source is either the dry cooler or borehole depending on which gives the largest temperature on the evaporator's cold side. If there is a need for defrost of the dry cooler, the heat is extracted from the wells while the defrost happens by using the blocking ring.
9	Charging blocking ring with free cooling	When there is a need for cooling in the building, free cooling is achieved by dissipating the building's heat into the blocking ring, as long as the blocking ring temperatures are low enough.
10	Charging blocking ring with dry cooler	If the heat pump does not need the dry cooler's heat or the free cooling is being used, the dry cooler heat is run to charge the blocking ring
11	Mechanical cooling and charging of the GeoTermos with the heat pump	When free cooling is not enough, the heat pump is started and controlled according to the cooling requirements. The heat from the heat pump is dissipated by charging the GeoTermos.

4. DISCUSSION

4.1 Improving peak power demand via BTES

The electricity consumption in Norway varies greatly with the outdoor temperature, as direct electricity is the most used energy carrier to provide heating in buildings. The electricity grid should be dimensioned so that it can cover all the demands power even during the coldest days. Statistically this happens seldom. Thus, it means a large investment for electrical grid companies to build networks that can cover the full capacity for such a short utilization. This means that the grid would be very expensive and seldom paid back. In addition, with the introduction of electrical cars the situation is even worse, as the short-term power peaks that are linked to cold periods are even increased.

As power coverage creates high costs for the grid companies, consumers are "penalized" financially through power tariffs that are often substantial. These penalizations are even larger for medium large users. Both in the interests of the electricity infrastructure and own economy, investments in measures that reduce such short-term power needs are of interest and will be even more in the short future. The whole Europe is talking more and more about the need for flexibility and this can be only achieved via wide spreading the use of storage.

In GeoTermos - Fjell2020, the combination of an energy storage, a CO_2 heat pump and short-term accumulators it is expected to be enough to meet the heat demand of the school during the winter. The energy storage will preferably be used to deliver base load at a uniform heat supply of approx. 80 kW. In early winter, the temperature level in the storage will be sufficiently high so that the storage can supply heat to ventilation heat and underfloor heating without the use of a heat pump. During the winter, when the storage temperature drops, only the underfloor heating demands can be covered directly from the energy storage. The maximum power requirement arises only a few hours per year and can be met by the short-term capacity of the accumulator tanks. Thus, by using thermal storage the peaks of extraction from the electrical grid can be reduced.

It remains to study how the use of the GeoTermos will be affected by short term periods of large power outlets as this come at the expense of energy production. This is because power outages will lead to a faster reduction in the temperature in the storage and thus reduce the ability to supply the buildings with heat at the desired level. High power output from GeoTermos will thus often lead to an increased need to extract electricity from the grid for production of heat to re-store the temperature in the storage, either directly or via the heat pump with air as a heat source. In the scenarios with peak power increased tariffs, this may make sense for both the consumer and the grid owner as it contributes to reduced marginal loss and investment needs in grid reinforcement. At the same time, it will contribute to increased security of supply and the flexibility in the grid. The GeoTermos can deliver significant power but requires "repayment" in the form of energy. The best strategies for charging and extraction of heat will be studied with the data obtained from the measurements to come.

5. CONCLUSION

The GeoTermos has the following objectives and the whole system has been designed to prove them possible:

- Demonstrate that solar heat production combined with seasonal storage of solar heat in ground works well technically, even in Norway.
- That this type of heat production can occur within acceptable economic limits.
- That it is possible to extract various temperature levels adapted to ventilation air and underfloor heating, without "assistance" from a heat pump.
- The blocking ring can further be used for free cooling
- Demonstrate that GeoTermos design can offer cost-effective thermal power reserve, including as a short-term storage

All in all, despite the use of several system to cover heating demands, the designed system is relatively simple and is feasible to keep the overview as all the control strategies are laid for the optimal operation. The system looks at the whole picture, enabling heat extraction and loading to be done efficiently owing to the utilization of the different temperature levels. Finally, the system gives the possibilities for a good follow up and the upcoming measurement data will lay the ground for a wider spread of the use of BTES in cold climates.

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