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Multivalent Seasonal Geothermal Cold Storage and Supply for Cooling Needs with Permanent Load Demand – MissElly

Roman IGNACY, Tilman CREMER, Gregor BUSSMANN, and Rolf BRACKE

International Geothermal Centre, Lennershofstraße 140, 44801 Bochum, Germany

roman.ignacy@hs-bochum.de

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ABSTRACT

In Germany, as well as worldwide, the production of process cooling and air conditioning is almost exclusively electrical. While for space heating and lighting the power consumption is decreasing, in Germany it rises up by 0,7 TWh per year in the area of process cooling, thus by about 2 % per year through the construction of new plants and the global warming. However, the energy transition from fossil to renewable energies can only succeed by reducing the absolute power consumption and greenhouse gas emissions. In the field of refrigeration, there are a variety of applications which require continuous cooling due to their requirements. These include, among others, cooling chambers and cold storage, data centers and test stands. All of these buildings have no need for heating, but only a need for refrigeration. If no customer for the dissipated heat from those buildings is found on site, then the entire heat energy must be released to the environment. Mostly the cold is generated by compression refrigeration machines and free coolers. Without a seasonal cold storage, the cold has to be produced at the moment of the needs and the cold production depends directly to the ambient temperature. This leads to the fact that particularly at unfavorable times particularly much cold must be produced and this happens then with a relatively poor efficiency. But in contrast to electrical energy, cold can be stored well and thus generate at times of favorable conditions. Temporary storage over days and also the seasonal storage is possible, whereby the winter of temperate latitudes turns into a location advantage. In this case, the cold does not have to be generated electrically, but is taken directly from the environment during the cold periods of the year. As part of the MissElly project, a demonstration plant will be developed, designed and implemented to provide around 1,2 MW of cold at a temperature of 18 °C. At this location the demonstrator will be implemented to provide cold for a testing stand for power electronics and accumulator cells. Since for this size and at this temperature the sole use of conventional cold storage, such as ice storage, is out of the question. The part of the cold that is needed during the summer period and which is not possible to be generated with the free coolers will be stored in the underground in a borehole heat exchanger field BHE and in an ice storage during the winter period for seasonal cold storage. Also short term periods, like cold weather conditions or cool nights will then be used for regeneration of the cold storage. A large part of the required cold can thus be obtained by conventional free coolers and does not have to be generated by means of a compression refrigeration machine. In the project the innovative entire system consisting of a test stand, compression refrigeration machine, free coolers, geothermal probe field and ice storage will be tested for its performance and the interaction of the different components. Simulations of the overall system form the basis for the demonstration plant. The simulation results will then be validating at the demonstration plant. First basic calculations show, that such a system would significantly reduce the average power consumption and greenhouse gas emissions at around 50 % in comparison to a standard system without cold storage.

1. COLD DEMAND IN GERMANY

Stationary refrigeration in Germany causes almost 14 % of total electricity consumption, with a growing trend. Of these, one third is for private refrigerators and freezers. Two thirds are caused by commercial refrigeration. Here, the greatest need is for air conditioning refrigeration, industrial refrigeration systems and supermarket refrigeration systems. The following Figure 1 gives an overview about the share of refrigeration electrical energy demand of various industrial sectors.

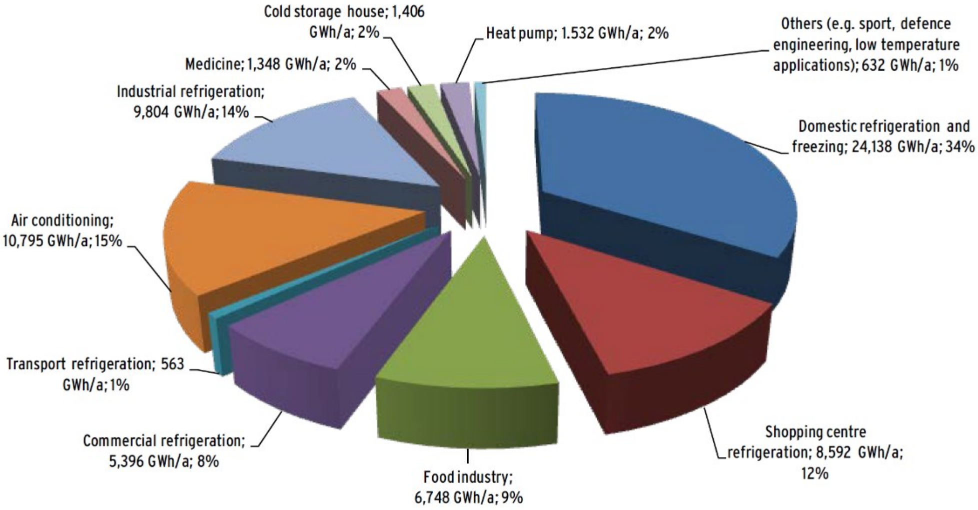

Figure 1: Share of refrigeration electrical energy demand of various industrial sectors (UBA25/2014).

With a share of 95%, cold is provided almost exclusively by means of electrically operated compression cooling machines CCM. Energy-saving alternatives are heat-driven adsorption or adsorption chillers, which however require a heat source at least at about 80 °C and accordingly can only be used to a limited extent. As a result, the demand for refrigeration will almost exclusively be covered by CCMs for the foreseeable future, which is problematic from a climate point of view. CCMs have both direct climate effects due to refrigerant emissions and indirect ones due to the high energy requirement. The following Table 1 gives an overview about the climate-relevant data of stationary refrigeration technology in Germany.

Table 1: Climate-relevant data of stationary refrigeration technology in Germany (UBA25/2014)

Characteristic number	Value	Comment
Electrical energy demand of stationary refrigeration technology in Germany	70,695 GWh/a	Data base 2008, (Guntram Preuβ 2011),
Share of final electrical energy demand in Germany	13.5 %	Data base 2008, (Guntram Preuβ 2011; Umweltbundesamt 2012a)
Green house gas emissions of stationary refrigeration technology in Germany	45.8 Mt	Data base 2008 for electrical energy (Umweltbundesamt 2012a), Data base 2007 for direct refrigerant emissions (Becken & Plehn 2010)
Share of final green house gas emissions in Germany	4.7 %	Data base 2008
indirect emissions (electrical energy demand)	40.2 Mt (81.6 %)	
Direct emissions (green house effect due to refrigerant)	5.6 Mt (18.4 %)	
Electrical energy demand of industrial cooling and building air conditioning	30,244 GWh/a (42.8%)	Share value based on final electrical energy demand of refrigeration technology in Germany

Potential for reducing the high demand for electrical energy is found especially in applications in which it is cooled at relatively high temperatures, such as in the air-conditioning refrigeration. So CCMs be used for air conditioning in buildings in general, although only temperatures of about 20 °C must be achieved. These temperatures prevail most of the year in our latitudes. In Germany for example the average long time air temperature is about 8,81 °C (DWD2019). Since heat, or cold can be stored relatively easily and without high losses, in contrast to electric current, a use of the existing, natural cold reservoirs is obvious. The surrounding temperature of the air is the primary and the subsurface ground temperature the secondary natural cold reservoir of the planned system.

2. SYSTEM COMPONENTS

2.1 Ice Storage

Water has a melting enthalpy of about 334 kJ/kg, which means that during the phase conversion about the same amount of heat is absorbed or released as when the water is heated from 0 °C up to 80 °C. This feature allows the storage of large amounts of heat in a low volume, at low material costs and a constant melting / freezing temperature. Cold storage, whose operation is based on the melting enthalpy of water, are referred to below as ice storage. Ice storage consist primarily of two assemblies: The container and the implemented heat exchanger. Depending on requirements, concrete tanks or insulated, coated or uncoated steel tanks are used. The volumes range from 1 m³ in private households and modular systems to well over 1000 m³ of underground concrete pits in large-scale plants. As a heat exchanger usually helically installed plastic or metal tubes are used. The density of water decreases with solidification, resulting in an increase in volume. In order to keep the pressure on the container wall low, internal coiled tubings are state of the art, which ensure ice formation from the container center towards the tank wall. The expansion thus merely forces liquid water from the tank walls of the container to the surface. The pressure on the container wall almost does not change. Further temperature reduction, after the water in the ice storage is completely solidified, in turn results in a volume reduction and thus represents no further stress on the tank walls. Typically, in order not to hinder the crystallization of the water, the water is not additionally circulated. In the planned ice storage, on the other hand, the still liquid water will be circulated as in an open geothermal system in order to considerably increase the efficiency. In principle, ice storage can be subdivided into two applications, depending on the predominant use for providing heat or cooling. An ice storage unit in combination with a CCM for building air conditioning provides cooling in the summer, but averaged over the year, the store in our latitudes is deprived of more heat for heating purposes than is fed in during the summer. On average, a heat flow in the ice storage is therefore desirable, which is why the conventional concrete container in this case receives no additional thermal insulation. In contrast, additional solar absorbers are regularly used in these systems in order to increase the heat flow into the container. In contrast to building air conditioning, ice storage in data centers is used to support CCMs, and thus throughout to provide cold. The operation of a CCM is more efficient at night, with low outside temperatures than during the day. Consequently, electrical energy can be saved, but also a smaller CCM can be used, as the maximum power that has to be achieved during the day can be reduced by the power of the implemented ice storage. The heat flow from the environment into the ice storage has to be kept as low as possible in this system. A thermal insulation of the ice storage is therefore useful (BWP 2018). An ice storage, comparable to the one that is planned in the project, with a capacity of 180 kW, was built by GALAB Laboratories GmbH 2013 in Hamburg. This ice storage is also operating in combination with a heat pump. With its much larger capacity of 1000 m³, it ensures the feasibility of the planned ice storage (GALAB 2016). The following Figure 2 shows the ice storage capacity and temperature with a volume of about 730 m³ and symbolizes an possible ice storage for the project MissElly.

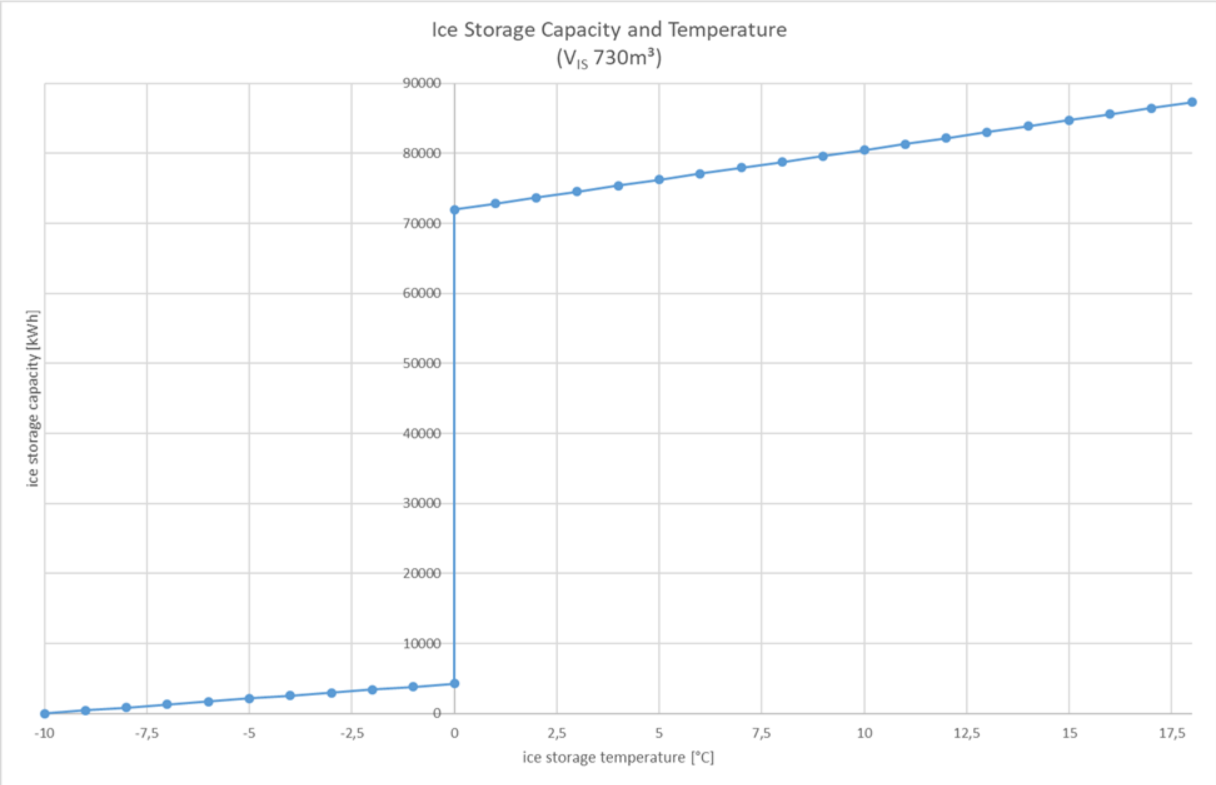

Figure 2: Ice Storage Capacity and Temperature of an possibe MissElly ice storge.

The capacity is near to 90 MWh. Around 78 % of the thermal energy are stored in the phase change of water to ice, around 18 % in water heat capacity and around 5 % in ice heat capacity.

2.2 Borehole Heat Exchanger Field

The seasonal heat storage in the underground has been realized for over 20 years. Pioneers here are Denmark and Sweden. But also in Germany, pilot plants have been set up in the last 15 years using tanks, basins, aquifers and near-surface geothermal probes. The latter were used in Sweden (1983), Neckarsulm (2001), Attenkirchen (2002), Crailsheim (2007) and Denmark (2012) with approx. 50 - 500 geothermal probes and at depths of 30 - 60 m at temperatures of up to 90 ° C used [Nußbicker-Lux, 2010]. However, all these systems are aimed at efficient use of heat in winter, but not at the targeted cooling of the substrate for cold storage. In the project MissElly a borehole heat exchanger field will be implemented. The size will be around 3.300 m borehole length with a cooling power of around 100 kW and will be used to cover a part of the baseload of the cooling system. Simulations will show the optimized spatial arrangement of the around 100 borehole heat exchanger in the subsurface.

2.3 Compression Cooling Machine

In conventional compression chillers (CCMs), a refrigerant goes through a closed loop process. This consists of evaporator, compressor, condenser and expansion valve. It enters the evaporator liquid and evaporates, whereby the enthalpy of vaporization is absorbed. Consequently, heat flows through the system boundary into the CCM at the evaporator, a cooling capacity is available. The gaseous refrigerant subsequently passes through the compressor, is compressed and additionally absorbs the waste heat from the compressor. Due to the increased pressure, condensation in the adjoining condenser is possible at a temperature above the evaporator temperature. The enthalpy of condensation released thereby leaves the system of the CCM. The final step of the cycle is an expansion in which the pressure of the refrigerant is lowered back to the evaporator pressure level. Figure 3 shows the schematic illustration of a CCM. A CCM, as well as a compression heat pump, thus promotes heat from the evaporator to the condenser. If the temperature difference to be overcome increases, a higher pressure difference between evaporator and condenser occurs. In this case the compressor does more work, the proportion of its waste heat increases and the ratio of heat flow to the required electrical power, the coefficient of performance COP, decreases. Consequently, higher COPs can be achieved with low temperature differences that have to be overcome.

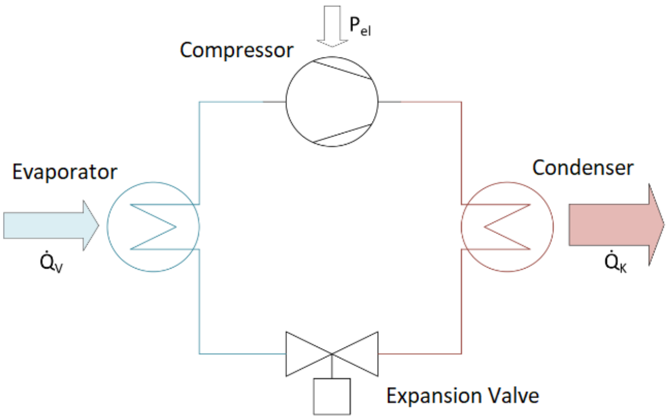

Figure 3: Schematic illustration of a CCM.

Basically, CCMs and compression heat pumps are based on the same principle. They are used everywhere, where heat has to be transferred from a low to a high temperature level. The target for CCMs can be the supply of cold at the evaporator or, in the case of compression heat pumps, the heat supply at the condenser. Large scale used CCMs have cooling capacities of up to several megawatts. The electrical power required for this purpose corresponds to the quotient of cooling capacity and coefficient of performance, and is consequently lower. KKMs are widely used. Areas of application include the air conditioning of buildings and data centers, the food industry or the process refrigeration supply in the chemical industry.

2.4 Free Cooler

In principle, a distinction is made between dry and wet air coolers. While the dry air cooler only achieves the cooling capacity by means of heat dissipation by convection to the outside air, the wet air coolers also uses the evaporation enthalpy of water (approx. 2 257 kJ/kg) for cooling. A combination of the two systems offers hybrid coolers and adiabatic back coolers, which cool wet or dry as needed. The fluid that has to be cooled flows through the cooler mostly over lamellar structures to create the largest possible contact surface with the ambient air for the heat transfer and the evaporation. A fan-driven convection prevents the heat accumulation in the cooler. The used pipes are usually made of good heat conducting materials such as copper. Wet cooling systems have additional cooling water injection, which uses sprinklers to wet the pipes with water. This removes additional heat during evaporation. Adiabatic back coolers spray the water directly into the air, so that the ambient air and not directly the lamellar structure cools down. As a result, a basically dry cooling process is possible, which nevertheless achieves cooling temperatures below the ambient temperature. Both hybrid coolers and adiabatic back coolers can switch to wet cooling mode when a specified set point temperature is exceeded. In principle, the wet bulb temperature is limiting for wet and adiabatic coolers. This depends on the outside temperature and the prevailing humidity. The following Figure 4 shows the air temperature and the first approximate calculation of the wet bulb temperature depending on the air humidity.

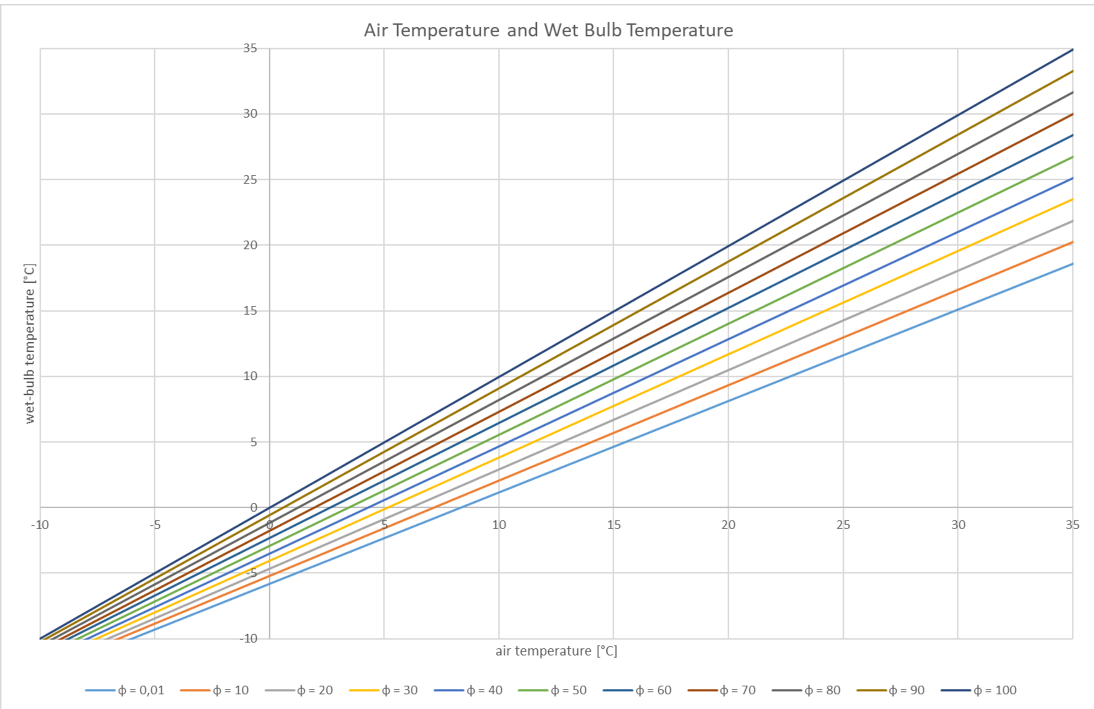

Figure 4: Air Temperature and Wet Bulb Temperature (first approximate calculation).

The following Figure 5 shows the outside temperature, wet bulb temperature and the difference between this both for the location Essen/Germany and represent the potential of the wet cooling for the system in the MissElly project.

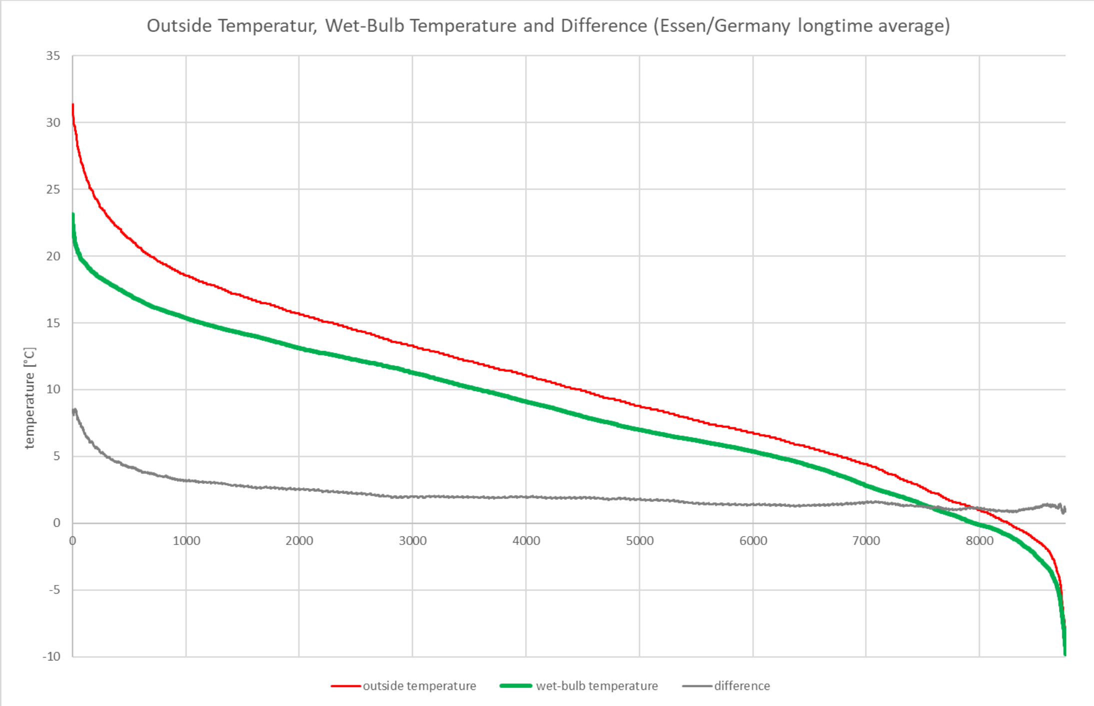

Figure 5: Outside Temperature, Wet Bulb Temperature and Difference for the location Essen/Germany.

The presented cooling systems are offered in a variety of different power levels. The range of customers is correspondingly broad. Basically, the coolers are suitable for all cooling applications, but compete with conventional cooling towers. Although these have lower investment costs, but higher operating costs. Hybrid coolers and adiabatic back coolers typically offer cooling capacities from 100 kW to approx. 4.000 kW. Logically, higher powers can be achieved in using of a cooler network. In addition to the building cooling, refrigerators are particularly popular in industry, for example in the food industry, the mining industry and the chemical industry. Other big customers are data centers.

3 MISSELLY SYSTEM

The company Voltavision GmbH operates development and testing center for power electronics and power energy storage. In cooperation with the Bochum University of applied Sciences / International Geothermal Center, it is planned to develop the classic cooling concept into an innovative cooling concept that is predominantly supplied with renewable energies in order to reduce the CO2 emissions of battery test centers. It is planned to scientifically investigate the innovative cooling concept on a demonstration object. This will supply two cooling lines, a high-voltage test section with about 700 kW and a low-voltage test section with about 400 kW waste heat output. The operation of the battery test stands is designed for continuous testing of the test items. This is accompanied by a permanent need for cooling in about the same dimension of the waste heat output. To meet the requirements for refrigeration demand, the previous system concept provides for the coupling of KKM and free cooling. Since the thermal requirements for the system are at 18 °C in the inlet and 23 °C in the return of the refrigeration supply, there are initially energetic potentials for direct cooling of the battery testing center via the air cooler. With increasing outside temperatures, the cooling capacity of the air cooler decreases until the CCM intervenes. From a certain outside temperature, the entire cooling capacity must be provided by the CCM. The combination of CCM and air cooler is used as a reference system concept, which provides information on potential savings in terms of electricity consumption and carbon dioxide emissions. If the cold supply is provided bivalent by CCM and air coolers, so relatively large cooling capacities and energies have to be provided for the use of a CCM. This is accompanied by the use of considerable amounts of electricity. The use of the two machines always follows the prevailing outside temperature. The planned project will develop an optimal system configuration for the innovative system solution for continuous cooling supply via the integration of cold storage systems that can be used up to seasonally time periods. Short-term storage between day and night or over weeks between low and high pressure weather conditions can be achieved through an additional ice storage. The seasonal storage will also be done via a borehole heat exchanger field. In general, heat can be dissipated more efficiently to the environment at lower outside temperatures. Thus, the operation of CCMs at these times is more powerful and efficient. As a result of the cold storage it is possible to achieve a reduction in the CCM power that has to be installed in addition to lower power consumption and a predominant mode of operation at the optimum operating point.

The primary objective of the MissElly project is to provide cold as sustainably as possible, using an intelligent cold storage system, to reduce the required electricity consumption and increase the share of use of ambient cooling. For this, the best procedure will be selected depending on the season, current weather and time of day. For example, in a cold winter night with the air cooler the ice storage and the probe field will be loaded, in a summer night, however, only the probe field because of the higher ambient temperatures. As the primary natural source of cold the ambient cold will be used from the air of the environmental at the location. This must be done sufficiently above the wet cooler unit designed for this case with a maximum cooling capacity of approximately 2 MW. The short-term storage in the ice storage will be developed to be able to provide cold with a cooling power up to 600 kW. This will be achieved through the innovative usage concept of the ice storage, which uses the liquid water in the ice storage as in a natural aquifer, an open system. For the planned borehole heat exchanger field, the first calculations show that it will be possible to provide cold at a realistic continuous power of about 100 kW at this location. As a result, the maximum cooling capacity of the CCM drops from 1,2 MW to 500 kW. A possible MissElly plant concept is shown in Figure 6 below.

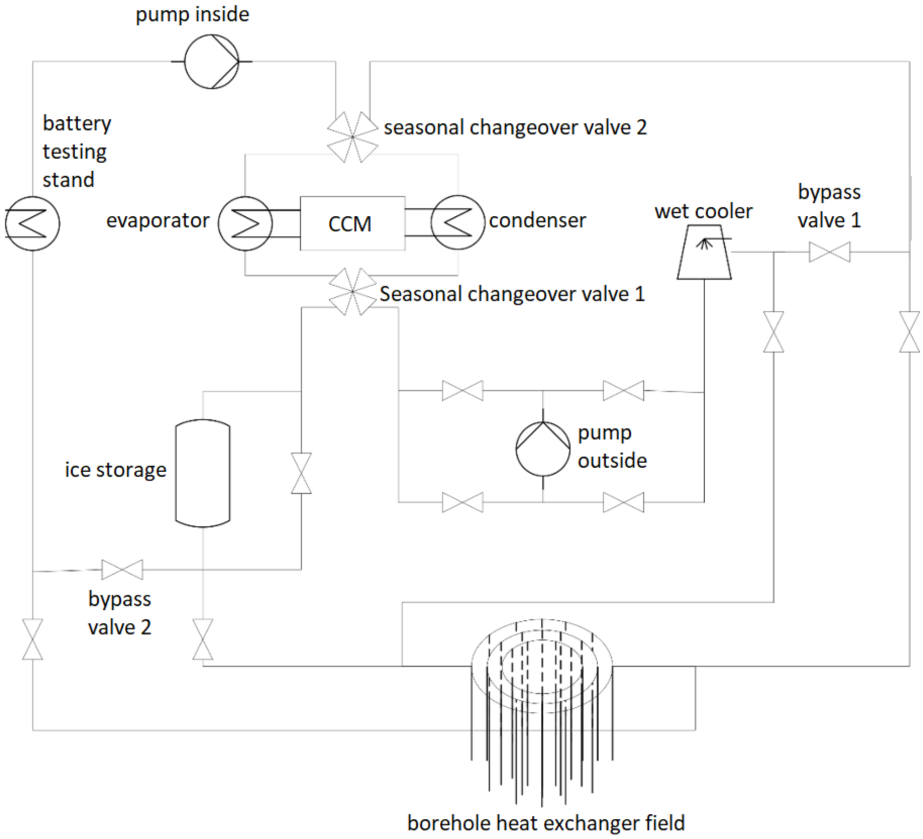

Figure 6: MissElly possible plant concept.

To reduce cold losses from the ice storage to the environment, it will be proven where the ice storage unit will be placed, if in the underground in the center of the probe field or at the surface with an insulation. In the case of an implementation in the underground, cold losses of the ice storage to the surrounding rock are thereby completely compensated by the probe field. A schematic representation with the exemplary temperature profile of the charged memory is shown in Figure 7. Initial calculations using analytical calculation tools show that the geological and thermophysical boundary conditions encountered at the site in a geometrically optimized geothermal borehole heat exchanger filed configuration will allow approximately 3.300 m to provide a continuous cooling power of 100 kW.

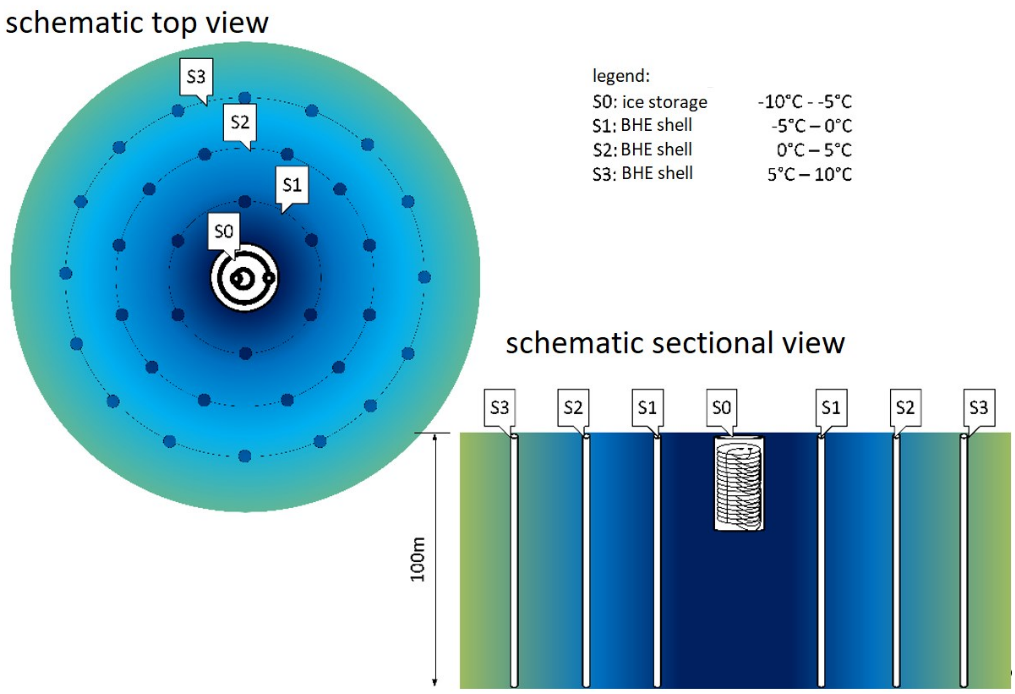

Figure 7: schematic representation with the exemplary temperature profile of the charged memory.

In the case of an ice storage with a volume of 730 m³, a permanent cooling power $Q_{IS,in}$ of 75 kW, a regeneration power $Q_{IS,reg}$ of 600 kW and the weather conditions of Essen/Germany the first ice storage simulation show the performance in the following Figure 8.

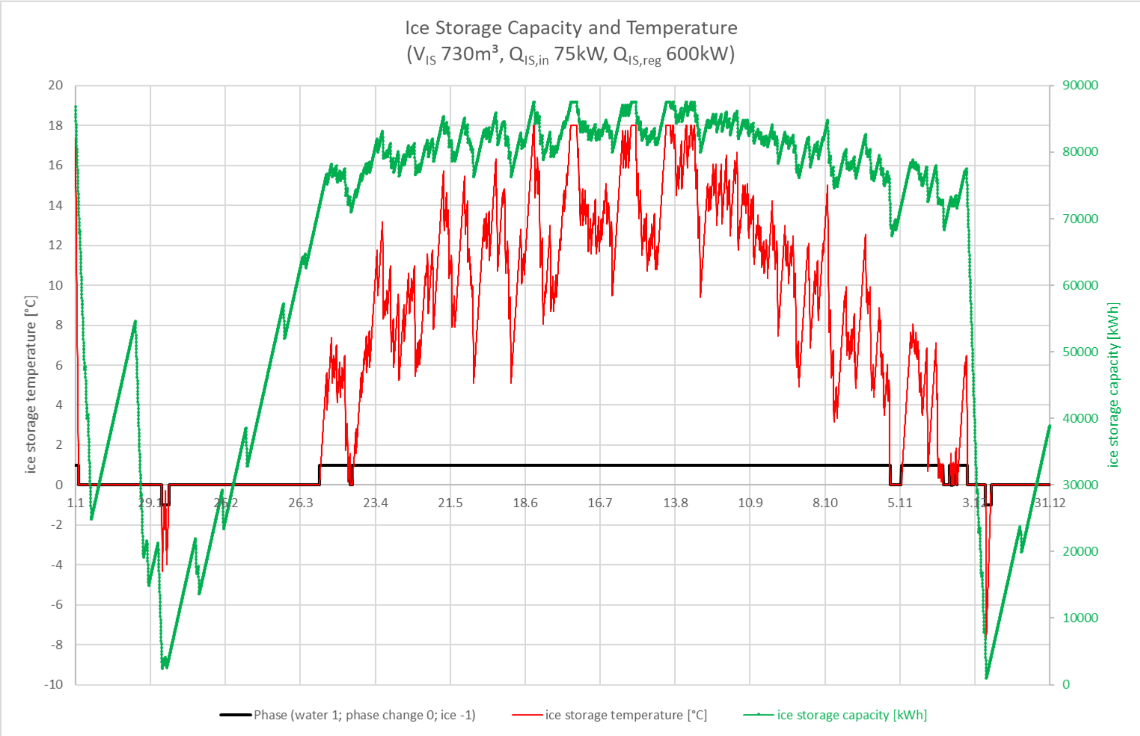

Figure 8: Example of an ice storage performance.

The maximum ice storage temperature is set at 18 °C and the reached minimum is near to -8 °C. At two short periods in the year the whole water in the ice storage is frozen and reaches temperatures less than 0 °C. Around one third of the year the ice storage could operate at 0 °C and provide cold at this temperature. During the rest time of the year the ice storage provide cold above 0 °C by using the heat capacity of the water. When the temperature reaches 18 °C, then the ice storage stands still until colder weather conditions regenerate it again.

4 CONCLUSION

The MissElly project will show, after the finishing of the simulation work packages, the theoretical potential to provide cold for permanent cooling needs almost via renewable environmental cold. In the second stage of the project the demonstration site will be build up and allows a scientific investigation of a real MissElly system under real conditions. The comparison of the theoretical and the real performance allows the calibration of the simulation models and the optimization of the real MissElly system. First energetic calculations of the proposed entire system show that it could be possible to decrease the electrical power consumption compared to the standard system from around 913 MWh/a to around 427 MWh/a. The adopted specific CO2 emissions for electricity with a value of 516 gCO_2/kWh where taken from the German Federal Environmental Agency from the year 2018. With this value it is easy to calculate the CO2 reduction of the MissElly system and it allows to reduce the CO_2 emissions from around 471 t CO_2/a to around 221 t CO_2/a, what results in an efficiency increasing of around 53 % in the supply of cooling needs with a permanent load demand.

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