Analysis and Evaluation of a Solar Thermal and Heat Pump Combination with Ice Storage

Nouman Akram
nouman.akram@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal
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Abstract – Almost half of Europe's energy consumption is for heating and cooling purposes and most of this thermal energy comes from fossil fuels (66%) and while renewable energy sources count for 13% only. Using solar assisted heat pumps with ice storage enables the use of renewable energy for heating and cooling of new and existing buildings while improving energy performance, efficiency, flexibility and the energy transition towards a sustainable low carbon future possible at all levels. These systems have become increasingly popular in Central European countries such as Austria. The objective of this thesis is to technically analyze and evaluate a solar assisted heat pump ice storage system for heating and cooling of a building using field data, and further explore the potential of this technology. This work is carried out at AEE Institute for Sustainable Technologies. The raw data from the plant was processed using python based tool. The ice storage is used for 51% of all the cooling done without any aid from the heat pump, which had a very positive effect on the overall Seasonal Performance Factor (SPF) that was 5.66 in this case. A better heat pump performance has been observed with mean SPF of 4.81 over the analysis period. The work done in this thesis is unique in its character, as not much detailed work is available on analysis of the cooling operation. There is a good prospect of research and development in correct dimensioning of the ice storages to further evaluate and optimize these systems.

1. Introduction

Almost half of Europe's energy produced is consumed for heating and cooling purposes and most of this thermal energy produced comes from fossil fuels (66%) and while renewable energy sources only count for 13% of the total thermal energy produced in EU (Energy 2020). This implies that there is a great potential in this sector not only to improve the energy efficiency but also to integrate renewable sources into the heating and cooling supply system. Although, need for space heating is generally preferred over space cooling in central European countries, the rise in temperatures in light of climate change might lead to much hotter summers in these countries as reported in (Henley 2019) which may increase the need for a space cooling systems in conjunction with the heating systems.

Heat pump technology is known since the mid-20th century as a solution for heating and cooling supply system and its market is on the rise since the start of 21st century (Hadorn 2015). Reversible heat pumps which are able to provide both operations are becoming more common and can be used and adapted effectively to address space heating and cooling needs. There is a wide variety of different combinations for heat pumps that are available in market alongside those which are still in research and development phase. Moreover, solar energy is commonly known as the most abundant form of renewable energy that can be easily harnessed and used directly or indirectly in various forms around the world. Most common use of solar energy is generally using it to heat up water using solar collectors or generating electricity using solar PV panels. Integration of heat pumps with solar thermal energy enables the use of renewable energy for heating and cooling of new and existing buildings while improving energy performance and efficiency. Over the past few years, different combinations of heat pumps and solar thermal collectors have entered the market (Ruschenburg, Herkel, and Henning 2013) and there is a continuing trend from different manufacturers to introduce newer combinations that also include different sources such as boreholes and ice storages that is discussed in this thesis.

Adding another source for heat pump apart from solar collectors adds flexibility to the operation of heat pump and increases its performance. Recently Ground Sourced heat pump (GSHP) have become popular for their higher performances, reduced primary energy consumption and CO_2 emissions (Philippen, Carbonell, et al. 2015) but due to the regulations established for drilling boreholes, SHP-Ice storage systems have been established as an alternative to ground source heat pump (GSHP) systems.

Ice storages are generally known in the HVAC sector for peak shaving of cooling loads at noon or for providing high cooling power for industrial processes (Hasnain 1998). The concept of using ice storage as a source for heat pump in combination with solar collectors is relatively a new field of application. Only a few hundred of such plants are in operation, of which approximately forty are in Switzerland with currently only three suppliers of complete ice storage/heat pump systems on the market having good experience in designing specialized ice storages for heating and cooling applications (Stefan Minder, Roland Wagner, and Weisskopf 2014). In these systems, heat at low temperature is supplied as a heat source for the heat pump when the collector heat is not available either due to weather conditions or some other reasons.

The objective of this thesis is to carry out a data supported technical analysis and evaluation of the combined solar thermal heat pump ice storage system installed in Wilfersdorf near Vienna, Austria for heating and cooling of an office and a warehouse building. The focus of the work is to technically analyze the operation of the system in its entirety and check how individual components behave when a certain mode of operation is in place. Technical analysis will be done based on standard procedures applied to this type of systems, which include characteristic graphs and energy balances. Since, most of the work done on SHP ice storage systems usually discuss heating mode only, this work will determine key characteristics and lay down evaluation methods for analysis of cooling mode using ice storages that can be useful for future plant concepts of this type. Based on this analysis, suggestions for future research work and recommendations on design and operational strategy will be given.

2. Literature review

Several examples of research done on SHP-Ice systems can be found in literature. For instance, (Dott et al. 2016) analyzes five different solar heat pump system combinations, of which solar ice storage heat pump system is of particular interest in the context of this thesis as the system uses an uncovered thermal absorber and a buried ice storage as heat source for a heat pump similar to the heating system analyzed in this thesis. The authors concluded that SHP Ice storage system can reach almost similar SPF as a ground source heat pump (SPF up to 4.5) and significantly above an air source heat pump (SPF ~3). Moreover, they also suggested that convective gains from air comprise almost half of the energy delivered by solar collectors. Similarly, Winteler et al. concluded that SHP Ice storage systems show comparable performances to heat pump systems with borehole heat exchangers, with SPF of around 4 (Winteler et al. 2014a).

SHP Ice storage systems can also be used for cooling in particular; free cooling using ice storage without the use of heat pump which means that Ice storage is regenerated using heat from the building instead of solar collectors. As much of the focus for the use of ice storages is for heating purposes in combination with heat pump and solar collector, most of the literature available on these systems discusses only heating mode. However, Frank (2019) mentions a few of such systems installed by Viessmann (Uznach, Schocherswil, Amriswil, Weltpoststrasse) which use ice storage for space cooling purpose in summer alongside heating (Frank and Gmbh 2019). The SHP-Ice system concept implemented in implemented in Amriswil, Switzerland consists of the ice reservoir that has a volume of 1,066 m³ and 396 m² installed surface area of uncovered solar collectors. This case is specifically relevant to the system analyzed in this thesis as both have almost similar volume of ice storage and same type of collectors used for both cooling and heating purposes. Unfortunately, the details about the performance of the system have not been made public; therefore no comparison can be made with the system analyzed in this thesis. However, a report has been published regarding the SHP Ice storage system installed in Uznach, Switzerland for heating and cooling via TABS and underfloor heating (Huber 2015). The system consists of four 50 m³ ice storage tanks and 80 m² of uncovered collectors on the roof. The report suggest that there is still optimization potential for cooling operation using ice storage which will be discussed in the next chapters.

The suppliers of SHP-Ice storage systems are using different approaches regarding the system components i.e. Viessmann tend to use larger ice storages with sizes 1 m³/MWh of heat demand for single family homes and well above 2 m³/MWh of heat demand for multi-family buildings using uncovered solar absorbers that can use utilize low solar irradiation and ambient air as heat sources (Daniel Carbonell et al. 2019). While others such as Consolar Solaera in contrast, develop smaller ice storages which are used in combination with glazed collectors with active rear ventilation that can also be used with at higher temperatures. Since the system analyzed in this thesis uses a Viessmann system, its characteristics are discussed in detail. Using an unglazed solar collector is advantageous as it can utilize low solar irradiation and ambient air as heat sources. It is also indicated for unglazed collectors that a reduced convective heat transfer due to lower wind speed or unfavorable design of the absorber reduces the seasonal performance by 6.5% to 11% and shows that ambient air has one of the biggest influence on the seasonal performance on system using unglazed collectors (Dott et al. 2016). Authors in (Igor Mojic et al. 2014), (I Mojic et al. 2013) simulated different systems for different climates and concluded that system with unglazed collectors in combination with an ice storage generally performed well in terms of SPF compared to all other systems including air source heat pump with standard glazed collectors and the reference system while the climate conditions also have an impact on the performance of the system.

Different simulation environments have been used by researchers and manufacturers alike to model and simulate SHP Ice storage systems. A reference framework for system simulations is described in (Dott et al. 2013) under the IEA SHC Task 44 / HPP Annex 38. Moreover, relevant to the scope of Ice storage systems, Carbonell et al. numerically analyzed three different systems using TRNSYS-17 and Polysun-6® with an aim to compare the differences among the two simulation environments (Daniel Carbonell et al. 2014). Similarly authors of (Haller et al. 2014; D. Carbonell, Philippen, Granzotto, et al. 2016; Haller et al. 2012; Daniel Carbonell et al. 2015; Bertram, Pärisch, and Tepe 2012; D. Carbonell, Haller, and Frank 2014; Winteler et al. 2014b; Igor Mojic et al. 2014; Schmidt et al. 2015; Daniel Carbonell et al. 2019; Winteler et al. 2014a; Daniel Carbonell et al. 2017; Loose, Bonk, and Drück 2012; Winteler et al. 2014a) used either of the two simulation environments to carry out their work. Simulation studies have been very helpful in improving the models available in different simulation environments especially Polysun, which was also used to simulate the system described in this thesis by manufacturer Viessmann.

A few projects such as (Philippen, Carbonell, et al. 2015) have also aimed at analyzing this system concept from an environmental and economic perspective. The life cycle assessments done during the project suggested that larger component sizes such as ice storages had positive effect regarding SPF values and the lowest ecological impact as long as it helps to reduce the need for an electric sourced backup. However, as a consequence, a high investment cost compared to conventional systems due to larger system components eventually balance out the positives and it depends on the user which criteria is more preferred. But it is expected that as the technology will become more mature the system costs are likely to be reduce, making this technology more favorable. Similar System design and life cycle assessment of solar thermal heat pump heating systems with ice storage are described in (Philippen, Zenhäusern, et al. 2015)

On component level, Ice storages are of prime interest for researchers. Various mathematical models have been developed to understand the heat transfer characteristics of ice storages. For example, Ice storages buried in the ground also gain or lose heat via ground which makes it important to consider the heat transfer from the ground. Authors in (D. Carbonell, Philippen, Haller, et al. 2016) presented a mathematical model of ice storage coupling with ground. Similarly, (Goeke 2019) also discusses heat transfer in ice storage and energy gains from the soil.

Moreover, for using ice storage as a sink or source, it is critical to use the correct heat exchanger concepts in order to extract the latent heat from ice keeping in mind that the thickness of the ice layer on the heat exchanger must not exceed so that there is not too high heat transfer resistance, in order for source temperatures for the heat pump to be optimal. (Philippen, Carbonell, et al. 2015) describes two main strategies for such a design of heat exchangers for ice storages, i.e. a) ice-on-hx and b) free-of-ice-hx. Most of the Ice storage systems installed in Europe are generally based on ice-on-hx concept in which large heat exchanger areas are homogeneously distributed throughout the whole storage volume. Generally, within ice-on-hx concept, ice-on-coil heat exchangers are used more commonly including the ice storage analyzed in this thesis while there are other heat exchanger concepts existing in market such as indicated by previously mentioned authors. In addition, many research projects have been undertaken to develop new heat exchanger models for ice storage in order to optimize the system combination with solar collectors and heat pumps and increase the available resources on simulation platforms for manufacturers and general users to easily model such systems which suite their requirements. (Philippen et al. 2019) developed a new model for ice storage with plate heat exchangers for Polysun and validated it with measurement data, contributing to the knowledge base on plate heat exchangers.

In conclusion, although individual characteristics of components of a system play a vital role in improved system performance, the right design of the system concept and optimal control strategy for system operation is essential for achieving high coefficients of performance. Despite numerous positive experiences and commercial offers from different manufacturers, this technology is still in the market launch phase. Although the first systems with ice storage and heat pump combination were launched more than a decade ago, there is still no long-term experience over the entire lifecycle with the durability of the ice storage tank in combination with heat pumps.

3. Methodology

The analysis and evaluation of SHP Ice storage plant is carried out on the basis of minutely measurement data obtained every day from the plant from the start of July 2019 till mid-October 2019. Mostly during this period cooling system was in operation with some instances of heating. Therefore, most of the data correspond to cooling operation.

A detailed literature review was done in order to gain complete understanding of the system in operation. Since this technology developed and manufactured in German speaking countries, a few very good research papers and projects done on this topic were in German which had to be translated for the sake of better understanding.

The measured data was then cleaned and processed using a tool based on the Python programming language developed for data preparation (Python Software Foundation, 2019) at AEE INTEC. Anaconda was used as Python distribution (Anaconda, Inc., 2019)and Spyder as development environment (Spyder: The Scientific Python Development Environment, 2019). Afterwards, the data was evaluated using Microsoft Excel and Microsoft Power BI and plausibility checks were done in order to ensure that correct data is analyzed and processed. Characteristic key diagrams were plotted using time series graphs, energy-temperature diagrams while energy balances were set up separately for heating and cooling operation as well as for individual components such as the ice storage.

The system was also evaluated based on some key performance indicators. Some of the performance indicators were adapted from literature while the others were developed and defined by the author of the thesis for a detailed analysis of the system to be done

4. Plant Design and Components

4.1. General Description

The project in question involves monitoring, analysis and evaluation of a plant which is a combined Solar thermal-heat pump ice storage (SHP Ice Storage) system installed as a supply system for heating and cooling in a newly built distribution warehouse including office space and logistics center for Audio Tuning Vertriebs GmbH, just outside of Vienna.

The ware house building has a gross floor area of 3,040 m² and the office building 1445 m². The buildings have a total heating load of 200 kW and a cooling load of 156 kW. The plant consists of unglazed solar collectors in connection with ice storage and a brine/water heat pump. Also, there are 2 buffer storages connected to heating and cooling distribution system.

The solar thermal system (SLK-600) has a gross collector area of approximately 290 m², which is mounted on the roof of the distribution warehouse. The ice storage tank is a cuboid chamber built underground just next to the warehouse building with a total volume of 1,125 m³ and filled with about 908.784 m³ of water. The remaining volume is required for the volume change during the water-ice phase change. There are two heat exchangers in the ice storage tank each for the heating

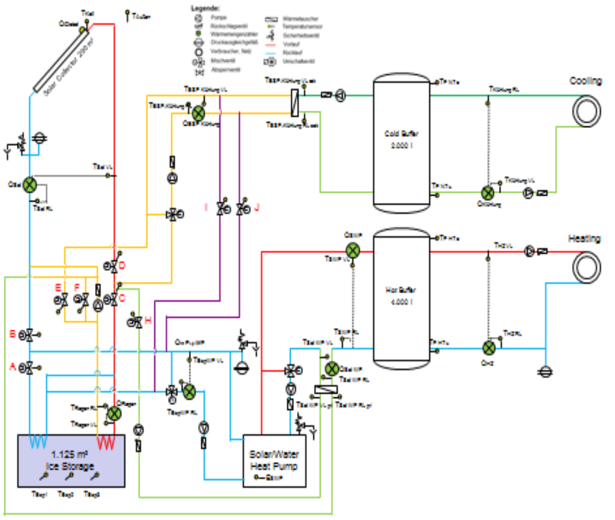

Figure 1: Schematics of the plant

and cooling modes. Both heat exchangers consist of spiral shaped plastic pipes, one in the center and the other one on the periphery of the ice storage. The central heat exchanger is used to extract heat from the ice storage thus called the extraction heat exchanger and the other one being used to dump heat into the ice storage thus being called the regeneration heat exchanger. Thus, the ice storage tank is frozen from inside to outside and regenerated from the outside to the inside. A reversible brine-water heat pump (Vitocal 300-G-Pro BW 302.C230) by Viessmann with a power output of 200 kW for heating and 160 kW for cooling, is installed in the system to supply heating and cooling to the building with either one of the two sources i.e. it can either use the solar system directly or an ice reservoir as a source. A 4,000 liter buffer storage tank for heating and a 2,000 liter buffer storage tank for cooling are available as a buffer between supply and distribution system. Moreover, in order to switch between different cooling and heating modes, valves are also critical part of this system. A schematic diagram of the system is shown in figure 1, includes all the individual system components, eight heat meters installed and nine different valves.

4.2. Operation Modes

In order to efficiently operate the heating and cooling operation of the plant utilizing the available sources, the plant operates in different modes with each having a different source or sink for heating and cooling of the building. In principle, there are eight different modes of operation for the plant. Depending upon the need to heat or cool and temperature/condition of different sources/sinks, the building management system decides on which source/sink should be used and as a result valve positions are adjusted automatically. Moreover, the system can also be manually being overridden if necessary. Different sensors installed by the manufacturer transmit required information to the management system which based on set parameters makes a decision to start or stop certain operation mode. There are two heating modes, four cooling modes and two ice storage regeneration modes. Following are the eight operational modes: Direktbetrieb (Solar Heating Mode), Entzugsbetrieb (Ice Storage Heating Mode), Natural Cooling (Ice Storage Direct Cooling Mode), AC RW Puffer (Heat Pump Cooling using Heating Buffer as a Heat Sink for the Heat Pump Condenser), AC RW Kollector (Heat Pump Cooling using Solar Collector as a Heat Sink for the Heat Pump Condenser), AC RW EES (Heat Pump Cooling using Ice Storage as a Heat Sink for the Heat Pump Condenser), Regeneration and Free Cooling.

4.3. Operation Strategy

The operation strategy for the plant is defined and controlled by plant manufacturer and operator Viessmann. In general, the plant operation is controlled by the building management system which has set criteria for turning a specific mode on or off based on temperatures and design limits of system components. The heating system should work only during winter months i.e. October to April, depending on local weather conditions. The heating system should automatically start when the temperature inside the building goes below the heating set point temperature. The cooling system should operate only during summer months i.e. May to September, depending on local weather conditions. Cooling system also operates in a similar way to the heating system and it usually operates when the temperature inside the building exceeds cooling set point temperature. Although both systems can run simultaneously in some cases but this is generally not the case with this specific plant which does not require simultaneous heating and cooling operation. With eight different operational modes out of which six are directly associated with heating and cooling operation of the building, enables flexibility in terms of sources available for heating and cooling. This implies that if one of the sources is not available at a particular time, for instance the solar energy, we can still use other sources for both heating and cooling operation. This not only provides flexible operation but also enables non-stop and continuous supply of energy for the building. Direktbetrieb or the solar heating mode is expected to be the prevalent mode of operation for heating based on the literature available and the other mode i.e. Entzugsbetrieb, is expected to kick in when there isn’t enough solar energy available due to overcast conditions or there is some problem in the solar circuit. On the other hand, Natural Cooling is expected to be the prevalent mode for cooling as it can save electricity required by the heat pump and run independently just using the cooling energy from the ice storage. The three active cooling modes are expected to be operational during late summer season when all the natural cooling available from the ice storage is exploited and cannot be further used due to lower difference of temperature between the HTF and the cold buffer. The two special modes i.e. Regeneration and Free Cooling generally depend on circumstances described previously in detail and building management system or the operator decides if they are needed to ensure that the conditions for Ice storage and the solar collectors remain with in the design limits.

5. RESULTS AND DISCUSSION

5.1. General Analysis

The system described in the previous chapter was analyzed for a period of approximately three and a half months i.e. from July till mid-October. At the start of the analysis period, the summer was at its peak and there was cooling demand that had to be met by the system using one of the operational modes. There were some instances of heating during the cooling period which will be discussed in detail later. Figure 2 represents the heating and cooling energies with the variation in the mean outside temperature. It can be easily observed that with the drop in mean outside temperature, heating mode takes over cooling by the month of October. The cooling demand during the month of August seems to be lower than September which is strange considering the high outside temperature but this is easily explainable in the light of the fact that considerable numbers of days in August were holidays during which the cooling system was turned off.

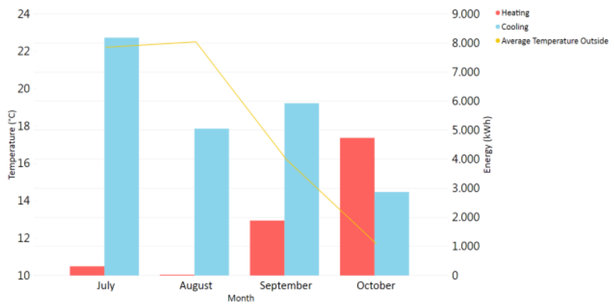

Figure 2: Monthly Heating and Cooling with Mean outside temp.

Moreover, as mentioned previously, the system in discussion has different operational modes which were operational throughout the analysis period. The analysis period includes mostly hot summer months of July and August, a mild weather month of September which includes some instances when heating was required due to low temperatures outside, and month of October when winter is about to start and heating requirement takes over due to lower temperatures. Figure 3 represents different operation modes active throughout the analysis period. Natural cooling mode is the most dominant mode for cooling while heating is mostly done using ice storage. Note that this graphical representation is irrespective of the time duration during which cooling or heating was done. It can also be observed that solar collectors are actively used for the regeneration of ice storage enabling efficient use of solar collectors while also storing this energy to be used in winter. This means that for more than half of the time, the system is in operation with only ice storage as the center of different operations without the involvement of the heat pump.

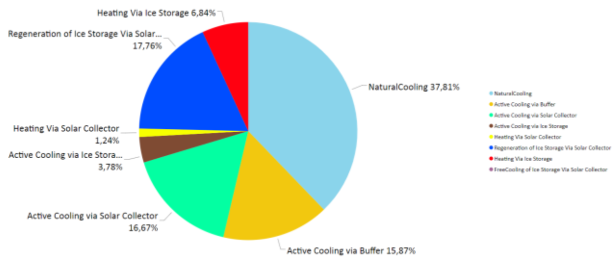

Figure 3: Different Operational Modes

5.2. Cooling System Analysis

A weekly energy balance was done over the whole duration of the analysis period that indicates how much cooling is done using each individual operational mode for cooling on weekly basis. The calculations for holiday season are ignored for the ease of analysis and more straight forward graphical representation of the weekly energy balance. As seen in Figure 4, for the first 6 weeks, all of the cooling is done using Natural cooling mode via ice storage. After reaching a certain temperature limit for ice storage which will be discussed later in this chapter, the natural cooling capacity of ice storage cannot be further utilized and it was observed that heat pump had to be used in order to do cooling.

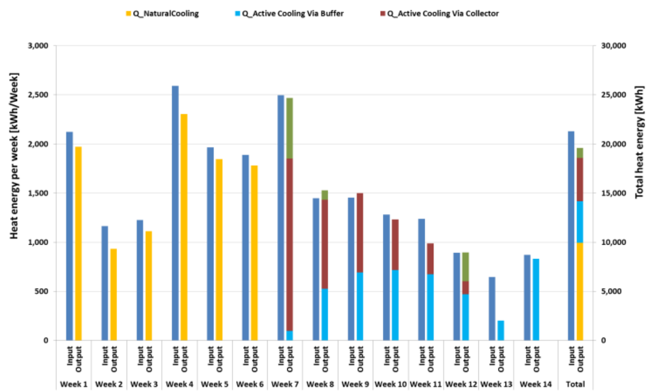

Figure 4: Weekly Energy Balance for Cooling

During week 7, three different active cooling modes were observed to be functional. All of the cooling was done via heat pump and the excess heat was put into different sinks. A large portion was released into the environment via the solar collector, then the ice storage and some heat was dumped into the hot buffer. Over the next few weeks, the cooling requirement decreased and most of the cooling was done either using active cooling via solar collector or active cooling via hot buffer, in both cases heat pump being used to drive the heat into these two sinks. In the latter half of the analysis towards the end of September and October, it was observed that cooling is being done over the hot buffer, which was ideal because at this time, there is also an increasing heat demand as the temperature during this duration sometimes went lower. Thus, the heat taken out of the building is being used again making an efficient use of the system and using the waste heat in the best possible way. It was observed at the end of the analysis period that almost 21,000 kWh of heat was dumped into different sinks with some losses inside the system. Figure 5, represents different cooling modes with percentages ascribed on energy basis. Natural cooling was the most prevalent mode of all being used for 51% of cooling during the whole analysis period in which ice storage was used solely with the aid of few pumps, while only 5% of cooling was done using ice storage in combination with the heat pump. Almost 22.5% of cooling was done using the active cooling mode over the solar collector while 21% was done using active cooling over the hot buffer. It can be observed that more than half of the cooling was done using only ice storage without the use of heat pump which not only improves the overall performance of the system in technical terms but also is economically and environmentally beneficial considering the absence of any heat pump usage which saves money going into electricity bills and also results in fractional CO_2 savings.

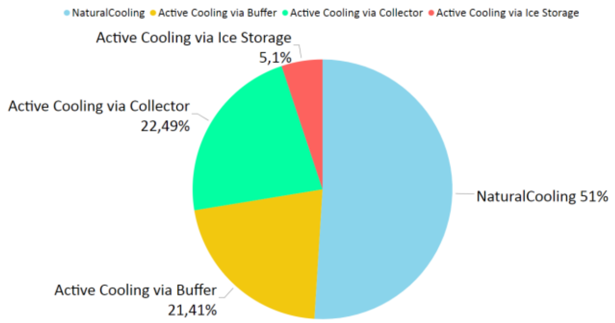

Figure 5: Different Cooling Modes

5.3. Analysis of the Ice Storage

Ice storage is one of the key components of this technology. As discussed in the previously, it was responsible for most of the cooling operation done over the analyzed period. During cooling mode, ice storage acts like a heat sink for the heat from the building. Most of the cooling done using the ice storage was without the use of heat pump in the natural cooling mode as represented in figure 6. Almost 10,000 kWh of cooling energy was effectively provided by the ice storage using the natural cooling mode which not only saved electricity that would have to be used if heat pump was used with the ice storage. Instead, this energy is stored for use during the heating season. It was also observed that the ice storage was regenerated via solar collector for further use in winter season. This special feature enables the ice storage to store excess heat available during summer season that can be used for heating during winter.

At the end of the winter season the ice storage is frozen for most of the part and is available as a heat sink for the cooling system. Over the summer season, the temperature inside the ice storage is supposed to rise in order for it to be regenerated again for use in winter season. During the analysis period, it was observed that the temperature inside the ice storage rose sharply from 3 °C to almost 19 °C as seen in figure 8. This behavior is partly due to the natural cooling operation mode and partly because of the regeneration mode in which ice storage acts like a sink for the heat from the solar collector

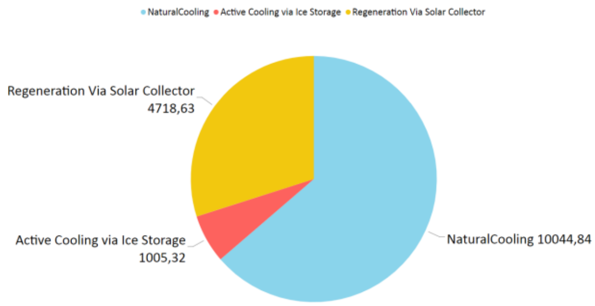

Figure 6: Energy Balance for Ice Storage

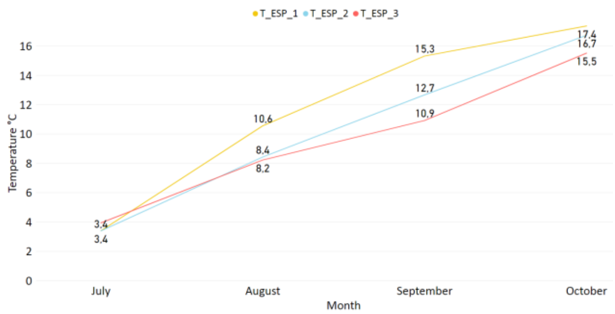

Figure 7: Temperature Variation inside Ice Storage

Overall, the basic purpose of cooling using the ice storage is regeneration for the later use during the winter months. As discussed before, natural cooling mode was responsible for more than half of the cooling done during the summer months. This implies that most of the regeneration should have happened during natural cooling mode. This became more evident when energy-temperature diagram or the qt-diagram was generated using a python based tool. Figure 9 represents the energy temperature diagram for the inflow and outflow temperatures of the ice storage. It can be interpreted from this diagram that most of the regeneration of the ice storage happened at low temperatures which was the case for natural cooling and the two peaks each for supply and return temperatures make a strong case for this interpretation. The regeneration at comparatively higher

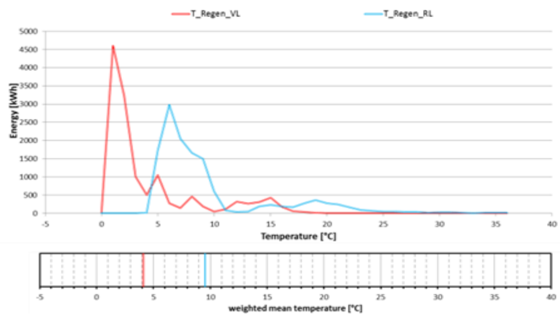

Figure 8: Energy Temperature Diagram for Input and Output Temperatures for the Ice Storage

temperatures is interpreted to be due to solar regeneration mode when compared with supply and return temperature data during this mode. While the small energy peaks in the middle represent regeneration due to active cooling mode which uses ice storage as a sink.

5.4. System Performance

After analyzing the operation of the system in different modes and understanding different key aspects of the system, it is important to evaluate the system and its components based on different performance indicators defined in the previous chapter and analyze if the system in question is really up to the mark or not.

i. Seasonal Performance Factor (SPF_{HP}) for Heat Pump

IEA SHC Task44 defines SPF as the overall useful energy output to the overall driving final energy. This can be mathematically represented as following:

$$SPF_{HP} = \frac{\int (\dot{Q}_H + \dot{Q}_C) dt}{\int \Sigma Q_{el}\, dt}$$

Table below represents the monthly calculation of SPF for heat pump. This calculation is also graphically represented in figure 9.

Month	Electricity Input (kWh)	Thermal Output (kWh)	SPF	Mean inflow temp. (°C)	Mean outflow temp. (°C)
Aug	607.76	2807.76	4.62	24.88	26.2
Sep	1857.51	8297.51	4.47	34.95	40.84
Oct	1383.25	7409.27	5.36	29.87	34.25
Total	3,848.28	18,514.5	4.81	29.90	33.76

Table 1: SPF Calculation for Heat Pump

The results show a good prospect for the solar water/brine heat pumps as SPF values obtained are quite high and comparable to systems with boreholes. Literature also suggests that overall SPF of 4.81 for this type of heat pump is way better than air heat pumps which usually have SPF around 3 (Philippen, Carbonell, et al. 2015).

ii. Solar Fraction

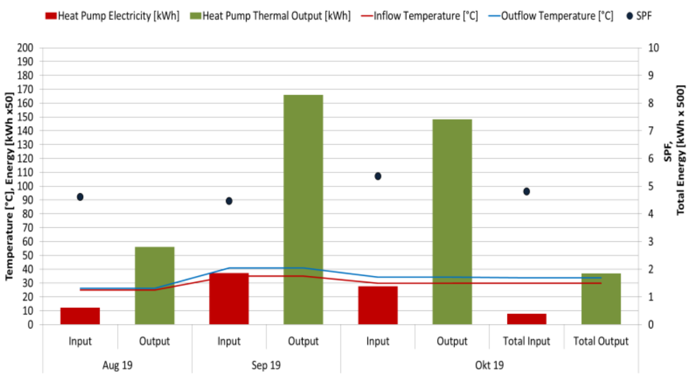

Figure 9: SPF Calculation for Heat pump

Solar fraction is defined as fraction responsible for the regeneration of ice storage. solar fraction representing the solar input into the ice storage was calculated.

$$f_{sol,regen} = \frac{4,718.63}{10,044.84 + 1,005.32 + 4,718.63} = 0.299$$

This result represents that solar collectors were used for almost 30% of regeneration of the ice storage. It is fair to say that this is actually good from the perspective of utilization of the solar collectors.

iii. Waste Heat Utilization

Calculation was made for waste heat utilization for the heat that is taken out of the building during cooling operation and can be reused during winter months if effective use of storage capacity is made possible. Following is the calculation for fraction of waste heat that is stored in ice storage and hot buffer.

$$f_{waste\ heat\ utilized} = 1 - \frac{4430.03}{9653.48235} = 0.54$$

This result means that 54% of the energy is stored in the system while 46% of the remaining heat is dumped into the air. The system efficiency can be increased if the amount of heat wasted can be stored or utilized in some way.

iv. Energy Density of Ice Storage

Energy density for the ice storage was calculated using the design temperatures provided by the manufacturers using following equation:

$$U = \frac{Qsensible, water + Qsensible, ice + Qlatent, ice}{V_{ice}} = \frac{109.7\ MWh}{908.784\ m^3} = 0.12\ MWh/m^3$$

The resulting energy density is quite good in comparison to the commercially available technologies for thermal energy storage.

v. Utilization of storage capacity

Utilization of storage capacity can be calculated as following:

$$USC = \frac{28866.82\ kWh}{109700\ kWh} = 0.26$$

This means that only 25% of the estimated storage capacity of the ice storage is currently being utilized which indicates that the system is overdesigned for its current use.

vi. Seasonal Performance Factor (SPF) for System

A similar procedure was adapted to calculate the SPF of the whole system but with different system boundaries than in the case of heat pump. The system boundaries now also include the heat output into the ice storage in order to consider all operational modes of the system including natural cooling.

The reason for very high SPF for the month of July is obvious due to the use of natural cooling which radically increases the efficiency of the system. The obvious advantage of this system over other systems for cooling is the use of cooling energy of the ice storage by just using ordinary pumping system which consumes way less electricity than any other comparable systems of this kind. As for the comparatively lower SPF for the month of September is concerned, it can be inferred that this is lower due to contrasting heating and cooling load throughout the month.
A comparable analysis for an Aquifer Thermal Energy Storage based cooling and heating system (ATES) was analyzed over a period of three years by (Desmedt, Hoes,

and Robeyn 2007). Although these results cannot be directly compared, they serve as a good reference for analysis done within the scope of this thesis.

Month	Total Electricity Input (kWh)	System Thermal Output (kWh)	SPF
Jul	408.778	8389.41	20.52
Aug	879.1044835	5054.26	5.74
Sep	2103.79654	8297.51	3.94
Oct	1784.355225	7605.86	4.26
Overall	5176.034248	29347.04	5.66

Table 2: SPF Calculation for System

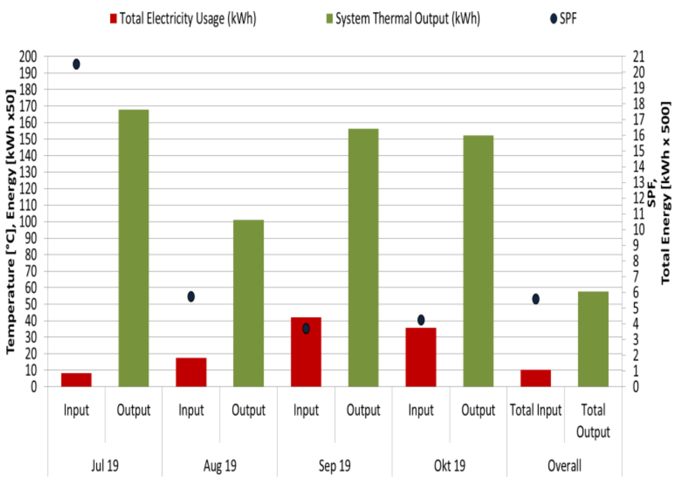

Figure 10: SPF calculation for system

vii. Primary Energy Ratio of Non-Renewable Energy Sources (PER_{NRE})

This performance factor enables us to know about the consumption of non-renewable energy sources for producing the useful energy output of the system. It is defined as the ratio of the useful energy output of the system to the primary energy input and mathematical represented in the equation below. The unit for PER_{NRE} is $kWh_{useful\ energy}/kWh_{primary\ energy}$.

$$PER_{NRE} = \frac{SPF}{CED_{NRE,el}}$$

$CED_{NRE,el}$	1.02
SPF	5.66
PER_{NRE}	5.55

Table 3: Calculation for Primary Energy Ratio of Non-Renewable Energy Sources

The reference value for $CED_{NRE,el}$ for Austria was taken from (BAUTECHNIK 2019). It can be inferred from the result that for every one unit of nonrenewable primary energy used for the production of electricity that is being input into the system, 5.5 units of useful energy are delivered.

viii. Fractional CO_2 Emission Savings Using the Natural Cooling Mode

A significant amount of cooling was done using the natural cooling mode which was done without the use of heat pump and by just using the cooling energy from the ice storage. This aspect of the combined solar heat pump ice storage system is particularly attractive in terms of fractional CO_2 emission savings and this parameter was calculated using the following equation:

$$f_{sav,pe} = 1 - \frac{\Sigma P_{el,final} \cdot GWP_{el}}{(\dot{Q}_{H} + \dot{Q}_{C}) \cdot \eta_{ref} \cdot GWP_{ref}}$$

GWP_{el} (kg CO_2equiv./kWh_{fe})	0.227
$\Sigma P_{el,Natural\ Cooling}$ (kWh)	601.64
$Q_{Natural\ Cooling}$ (kWh)	10,044.84
COP_{HP}	4.7
$f_{sav,CO2}$	0.987

Table 4: Calculation for Fractional CO_2 Savings Using Natural Cooling

For calculating the fractional emission savings for the natural cooling mode, a heat pump reference system was chosen based on data sheet provided by manufacturer of this system. As shown in table 4, the results indicate that for producing the same amount of cooling using the heat, using the natural cooling mode will have 98% of the equivalent CO_2 emissions.

ix. Equivalent Warming Impact (EWI)

EWI is the ratio of the greenhouse gas emission to the useful energy output of the system. Calculation was made using equation 7 and the calculations are presented in table 5.

GWP_{el} (kg CO_2equiv./kWh_{fe})	0.227
SPF	5.66
EWI	0.05

Table 5: Calculation for EWI

The value of 0.05 for EWI represents that 0.05 kg of CO_2 was released to deliver 1 kWh of useful energy which is comparable to carbon foot print of renewable energy sources such as solar, wind etc according to (Allen 2011).

5.5. Discussion and Conclusion

In summary, the combined solar heat pump ice storage systems are still in their initial phase for making a good place in the market. The technology itself has shown great prospects in technical as well as environmental terms, but costs are however a comparatively higher than the other less efficient technologies. The system analyzed in this thesis was designed for both heating and cooling purposes but due to time constraints, the scope of this thesis mostly covers the cooling operation. Although there were some data limitations due to lack of sensors at some places inside the system but it was possible to do a balanced and representative data analysis and evaluation of the system.

One of the main system components was the ice storage, which played a crucial role in supplying cooling energy for the building and serve as the heat storage during the same period. The ice storage was solely used for 51% of all the cooling done with the aid of small pumps which did not consume a lot of electricity and had a very positive effect on the overall system performance. The system had an SPF of 5.66 which is very satisfactory when compared to other systems used for the same purpose, for instance, the air heat pumps have a SPF of around 3.

Moreover, the system analyzed had a comparatively large sized ice storage i.e. 1125 m^3, which are not so common. Generally, systems under 500 m^3 and typically under 100 m^3 capacity are more common in Switzerland, Germany and Austria. Sizing of the ice storage is still a hot topic among the researchers and companies manufacturing ice storages. There is a good prospect of research and development in correct dimensioning of the ice storages with both heating and cooling in focus. Unfortunately, due to limitations of sensors and data, it was not possible to include this topic within the scope of this thesis.

Heat pump was designed as a main component of this system especially in regards to heating. It showed quite an impressive SPF of 4.81 which is comparable or even better than system with boreholes. The COP of the heat pump is 4.7 as per the manufacturer data sheet which shows that the system should be quite efficient and perform better under normal conditions. Generally, no unusual behavior was observed regarding functioning of the heat pump.

In conclusion, it can be said that better performance of the system also heavily depends on the control strategy in parallel to the design of the system itself. The overall performance of the system was very satisfactory and there is a huge market potential for these systems to be used for both heating and cooling with natural cooling using the ice storage as a special feature that saves a lot of electricity and results in higher systems performance. A whole year of operational analysis would have been a good representation of the results and the system. However, this was not possible due to the time constraints. A basic framework for analysis of this system was developed by the author of this thesis that can accommodate the data analysis for the rest of the monitoring period that is supposed to last 12 months. The work done in this thesis is unique in its character, as not much detailed work is available on analysis of cooling operation of combined solar heat pump ice storage system. Therefore, it opens up new research questions and opportunities to optimize the cooling operation of this technology.

6. REFERENCES

Allen, Stephen. 2011. “Carbon Footprint of Electricity Gerenation.”https://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf.

“Anaconda,Inc.”2019.https://anaconda.org/anaconda/spyder.

Bautechnik, Richtlinien Des Österreichischen Instituts Für. 2019. “OIB Richtlinie: Energieeinsparung Und Wärmeschutz.”

Bertram, Erik, Peter Pärisch, and Rainer Tepe. 2012. “Impact of Solar Heat Pump System Concepts on Seasonal Performance-Simulation Studies.” *Proceedings of the EuroSun {…}*. http://task20.t.iea-shc.org/data/sites/1/publications/2012.001.pdf.

Carbonell, D., M. Y. Haller, and E. Frank. 2014. “Potential Benefit of Combining Heat Pumps with Solar Thermal for Heating and Domestic Hot Water Preparation.” *Energy Procedia* 57: 2656–65. https://doi.org/10.1016/j.egypro.2014.10.277.

Carbonell, D., D. Philippen, M. Granzotto, and M. Y. Haller. 2016. “Simulation of a Solar-Ice System for Heating Applications. System Validation with One-Year of Monitoring Data.” *Energy and Buildings* 127: 846–58. https://doi.org/10.1016/j.enbuild.2016.06.058.

Carbonell, D., D. Philippen, M. Y. Haller, and S. Brunold. 2016. “Modeling of an Ice Storage Buried in the Ground for Solar Heating Applications. Validations with One Year of Monitored Data from a Pilot Plant.” *Solar Energy* 125: 398–414. https://doi.org/10.1016/j.solener.2015.12.009.

Carbonell, Daniel, Michel Y. Haller, Daniel Philippen, and Elimar Frank. 2014. “Simulations of Combined Solar Thermal and Heat Pump Systems for Domestic Hot Water and Space Heating.” *Energy Procedia* 48: 524–34. https://doi.org/10.1016/j.egypro.2014.02.062.

Carbonell, Daniel, Daniel Philippen, Mattia Battaglia, and Michel Y. Haller. 2017. “Cost Energetic Analyses of Ice Storage Heat Exchangers in Solar-Ice Systems.” *ISES Solar World Congress 2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings*, no. October 2018: 2190–2201. https://doi.org/10.18086/swc.2017.33.02.

Carbonell, Daniel, Daniel Philippen, Elimar Frank, Martin Granzotto, and Michel Haller. 2015. “Simulation of Combined Solar Thermal, Heat Pump, Ice Storage and Waste Water Heat Recovery Systems. Design Criteria and Parametric Studies,” no. September: 1–10. https://doi.org/10.18086/eurosun.2014.03.04.

Carbonell, Daniel, Jeremias Schmidli, Daniel Philippen, and Michel Haller. 2019. “Solar-Ice Systems for Multi-Family Buildings: Hydraulics and Weather Data Analysis.” *E3S Web of Conferences* 111 (201 9): 01013. https://doi.org/10.1051/e3sconf/201911101013.

Desmedt, Johan, Hans Hoes, and Nico Robeyn. 2007. “Experiences on Sustainable Heating and Cooling with an Aquifer Thermal Energy Storage System at a Belgian Hospital,” no. August: 8.

Dott, Ralf, Michel Y Haller, Jörn Ruschenburg, Fabian Ochs, and Jacques Bony. 2013. "The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38 Part B: Buildings and Space Heat Load A Technical Report of Subtask C Report C1 Part B Final -Revised," no. October. https://doi.org/10.13140/2.1.2221.4727.

Dott, Ralf, Christian Winteler, Thomas Afjei, and Bernd Hafner. 2016. "Key Facts for High Efficient Solar Ice Storage Heat Pump Systems," no. May. Energy, Directorate-general F O R. 2020. "EUROPEAN COMMISSION DIRECTORATE-GENERAL FOR ENERGY Directorate C. 2 – New Energy Technologies, Innovation and Clean Coal," no. September 2016.

Frank, Elimar, and Frank Energy Gmbh. 2019. "IceCheck Auswertung Solarer Eisspeicher-Systeme Für Mehrfamilienhäuser in Der Schweiz," no. February. https://doi.org/10.13140/RG.2.2.34903.93609.

Goeke, Johannes. 2019. "Wärmeübertragung in Eisspeichern Und Energiegewinne Aus Dem Erdreich." *Bauphysik* 41 (2): 96–103. https://doi.org/10.1002/bapi.201900001.

Hadorn, Jean Christophe. 2015. "Solar and Heat Pump Systems for Residential Buildings." *Solar and Heat Pump Systems for Residential Buildings*, 1–254. https://doi.org/10.1002/9783433604830.

Haller, Michel Y., Erik Bertram, Ralf Dott, Thomas Afjei, Fabian Ochs, and Jean Christophe Hadorn. 2012. "Review of Component Models for the Simulation of Combined Solar and Heat Pump Heating Systems." *Energy Procedia* 30 (December): 611–22. https://doi.org/10.1016/j.egypro.2012.11.071.

Haller, Michel Y, Daniel Carbonell, Igor Mojic, Christian Winteler, Erik Bertram, Mircea Bunea, Werner Lerch, and Fabian Ochs. 2014. "Solar and Heat Pump Systems - Summary of Simulation Results of the IEA SHC Task 44/HPP Annex 38." *11th IEA Heat Pump Conference*, no. 2012: 1–12.

Hasnain, S. M. 1998. "Review on Sustainable Thermal Energy Storage Technologies, Part II: Cool Thermal Storage." *Energy Conversion and Management* 39 (11): 1139–53. https://doi.org/10.1016/S0196-8904(98)00024-7.

Henley, Jon. 2019. "Climate Crisis Blamed as Temperature Records Broken in Three Nations." Https://Www.Theguardian.Com/World/2019/Jul/24/Summers-Second-Heatwave-Set-to-Break-Records-across-Europe. 2019.

Huber, Ruedi. 2015. "Planungszentrum Linth AG, Uznach Heizen Und Kühlen Mit Saisonalen Energiespeichern, Solar-Luft-Absorbern Und Sole-Wasser-Wärmepumpen, Erfolgskontrolle."

Loose, Anja, Sebastian Bonk, and Harald Drück. 2012. "Investigation of Combined Solar Thermal and Heat Pump Systems - Field and Laboratory Tests." *EuroSun 2012*.http://task44.ieashc.org/Data/Sites/1/publications/2012.015.pdf.

Mojic, I, M Y Haller, B Thissen, and E Frank. 2013. "Wärmepumpen-Systeme Mit Selektiven Unabgedeckten Und Frei Belüftbaren Abgedeckten Kollektoren Als Einzige Wärmequelle," no. April.

Mojic, Igor, Michel Y. Haller, Bernard Thissen, and Elimar Frank. 2014. "Heat Pump System with Uncovered and Free Ventilated Covered Collectors in Combination with a Small Ice Storage." *Energy Procedia* 48: 608–17. https://doi.org/10.1016/j.egypro.2014.02.071.

Philippen, Daniel, Daniel Carbonell, Mattia Battaglia, Bernard Thissen, and Lars Kunath. 2019. "Validation of an Ice Storage Model and Its Integration Into a Solar-Ice System," no. May 2019: 1–12. https://doi.org/10.18086/eurosun2018.13.12.

Philippen, Daniel, Daniel Carbonell, Daniel Zenhäusern, Martin Granzotto, Michel Haller, and Stefan Brunold. 2015. "High-Ice System Development for High Solar Thermal Gains with Ice Storage and Heat Pump." *Bfe*, no. July.

Philippen, Daniel, Daniel Zenhäusern, Daniel Carbonell, Martin Granzotto, Michel Haller, and Stefan Brunold. 2015. "Systemauslegung Und Ökobilanzierung von Solarthermie- Wärmepumpen-Heizungen Mit Eisspeichern Und," 8640.

"PythonSoftwareFoundation."2019.https://www.python.org

Ruschenburg, Jörn, Sebastian Herkel, and Hans Martin Henning. 2013. "A Statistical Analysis on Market-Available Solar Thermal Heat Pump Systems." *Solar Energy* 95: 79–89. https://doi.org/10.1016/j.solener.2013.06.005.

Schmidt, Christian, Ivan Malenković, Korbinian Kramer, Michel Y. Haller, Robert Haberl, Anja Loose, Sebastian Bonk, Harald Drück, Jorge Facão, and Maria João Carvalho. 2015. "Laboratory Test Procedures for Solar and Heat Pump Systems." *Solar and Heat Pump Systems for Residential Buildings*, 103–30. https://doi.org/10.1002/9783433604830.ch05.

"SPYDER: The Scientific Python Development Environment." 2019. https://www.spyder-ide.org.

Stefan Minder, Martin Mühlebach Roland Wagner, and Thomas Weisskopf. 2014. "Eisspeicher-Wärmepumpen-Anlagen Mit Sonnenkollektoren Technologiestudie," no. September: 102.

Swardt, C. A. De, and J. P. Meyer. 2001. "A Performance Comparison between an Air-Source and a Ground-Source Reversible Heat Pump." *International Journal of Energy Research* 25 (10): 899–910. https://doi.org/10.1002/er.730.

Winteler, Christian, Ralf Dott, Thomas Afjei, and Bernd Hafner. 2014a. "Seasonal Performance of a Combined Solar, Heat Pump and Latent Heat Storage System." *Energy Procedia* 48: 689–700. https://doi.org/10.1016/j.egypro.2014.02.080.