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

Nouman Akram

Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

Supervisors: Prof. Carlos Augusto Santos Silva
DI Walter Becke

Examination Committee

Chairperson: Prof. Susana Isabel Carvalho Relvas
Supervisor: Prof. Carlos Augusto Santos Silva
Member of the Committee: Prof. Luís Filipe Moreira Mendes

December 2019

Acknowledgements

In the name of Allah, the Most Gracious and the Most Merciful. A remarkable journey ends with this Master thesis. Two years ago, I started this journey with InnoEnergy Master School in Poland for 1st year of my Masters, from where I had the opportunity to travel to different innovation and technological hubs and see what is happening in the energy sector and how. Then, I moved to the south-western coast of Iberian Peninsula; to Lisbon for my 2nd year of Masters and then finally to Graz in Austria near the Alps. Every country and every experience was unique and different in its character yet helping me define who I am and what I can do to make world a better place. However, I think the most important factor in making these experiences unique and worth remembering are the people whom I met; whom I learned from; whom I spent time with; whom I admire.

I would like to thank DI Walter Becke at AEE INTEC for all the help he provided for the successful completion of tasks for this thesis, for sharing his experiences with other projects and how the things could be improvised for this thesis in the light of those experiences. His feedback meant a lot for improvements I made in in regards to this particular area of knowledge in the duration of this thesis. A special thanks to Marnoch Hamilton-Jones for being a very supportive help desk for python related issues. I would also like to thank Michael Reisenbichler, Lorenz Leppin, Ahmed Junaid Tahir, Stephanie Chan, Imanol Esnal Roig, Salman Malik and Dr. Hermann Edtmayer for all the professional help and advice they provided during the time I was at AEE INTEC. Thanks to Rebekka Köll and all the volleyball team for having me this summer, it was wonderful. And a big thanks to Ewald Selvicka and Werner Weiss for providing me with this opportunity to do my thesis at AEE INTEC. I am also really grateful to Dr. Carlos Augusto Santos Silva for supervising me for this thesis and providing his timely feedback on my thesis. His lectures for the courses of Solar thermal Energy and Energy Management were very informative and helpful for the work within the scope of this thesis and outside of it. I would also like to thank all the professors who taught me at Instituto Superior Técnico, Lisbon and Silesian University of technology.

I am grateful to Yousuf, Abdul Rehman, Omais and all the people in Lisbon, Gliwice, Munich, Stuttgart, Graz who made my time memorable, and were always there for me. I am also grateful to all my friends back home in Pakistan who were just one call away and supported me for what I do. In the end, I would like to thank and dedicate this thesis to my late Grandparents, both of my Parents, Akram and Shaheena, my brothers Usman and Shayan, and my uncles Irfan, Imran and Kamran whose help, support and prayers were always there for me and were always a source of motivation to keep striving and be successful.

Thank you, Obrigado, Dankeschön, Dziękuję, Gracias and شکریہ

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.

Key-words: heat pump, solar collector, ice storage, heating, cooling, data analysis, thermal energy storage

Resumo

Quase metade do consumo de energia na Europa destina-se ao aquecimento e arrefecimento, sendo que a maior parte provém de combustíveis fósseis (66%). A utilização de bombas de calor solares assistidas com armazenamento de gelo permite a utilização de energias renováveis para aquecimento e arrefecimento de edifícios novos e existentes, melhorando simultaneamente o desempenho energético, a eficiência, e a flexibilidade. Estes sistemas tornaram-se cada vez mais populares em países da Europa Central como a Áustria. O objetivo desta tese é analisar e avaliar tecnicamente um sistema de armazenamento de gelo com bomba de calor solar assistida para aquecimento e arrefecimento de um edifício usando dados de campo, e explorar ainda mais o potencial desta tecnologia. Este trabalho foi realizado no Instituto AEE para Tecnologias Sustentáveis. Os dados brutos da planta foram processados utilizando uma ferramenta baseada em python. O armazenamento de gelo foi usado para 51% de todo o arrefecimento feito sem qualquer ajuda da bomba de calor, o que teve um efeito muito positivo no Factor de Desempenho Sazonal (SPF) que foi de 5,66. Um melhor desempenho da bomba de calor foi observado com um FPS médio de 4,81 durante o período de análise. O trabalho feito nesta tese é inovador, pois não há muito trabalho detalhado disponível sobre a análise da operação de arrefecimento.

Palavras-chave: transição de energia, bomba de calor, coletor solar, armazenamento de gelo, aquecimento, refrigeração, análise de dados, armazenamento de energia térmica

Table of Contents

List of Figures

List of Tables

Nomenclature

Q	energy yield of the collector system per square meter aperture area
G	shortwave solar irradiance in collector plane
L	relative long wave sky irradiance
α	shortwave absorptivity of the absorber
ε	long wave emissivity (absorptivity) of the absorber
T_a	ambient temperature
V_e	exit temperature of the fluid
T_i	Inlet temperature of the fluid
U_L	overall heat loss coefficient
F_R	heat removal factor
$\dot{m}_C$	heat capacity rate of fluid
SPF	Seasonal performance factor
SHP	Solar heat pump
GSHP	Ground source heat pump
EWI	Equivalent warming impact
GWP	Global warming potential
Eisspeicher	Ice storage
Kollecterflache	Collector surface
Sole/Wasser	Solar/Water
WP	Heat pump
Kaltepuffer	Cold buffer
Heizungspuffer	Hot buffer

Chapter 1: Introduction

The aim of this thesis is to do an analysis and evaluation of a system which includes a solar thermal system with gross collector area of 289.71 m², with a brine/water heat pump in combination with ice storage of 1125 m³ volume. This thesis is part of the accompanying research of the Solarthermie – Solare Großanlagen Program initiated by the Klima –und Energie funds Austria and partnered by AEE – Institute for Sustainable Technologies. This program was initiated in 2010 to build a bridge between research and the market and to raise the cost reduction potential of new materials, storage technologies and system solutions. Solar thermal energy for space heating and hot water supply in Austria has become an important branch of industry. Reducing the costs of solar thermal systems is a key factor for the long-term success of this climate-friendly energy technology. This funding program admits different projects in Austria under the different priority areas that range from solar process heat, solar feed-in to grid-connected heat supply systems, high solar coverage rates in commercial and service operations, solar thermal in combination with heat pumps, and new technologies and innovative approaches. The projects admitted are provided with certain subsidies or funds if they approved by the funding agency. So far, nine successful tenders have been carried out, and funding commitments have been awarded to more than 230 projects. This has created a basis for the development of the future-oriented large-scale plants market. In 2015, the funding program was evaluated by international experts who concluded that the program is highly efficient and makes a significant contribution to the dissemination of large-scale commercial plants in Austria. Proposed improvements, such as an increase in the maximum permissible plant size, were taken up and the guideline was made even more user-friendly. In addition, to accompany particularly innovative projects and support plant operators in optimizing their plants, the selected projects are supported by accompanying research program and intensively monitored for a period of one year. The findings from this accompanying research serve further development of the technology and are continuously incorporated into the implementation of new large-scale solar plants. The project evaluated in this thesis is included under the new technologies and innovative approaches category as it includes use of new collector technologies (Solar Unglazed Collectors) and use of new storage technologies (Ice Storage) both of which are important assessment criterion for this category. In the following sections, a background on the situation of the heating and cooling sector along with the current state of research and development specially with in solar heat pump systems will be discussed in detail followed by short description of advantages and disadvantages of using ice storage with Solar heat pump system.

1.1. Situation of heating and cooling sector

On 21st of September 2019, the world leaders gathered at the UN Climate Action Summit 2019 to renew their commitments made under the Paris climate agreement. The European countries are expected to commit by 2020 to more aggressive climate plans, known as nationally determined contributions (NDCs), than those they set in 2015 when the agreement was signed. These countries are concerned about environmental problems and energy security, are making efforts to enable an energy transition towards a sustainable low carbon future possible at all levels by improving energy efficiency and accelerating integration of renewable energy to the present energy infrastructure.

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 [1]. 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 [2] which may increase the need for a space cooling systems in conjunction with the heating systems.

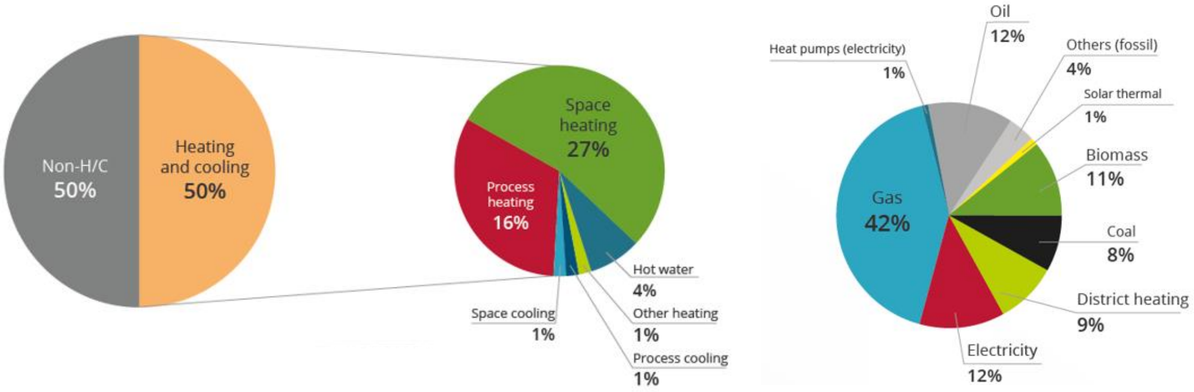


Figure 1: Heating and Cooling Sector Energy Consumption [3]

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 [4]. 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. Different types of heat pumps combinations will be discussed in detail in the next chapters. 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 Photo Voltaic 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 [5] 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.

1.2. State of the Art

1.2.1. Solar Heat Pump (SHP) Systems

The concept of using combination of solar thermal collectors and heat pumps has received a large attention on commercial level during the last decade. In order to develop reference framework for the analyzing these systems, investigating improvements, and providing standards for testing these systems, efforts were made under the research done in the framework of the International Energy Agency (IEA), Solar Heating and Cooling program (SHC Task 44) and Heat Pump program (HPP Annex 38) Solar and Heat Pumps, known under the combined name Task44/Annex38 (T44/A38) [4]. This research T44/A38 provides us with theoretical basics for the components of the solar thermal heat pump systems i.e. the collector, the storage tank, the borehole, and the heat pump. Further, definitions of the performances indicators of such systems such as the coefficient of performance (COP) and Seasonal Performance Factor (SPF), the testing methods for Solar Heat Pump (SHP) systems in a laboratory for characterization and optimization, the basics of monitoring SHP systems and recommendations for data acquisition of SHP systems are presented in the work. Alongside this, the simulations for SHP systems with in the T44A38 framework are also discussed with some important results on SHP combinations and sensitivity analyses. Finally, it provides an interesting approach to evaluate the cost of an SHP system comparable to classical or non-solar system.

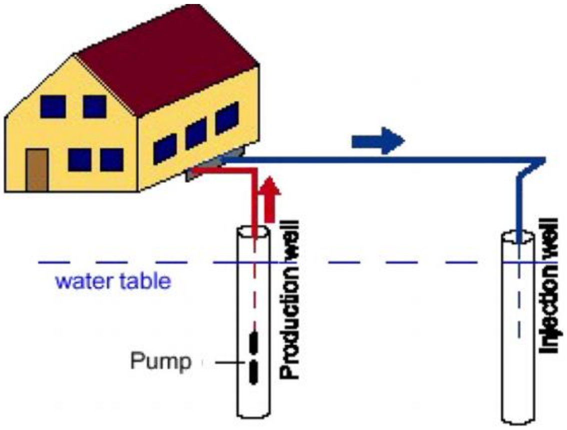


Figure 2: Ground Source Heat Pump Concept [6]

[6] made comparison of different solar thermal heat pump systems such as Solar Air Source heat pump (SASHP), Solar Ground Source Heat Pump (SGSHP) and Solar Ice Storage Heat Pump system (SISHP), using the two simulation platforms TRNSYS-17 and Polysun-6®. The authors analyzed parallel and series combined solar and heat pump systems (described in section 2.2.1) within the IEA SHC Task44/ HPP Annex38 reference conditions for different buildings and a typical Central European climate. The results indicate a comparable system performance of SISHP system and SGSHP making a good case for the use of SISHP system for heating in particular. Similarly, authors in [7] numerically analyzed parallel combination of solar heat pump systems and recommended that the SPF of the overall heating system increases with the addition of a solar thermal system to both air source and ground source heat pumps but the potential benefit of ground source based systems is higher than that of an air source heat pump.

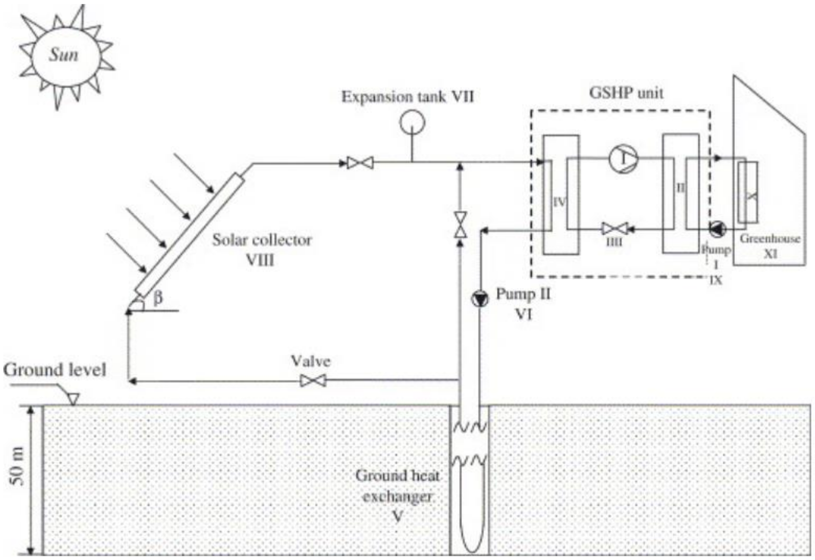


Figure 3: Solar assisted ground source heat pump concept

1.2.2. Solar Heat Pump Ice Storage Systems

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 [7] 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 [8]. 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 [9]. 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.

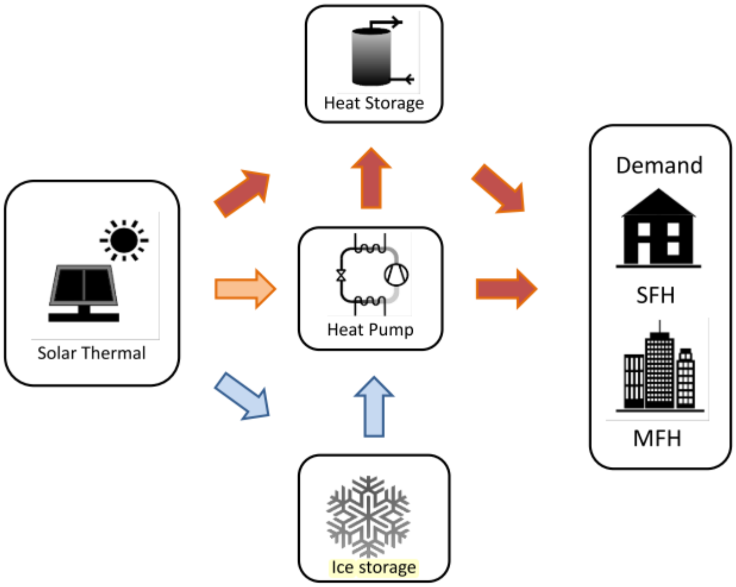


Figure 4: General concept of solar heat pump ice storage system [10]

Several examples of research done on SHP-Ice systems can be found in literature. For instance, [11] 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 absorbers. 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 [12].

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 i.e. ice storage being charged with thermal energy for use in winters. 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 [13]. 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 Thermally Activated Building System (TABS) and underfloor heating [14]. 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 [15]. 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 [11]. Authors in [16], [17] simulated different systems for six different climates i.e. Zurich, Davos, Graz, Wurzburg, Carcassonne and Helsinki. They 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 [18] 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 [19]. Similarly authors of [10], [12], [12], [15], [16], [20]–[28] 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 [7] 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 [29]

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 [30] presented a mathematical model of ice storage coupling with ground. Similarly, [31] 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. [7] 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. [32] 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.

1.3. Advantages and Disadvantages of SHP Ice Storage Systems

SHP Ice Storage systems have several advantages with respect to GSHP systems as described in [30], [33]:

a) SHP-Ice systems are usually not restricted to regulations related to water and soil.
b) They have higher performance compared to GSHP.
c) There is no need to regenerate the ground as in regions densely populated with boreholes
d) Ice storages are accessible which allow any repair work like leakages or replacing heat exchangers
e) Ice storage installation can also be done in a cellar when no ground space is available
f) Flexible system that can adjust to building size restrictions and can give similar system performance with different combinations of collector area and ice storage volume.

However, SHP Ice Storage systems have some disadvantages also respect to GSHP such as:

a) Higher number of hydraulic components
b) Added complexity of the control
c) Higher installation cost if the same performance is desired

Moreover, Particular advantages of ice storages described in [30] are:

a) The phase change characteristic of ice enable the use of latent heat which means higher energy density and less space required.
b) Low temperatures inside the ice storage decrease chances for heat loses. In fact, there is heat gain if the ice storage temperature is lower than the temperature of surrounding ground.
c) Thermal insulation is not necessary if the ice storage is built outside the building in the ground.
d) Heat from solar collectors even at low temperatures that cannot be used in any other applications can be used for regeneration of the ice storage which leads to additional solar gains and improved system performance.

e) Ice storage can also be used directly for cooling as a sink for building air conditioning.

1.4. Objective of Thesis

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.

In summary, this thesis will deal with following questions:

- What are different operation modes of the system and how does the system function in each of the different modes?
- How do individual components behave in a complex system combination of solar thermal collectors, heat pump and ice storage? What are factors and measures to determine optimal plant operation?
- Is ice storage effective for cooling operation?
- What are the optimization potentials and recommendations for the plant in discussion and technology in general?

1.5. 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 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 [34] at AEE INTEC. Anaconda was used as Python distribution [35] and Spyder as development environment [36]. 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 that are defined in chapter 2 of this thesis. 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.

Chapter 2: System background

2.1 Concept of the Technology

From the literature review, it can be inferred that Solar Heat pump systems in combination with ice storage are becoming popular especially in central Europe where there is a huge demand for heating and certainly due to climate change and hotter summers, an increased demand for cooling. Solar thermal collectors and heat pump can be combined into a system in different ways, which makes it important to understand the interaction of these two before understanding the combined system with ice storage that is described in section 2.1.3 in detail. In general, the ice storage acts both as a source/sink for the heat pump and as a seasonal thermal energy storage.

2.1.1. Configurations of SHP System

As a contribution towards development of Task 44/Annex 38 of the International Energy Agency (IEA) Solar Heating and Cooling Program / Heat Pump Program, Frank and Haller [37] systematically classified combined solar thermal heat pump systems using a new approach which also provides a visualization scheme similar to energy flow charts used in building energy engineering and a notation scheme that represents information of different concepts of solar heat pump systems. The authors also discussed previous classifications of such systems in literature and came up with new classification based on more practical approach. The classification of solar heat pump systems is generally based on three types of interaction between solar collectors and heat pumps:

a- Parallel configuration: Collector and heat pump independently supply useful energy, occasionally via storage.
b- Series configuration: Collector acts as a heat source for the heat pump, either exclusively or as additional source, and either directly or via a storage
c- Regeneration: A collector is used for the regeneration of another source, usually ground.

It must be noted that these three configurations can also be inclusive of the each other resulting in seven possibilities for a solar heat pump system i.e.

i- SHP/Parallel
ii- SHP/Parallel, Series
iii- SHP/Parallel, Series, Regenerative
iv- SHP/Parallel, Regenerative
v- SHP/Series
vi- SHP/Series, Regenerative
vii- SHP/Regenerative

The combination that is analyzed in this thesis can be classified under the SHP/Series, Regenerative approach although the SHP system is also used for cooling purposes which might result in a difference in system visualization. System visualization is also very important to correctly understand the interaction between different components which is discussed in section 2.1.2.

2.1.2. Visualization Scheme

An example of visualization scheme devised by the authors of [37] is shown in Figure 5:

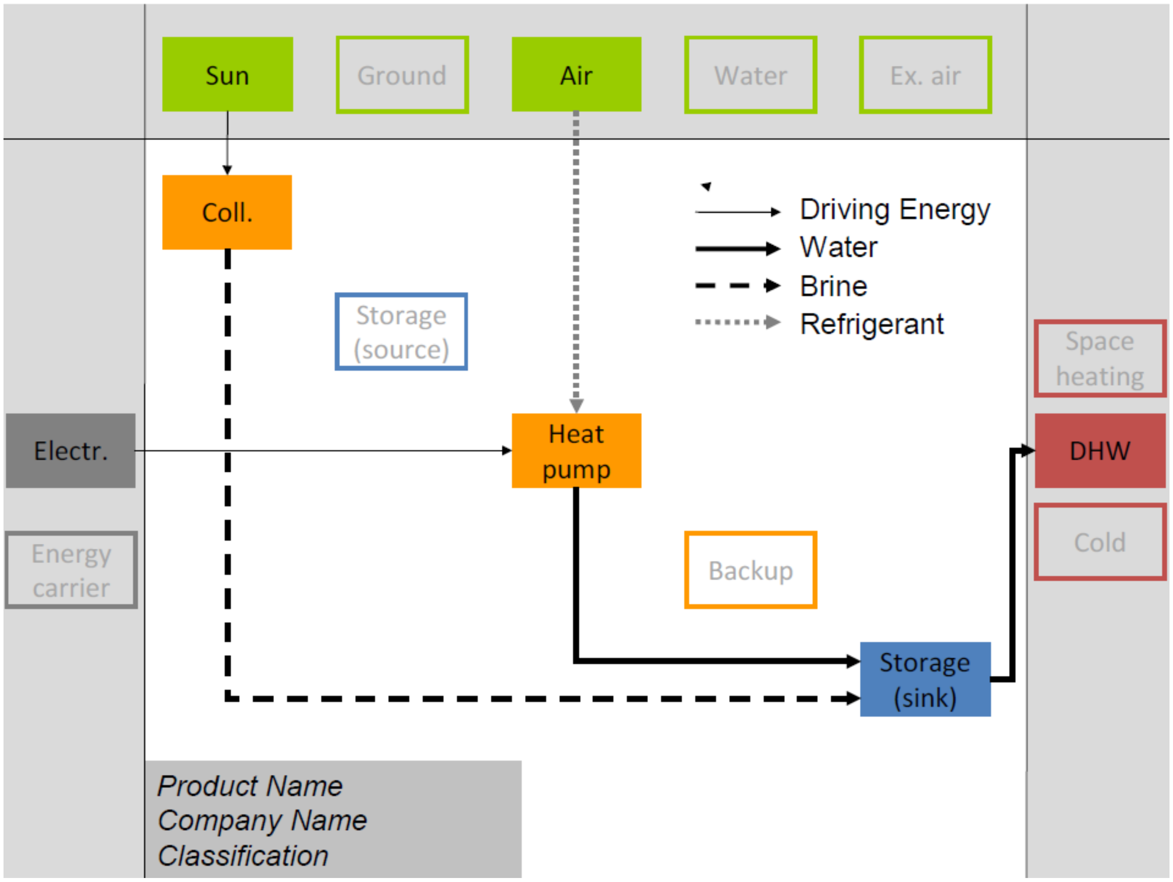


Figure 5: Visualization scheme described in [37]

The scheme can be interpreted in the following way as defined by the authors in[37]:

- Heating/Cooling system represented centrally against white background
- Energy-storing components (blue objects)
- Energy-transforming components (orange objects)
- Five recurring components: collector, heat pump, and backup heater, complemented by storages, on the source and the sink side of the heat pump.
- Defined boundaries (gray background)

- Environmental energy (green objects) enters the system from above
- Final energy – from the left side (dark gray objects)
- Useful energy such as DHW leaves to the right (red objects)
- Energy flows connecting the components are differentiated using distinctive line style based on carrier medium such as brine, water etc.

2.1.3. SHP Ice Storage System

The interactions between solar thermal collectors, heat pump and ice storage are generally classified under SHP/Parallel, Series, Regenerative due to variety of option available to use as source/sink for heating and cooling operation which also makes this type of system complex and difficult to analyze.

In general, ice storage and solar collectors serve as a heat source (or in case of cooling sink) for the heat pump. In case of ice storage, it also serves as seasonal thermal energy storage due to its ability to store heat in both latent and sensitive forms. The term “regeneration” is used for storages and in this case, ice storage is regenerated via two sources i.e. solar collectors and ground. Excess energy from the solar collector when it is not used directly as a source for heat pump can be used to regenerate ice storage. Not only this, it will also result in increase in performance efficiency for solar collector i.e. maximum utilization of collectors in system operation, which is very much desirable in case of solar thermal collectors. On the other hand, as the ice storages are usually not insulated, it can use the ground around it as a heat source especially during winters when the temperature of ice storage is lower than the surrounding ground. In case, when there is not enough heat provided by the solar collectors, ice storage can assist the heat pump in its heating operation. Similarly, when heat pump is used for cooling operation, at first ice storage should be used as a heat sink until its maximum capacity, only then collectors should be used as a sink and to release the heat out of the system. This provides very flexibility of operation for the heat pump but at the same time, difficult to devise a control strategy for the system. By using this combination, it is possible to extract both sensible and latent heat from the ice storage which is done using heat exchangers through which a brine medium heat transfer fluid flows which extract/dump energy from/into the ice storage.

2.2. Components of SHP Ice Storage System

This section is primarily based on the third chapter of [4].

2.2.1. Solar Thermal Collector

Solar radiation can be used as a heat source for space heating and domestic hot water using solar thermal collectors. Solar collectors can be used in combination with heat pumps to supply heat as discussed in the first chapter. There are different types of collectors available in the market for which mainly the differentiating feature is the presence or absence of a transparent cover. There are covered and unglazed collectors (or wind and infrared sensitive collectors), both of which have different performance characteristics such as shown in figure below.

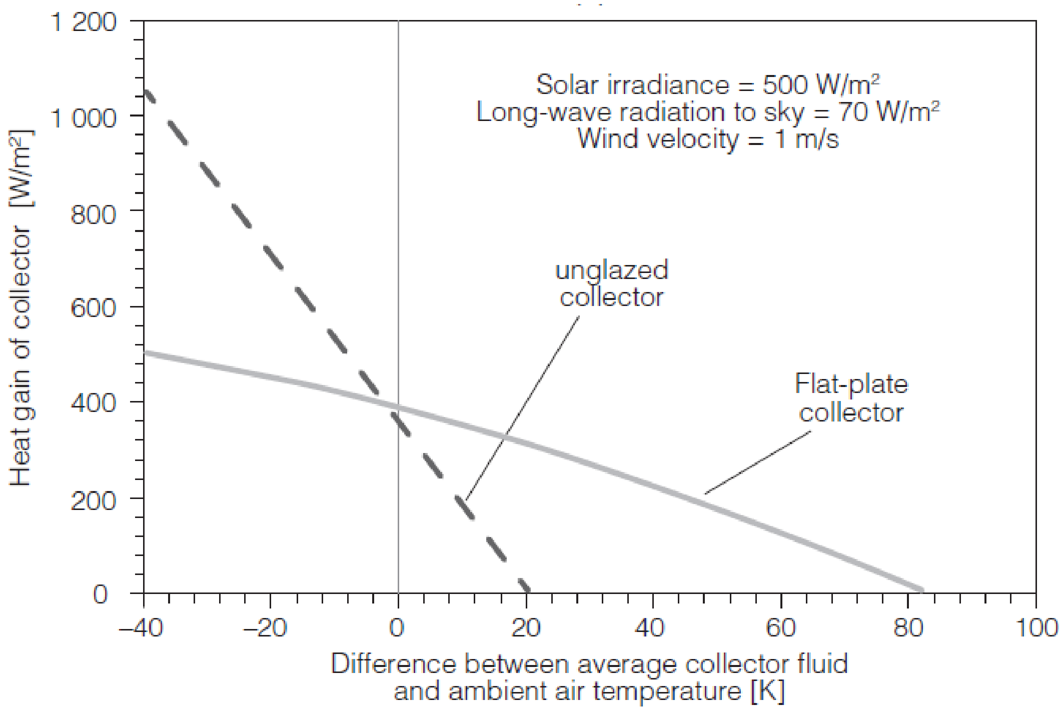


Figure 6: Performance of collectors under different conditions [4]

For our case, operation of unglazed collectors is of more interest as the system analyzed in this thesis also uses unglazed solar collectors. These collectors in combination with heat pump or ice storage can also be used as air heat exchangers even when solar irradiation is absent or during night. Although this type of collectors is usually used for swimming pool heating but due to their high thermal performance owing to larger solar gains at temperature levels close to ambient air temperature and high convective heat exchange with ambient air, they are useful in specific applications such as in this case with an ice storage. An energy balance defined for unglazed collectors that adapts classical collector energy balance with heat flows at low temperature conditions is provided by [4] shown in Figure 7 and described in Equation 1.

The possible heat gains consist of the absorbed shortwave solar radiation $Q_{rad,S}$, longwave radiation exchange $Q_{rad,L}$, convective heat exchange with the air (split into sensible heat exchange $Q_{amb,sens}$ and latent heat exchange $Q_{amb,lat}$), heat conduction Q_k (usually at the rear side), and energy gains from rain Q_{rain}.

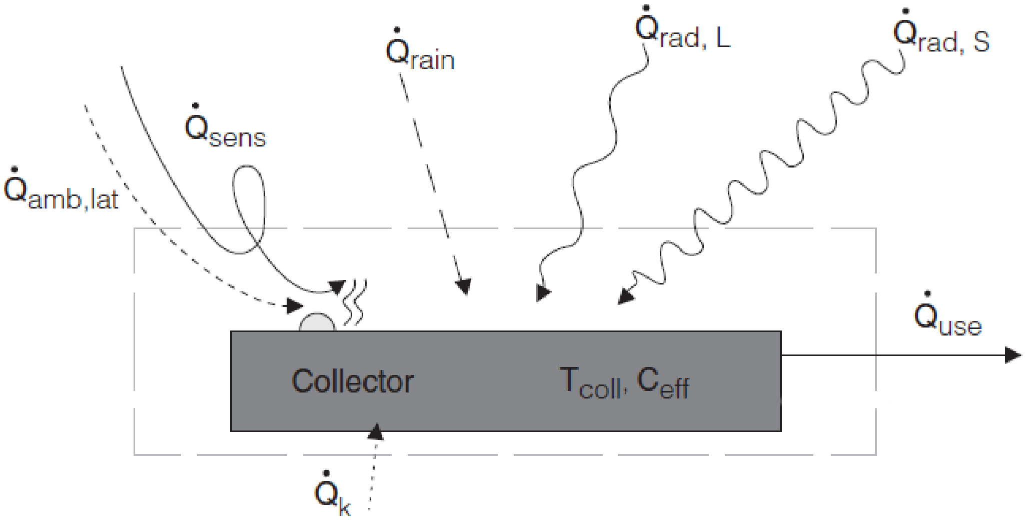


Figure 7: Energy balance for unglazed collector [4]

$$\frac{\dot{Q}gain}{Acoll} = \dot{Q}rad, S + \dot{Q}rad, L + \dot{Q}amb, sens + \dot{Q}amb, lat + \dot{Q}k + \dot{Q}rain \qquad (1)$$

The influence of wind on the convective heat and mass transfer coefficients of the absorber is a frequently discussed topic because of uncertainties involved in this concept. A range of different mathematical models exists both for the estimation of the effect of local wind speed on the convective heat transfer and for the estimation of local wind speed based on meteorological wind speed also presented in [38].

2.2.2. Heat Pump

Heat pumps are machines based on vapor compression refrigeration cycle which can extract heat from source to deliver it to the sink. The term heat pump is generally used when heat from the environment at a low temperature level is extracted by the heat pump and is delivered to a higher temperature level sink. The reversible heat pumps can perform both heating and cooling operations generally due to inter-switch ability of evaporative and condensating heat exchanger. In order to drive the heat pump process, a high exergy source is required which is electricity that is used to drive the compressor in the refrigeration cycle. The concept of a heat pump is shown in Figure 8.

The energy balance of a heat pump process given in [4]:

$$\mathring{Q}sink = \mathring{Q}source + Pel, comp \tag{2}$$

Where $\dot{Q}_{sink}$ is the useful heat output from the condenser, $\dot{Q}_{source}$ is the heat input into the evaporator, and $P_{el,comp}$ is the electric power needed to drive the compressor.

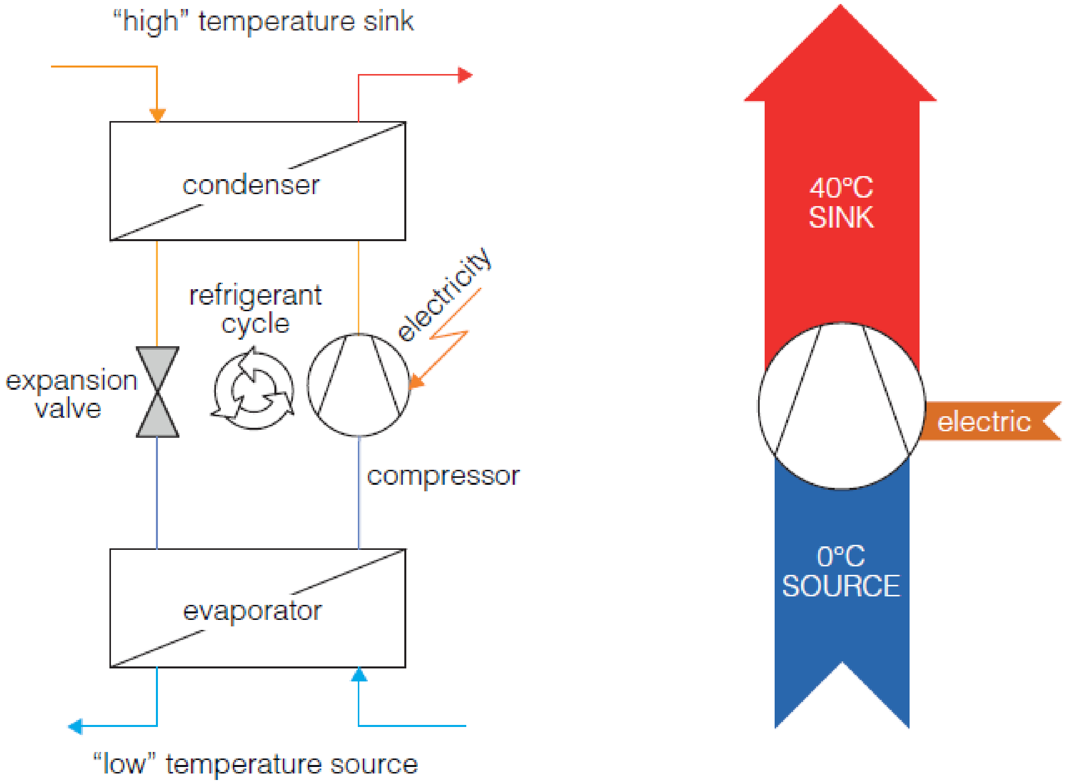


Figure 8: Refereigertion cycle for heat pump [4]

2.2.3. Ice Storage

Ice storages are water filled tanks with special heat exchangers designed to extract and dump heat that can be stored in the form of sensible or latent heat. The phase change process (solid–liquid and liquid–solid) of ice at 0° C enables it to store heat in the form of latent thermal energy. This means that the heat is stored at constant temperature. In case of freezing the water in ice storage, a high amount of heat can be extracted. Theoretically 333 kJ (0.093 kWh) per kilogram of water of heat is released during this cooling process. Compared to that, using the sensible heat of water at temperatures above 0 °C, 4.19 kJ/(kg K) or 0.001 kWh/(kg K) can be extracted. It can be deduced that by freezing 1 kg of water the same amount of heat is released as by cooling 1 kg of water from approximately 80 °C to 0 °C. This process can be easily understood via graphical explanation by [39] in the following figure:

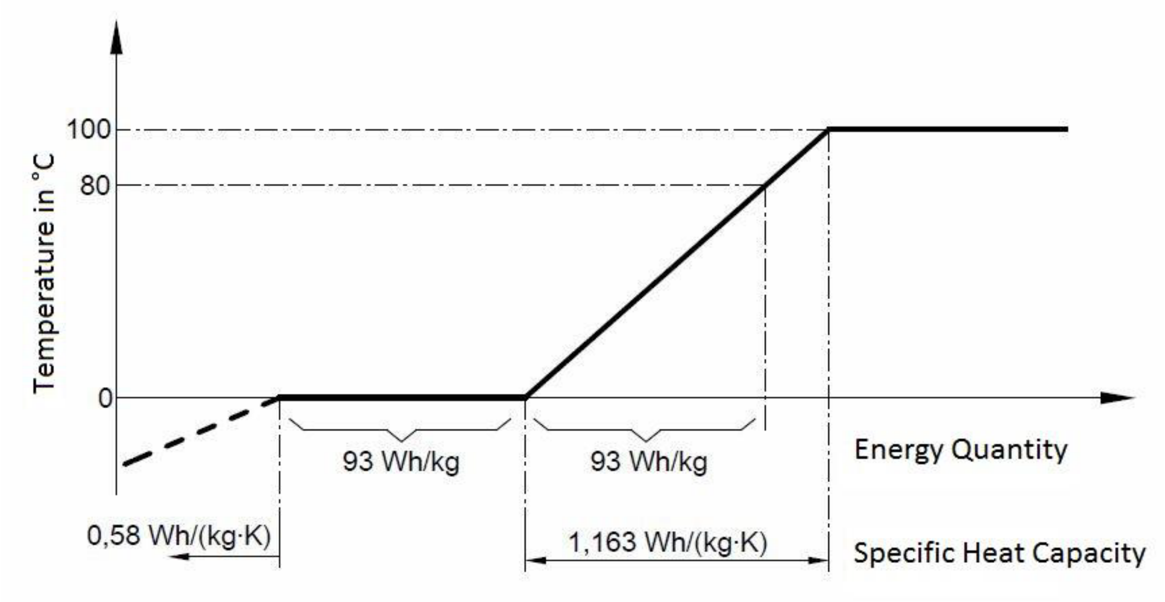


Figure 9: Phase change behavior of ice [39]

Ice storages are used in combination with heat pumps and solar collectors in order to overcome the fluctuation and mismatch between heat production and heat consumption. It is the only phase change latent heat thermal energy storage technology that is commercially available in the market with validated economic benefits for HVAC systems [4].

Usually, the ice storages are steel-reinforced concrete containers implanted in the ground. In case of coil type heat exchangers, which is mostly used in commercial systems, two heat exchangers are used, one for extraction of heat and the other for regeneration of the ice storage. The extraction heat exchanger is usually at the center while the regeneration heat exchanger is at outer circumference of the ice storage. This means that the water in ice storage is frozen from inside to outside and being melted from outside to inside.

2.3. Key Performance Indicators

Generally, the performance of any energy conversion system for heating or cooling application such as in the case of solar and heat pump system is often equated with its efficiency, whereas this efficiency is usually a number without any reference to operating conditions or system boundaries used to calculate this number. This implies that performance of a system can be described as a larger concept that include operation of a particular system defined within certain system boundaries for a specified time period. This system performance can aid the process of optimization of a particular system both at component and system level.

Performance indicators in the case of solar heat pump systems can be defined both at the component and system level and a range of different standards are available which define performance indicators in different manners but a comprehensive nomenclature system for different performance indicators was defined within the Task 44 Annex 38 [4]. Some of the key performance indicators (KPI's) for heat pumps, solar collectors separately and for the system will be defined in the following section. However, there aren't many separate or special performance indicators, defined for the ice storage in particular in the Task 44 Annex 38 and also in the relevant literature. Moreover, the KPI's defined for systems with ice storages in literature are mostly dealing with heating operation only and usually more relevant to the performance of heat pumps. Therefore, this gives an opportunity for the author of this thesis to develop key performance indicators for ice storage as well as for cooling operation of SHP-Ice Storage system. In the following sections definition for different performance indicators will be described in detail.

2.3.1. Component performance figures

2.3.1.3. Heat Pump

i. Seasonal Performance Factor (SPF_{HP})

[4] defined the SHP_{HP} of the heat pump as the ratio between heating and cooling done by a heat pump and the overall electricity consumption, both measured under steady-state operating conditions. The system boundary for the energy balancing corresponds to boundary of Heat Pump. Hence, the SPF_{HP} can be calculated as:

$$SPF_{\mathrm{HP}} = \frac{Q_{HP}}{Q_{el,HP}} \tag{3}$$

Where, Q_{HP} is the thermal energy output of the heat pump and $Q_{el,HP}$ is the electrical energy input to the heat pump. The block diagram explaining the boundary conditions is shown in the following figure:

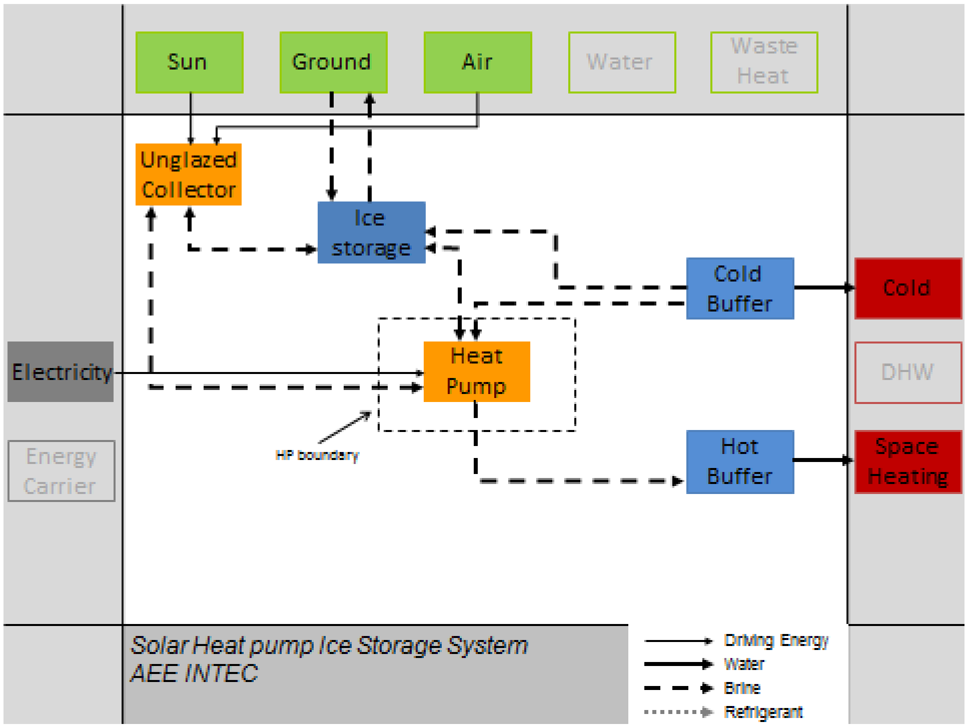


Figure 10: Boundary conditions for calculating SHP for heat pump

2.3.1.4.Solar Collector

i. Solar Fraction

According to standards EN 12976, EN 12977, solar fraction can be defined as the ratio of energy supplied by the solar collectors to the total system load. This definition has to be further modified based on the usage for heating or cooling application. The authors in [4] generally presented this definition mainly for heating applications such as space heating and DHW but for the case analyzed in this thesis, this definition has to be modified for cooling application using the solar collectors. Thus, solar fraction is defined in two ways so it fits the need of the analysis by giving the right parameter i.e. solar fraction responsible for the regeneration of ice storage and solar fraction used as for heating mode:

$$f_{sol,regen} = \frac{Q_{\text{solar regeneration}}}{\sum Q_{solar}} \tag{4}$$

Where $Q_{\text{solar regeneration}}$ is the energy input by the solar collectors into the ice storage during regeneration operation while $\sum Q_{solar}$ is the sum of solar energy inputs during natural cooling and active cooling via ice storage modes. Another interesting parameter that can be of interest regarding utilization of waste heat is calculating the ratio of the amount of heat that is input into the collector during active cooling mode to the total heat output during all active cooling modes. This performance indicator will determine the amount of heat dumped into the air while the rest was stored in the system. Mathematical expression for this performance indicator is following:

$$f_{waste\ heat} = \frac{Q_{activecoolingviaSolar}}{\sum Q_{activecooling}} \tag{5}$$

2.3.1.5.Ice Storage

For Ice storages, the literature available does not define any specific key performance indicators that can serve as reference for judging the performance of the ice storage analyzed in this thesis. Therefore, the author of this thesis took up the task to develop and enlist KPI's for analyzing the performance of the ice storage and can serve as basis for any future work.

i. Energy density

Energy density is usually calculated for thermal energy storages in order to evaluate their performance and compare it with other technologies available. It is defined as the energy that can be stored or absorbed by the storage per unit volume of the storage available. Energy stored in ice storage can be calculated using equation used by [40].

$$Q_{\text{storage capacity}} = \int_{T_{\text{i}}}^{T_{\text{m}}} mC_{\text{p}}\, dT + ma_{\text{m}}\Delta h_{\text{m}} + \int_{T_m}^{T_f} mC_p\, dT \tag{6}$$

Where, m is the mass of water, C_p is the specific heat of water, m_{am} is the mass of water melted and Δh_m is the latent heat of melting. Dividing this equation by the volume of water inside the storage gives the energy density for the energy storage. Although, ice storages might not have as high storage densities as other Latent heat technologies but it is the only technology that is commercially available while rest are still in research and development phase.

ii. Utilization of storage capacity

The utilization of storage (UC) capacity of thermal energy storage is defined as the energy stored divided by the total thermal storage capacity of a storage both for latent and sensible heat. The result will be a dimensionless number which will help to some extent in answering questions like is the storage optimally sized according to the system and indicate to what extent the storage capacity is used. This can also help in determining whether the storage is over or under designed for the system.

$$UC = \frac{Q_{\text{stored}}}{Q_{\text{storage capacity}}} \tag{7}$$

2.3.2. System Performance Indicators

2.3.2.1.Seasonal Performance Factor (SPF_{sys})

IEA SHC Task44 defines SPF as the overall useful energy output to the overall driving final energy. This gives the final energy efficiency of the whole system or a defined subsystem. This factor can be defined as performance of a system over a year or a season i.e. heating or cooling season. The same definition can also be used for shorter time periods, such as a week or a month, but a different nomenclature for the figure has to be used. This can be mathematically represented as following:

$$SPF_{\text{sys}} = \frac{\int \left(\dot{Q}_{\text{H}} + \dot{Q}_{\text{C}}\right) dt}{\int \Sigma Pel\, dt} \tag{8}$$

Where, $\dot{Q}_H$ is the useful heating output, $\dot{Q}_C$ is the useful cooling input and P_{el} is the final electrical energy input. It should be noted that positive values for $\dot{Q}_c$ should be used in equations although it has an opposite algebraic sign to useful heat energy. SPF can also be defined for different operating modes separately indicating the mode in the subscript (e.g., heating only, heating and DHW, cooling etc.)

2.3.2.2.Primary Energy Ratio and CO2 Emissions Reduction

Previously described indicators are more relevant for technical evaluation of the systems. However, with increasing concern about climate change and CO_2 emissions abatement, the environmental impact of systems and technologies must also be evaluated. Some performance evaluation figures were devised by IEA SHC Task 44 and defined in [4] are describe as follows:

i. 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. This performance indicator does not account for production, distribution, installation, and end of life disposal 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_{ue}/kWh_{pe}.

$$PER_{NRE} = \frac{SPF_{\mathrm{sys}}}{CED_{NRE,el}} \tag{9}$$

Where SPF is the seasonal performance factor of the system and $CED_{NRE,el}$ is the non-renewable primary energy used to provide the final energy per unit of electrical kWh, including the energy used for construction of the electric grid and power plants. The numerical reference values for $CED_{NRE,el}$ can be found in [41] and [42].

ii. Equivalent Warming Impact (EWI)

EWI is the ratio of the greenhouse gas emission to the useful energy output of the system. The greenhouse gas emission is expressed as equivalent CO_2 emission for the delivery of the energy carrier on installation site (final energy) and its consumption. Mathematically it can be represented as:

$$EWI = \frac{GWP_{el}}{SPF} \tag{10}$$

Where GWP_{el} is global warming potential, which is weighted addition of the emission of different greenhouse gases when providing final energy, including emissions generated during construction of the electric grid and power plants. It does not take into account refrigerant leakage during the system operation. It is expressed in terms of equivalent quantity of carbon dioxide per quantity of final energy (kg CO_2 equiv./kWh_{fe}) for a time frame of 100 years. The numerical reference values for GWP_{el} can be found in [41] and [42].

iii. Fractional CO_2 Emission Savings

The fractional CO_2 emission savings can be calculated using the following equation:

$$f_{sav,pe} = 1 - \frac{\Sigma P_{el,final} \,.\, GWP_{el}}{\left(\dot{Q}_{H} + \dot{Q}_{C}\right) . \, \eta_{ref} . \, GWP_{ref}} \tag{11}$$

Where, η_{ref} is the conversion efficiency of the reference system.

Chapter 3: Plant Design and Components

3.1. 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 centre for Audio Tuning Vertriebs GmbH, just outside of Vienna. The monitoring of this plant is a part of Accompanying Scientific Research program under the Solarthermie –Solare Großanlagen Program initiated by the climate and energy fund under the category of New Technologies and Innovative Approaches. The monitoring period for the current project started in July 2019 and will continue for one year after which results will be published.

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 cuboid shape ice storage and a brine/water heat pump. In addition, there are two buffer storages each one connected to heating and cooling distribution system.

The collectors from Viessmann Eis-Energiespeicher GmbH (Type SLK 600) are installed on the flat roof of the building with an inclination of 5° to the south. These are unglazed collectors specially designed for the use of an ice storage tank. The collectors are currently neither certified according to Solar Keymark nor according to the Austrian Environmental Label. According to ASIC, the collectors are an innovative technology because only polyethylene and aluminium are used as materials and because of their design, expansion and contraction due to heat and cold is not a problem. The performance of the collectors was measured by TÜV Rheinland Energie und Umwelt GmbH in accordance with DIN EN 12975. With regard to the functional and practical suitability, it should be noted that this has already been proven with smaller systems.

According to ASIC, the innovative content of the present project lies in the use of geothermal energy and stored solar energy as a source for a heat pump and the realisation of a seasonal storage tank as well as the special arrangement of the heat exchangers in the ice storage tank, so that there is no explosive effect on the tank walls. Furthermore, there is multiple use of the collector field (air absorber without solar radiation, heat sink in summer operation for recooling the cooling energy from the building) and no expansion vessels and safety groups in the solar circuit are necessary (no stagnation).

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 as shown in Figure 12. 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 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 (Figure 13). 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 14, includes all the individual system components, eight heat meters installed and nine different valves.

Figure 11: Project Site

Figure 12: Solar Unglazed Collectors (Source: Audio Tuning Vertriebs GmbH)

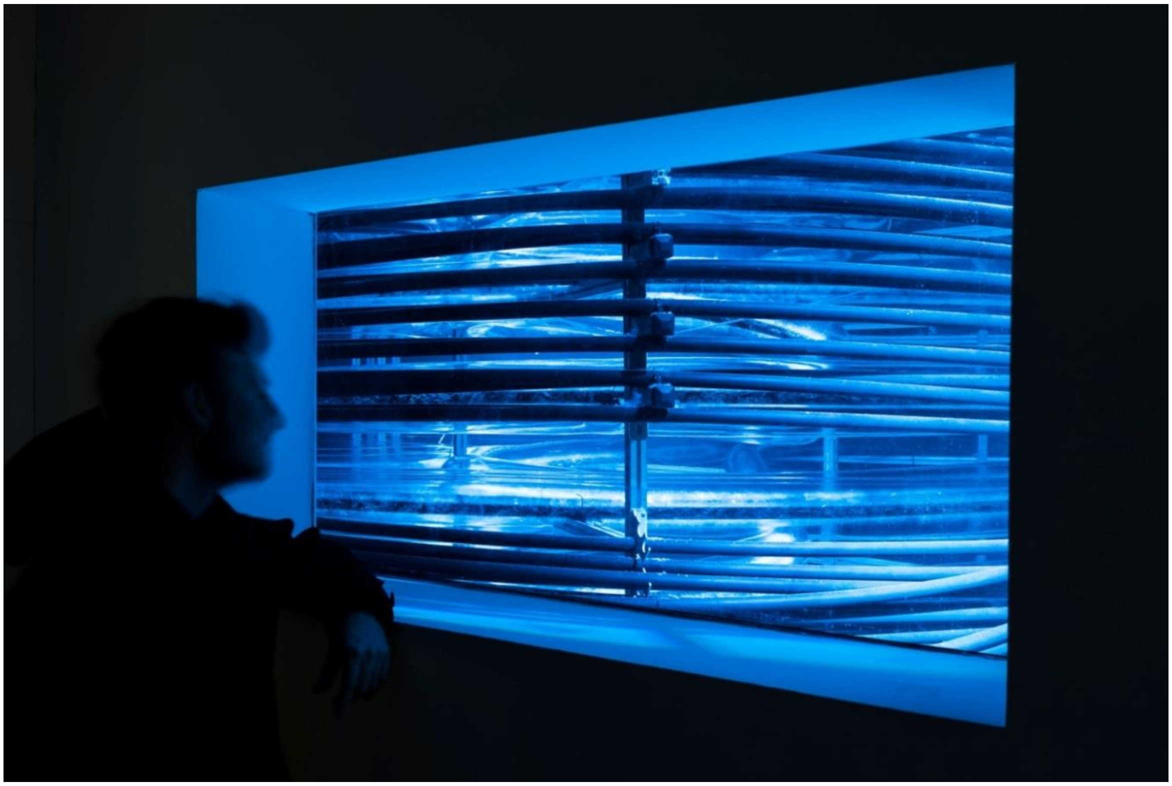


Figure 13: Ice Storage Regeneration Heat Exchangers (Source: Audio Tuning Vertriebs GmbH)

3.2. Hydraulics and Monitoring Procedure

The hydraulic scheme of the plant shown in Figure 14: Schematic Diagram of SHP Ice Storage System is a simplified scheme which represents the general layout of the plant and helpful in understanding the operational procedure. There are nine different valves used in different combinations that result in different operation modes for both heating and cooling operations that will be described later in this chapter. The schematic diagram also shows estimated position of eight heat meters that were used to measure temperature, flow rate, power and energy at different positions in order to do complete analysis of the plant. The translation from German to English for each component defined in the legend is given in the Nomenclature. For instance, Q_{sol} measures the described parameters for the solar circuit i.e. temperature, flow rate, power, and energy going in or out of the solar collector. The monitoring period for this plant started in July 2019 and will continue for one year. The monitoring data was acquired directly from the plant by the monitoring department of AEE INTEC which was necessary for impartial analysis of the plant.

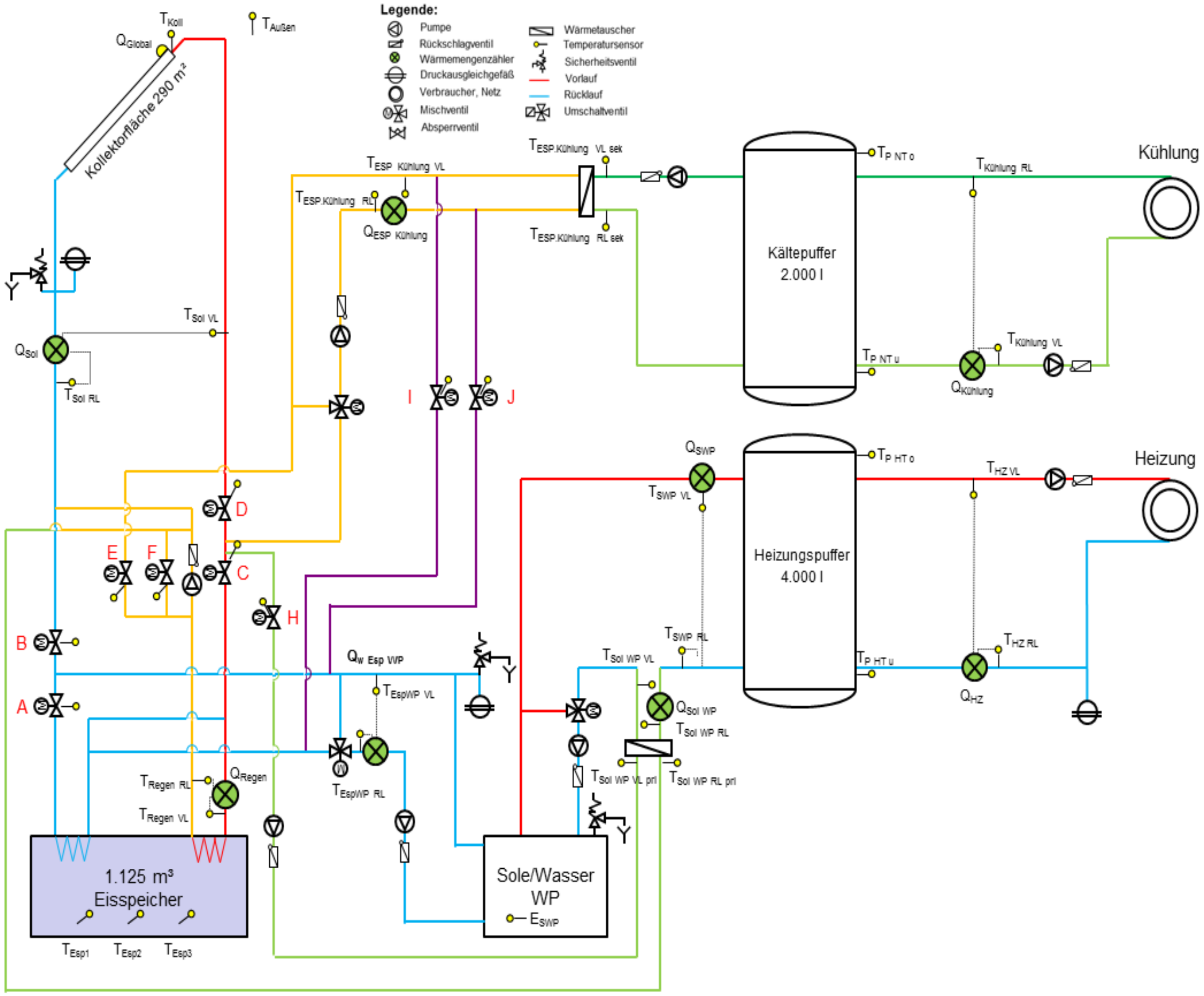


Figure 14: Schematic Diagram of SHP Ice Storage System

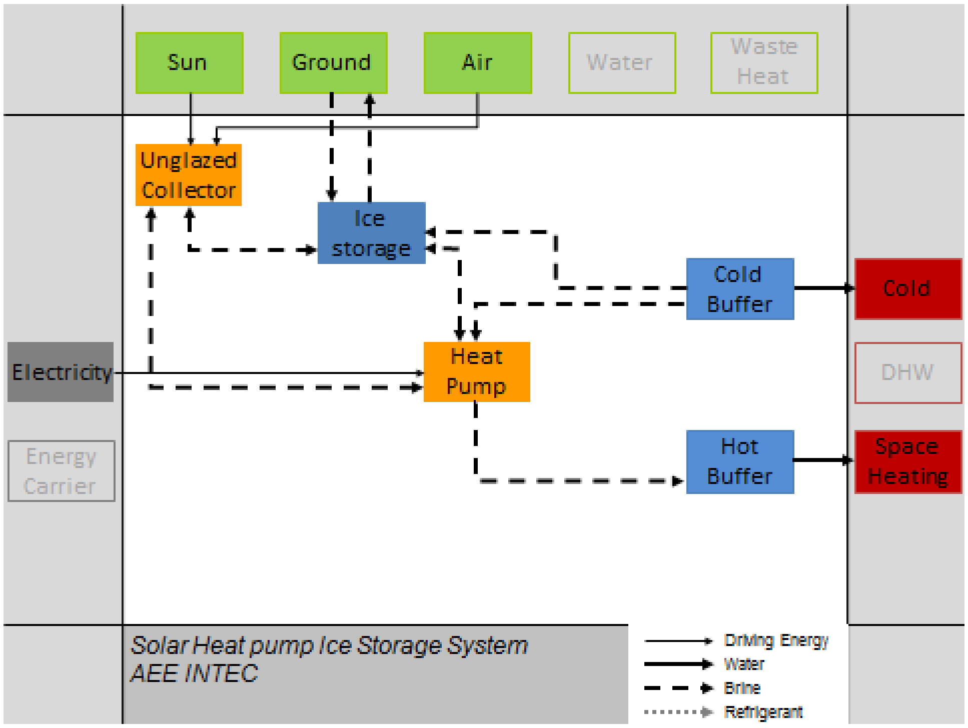


Figure 15: Schematic Representation of the System According to T44A38

3.3. Modes of Operation

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.

3.3.1. Solar Heating Mode:

Solar heating mode is one of the two heating modes, which use heat from the solar absorber/collector as a source for the Heat pump evaporator. This mode generally holds preference over other heating mode usually because it is one of the main components of this solar heat pump system. During this mode, valves B, C and D are open to allow flow of hot HTF to the heat pump to be supplied by the heat pump to the hot buffer which acts as the supplier of heat to the system.

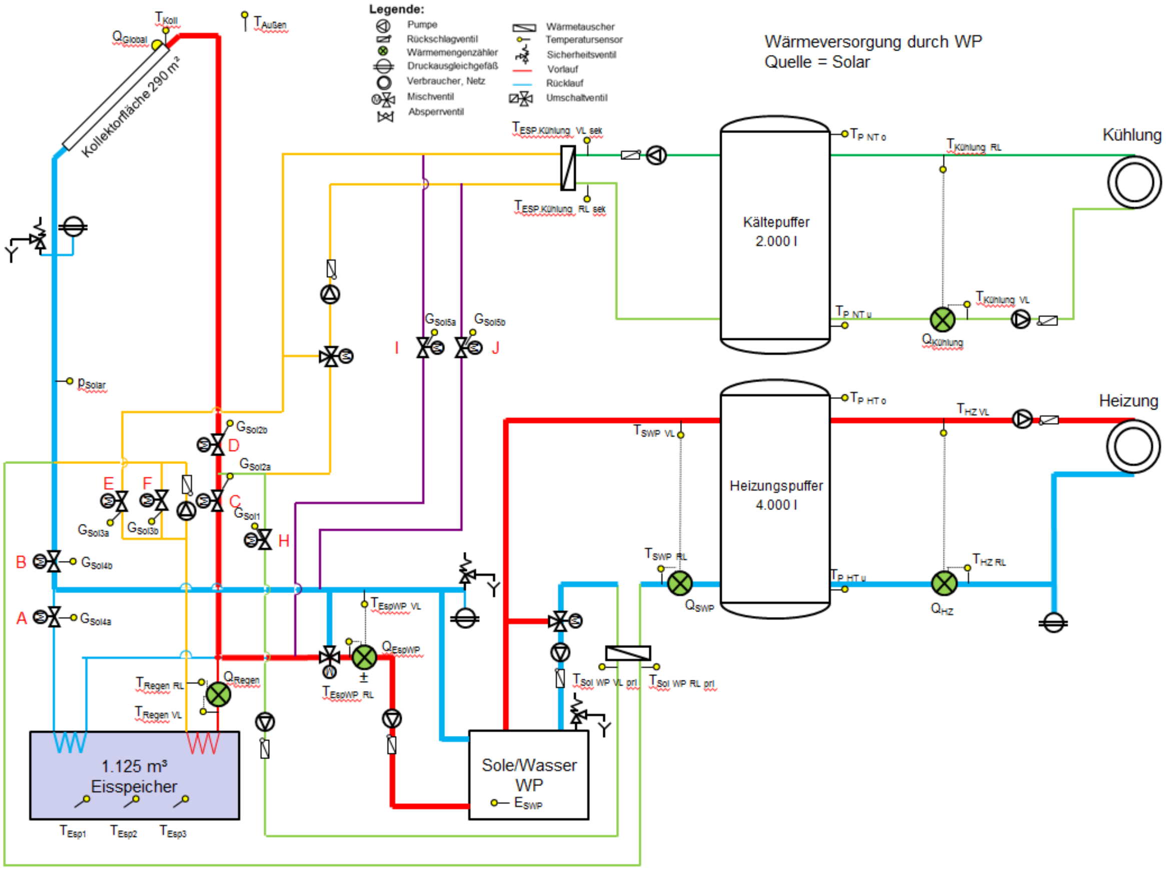


Figure 16: Solar heating mode

3.3.2. Ice Storage Heating Mode:

At the end of summer season, the ice storage is charged with considerably higher temperature to serve as a heat source for the heat pump. When the solar collectors are not able to provide sufficient heat to the heat pump either because of low irradiation or low temperatures outside, the building management system turns on the Ice Storage heating mode. Only valve A is open during this mode and all other valves are closed in order to smoothly run the heating operation and avoid mixing. Heat extracted from the ice storage is used as a source for evaporator of the heat pump and supplied to the hot buffer which acts as a buffer to the supply system for heating. The extraction heat exchanger which is present in the center of the ice storage is used for heat extraction which means that the water is being frozen inside to outside which is a special feature of this ice storage.

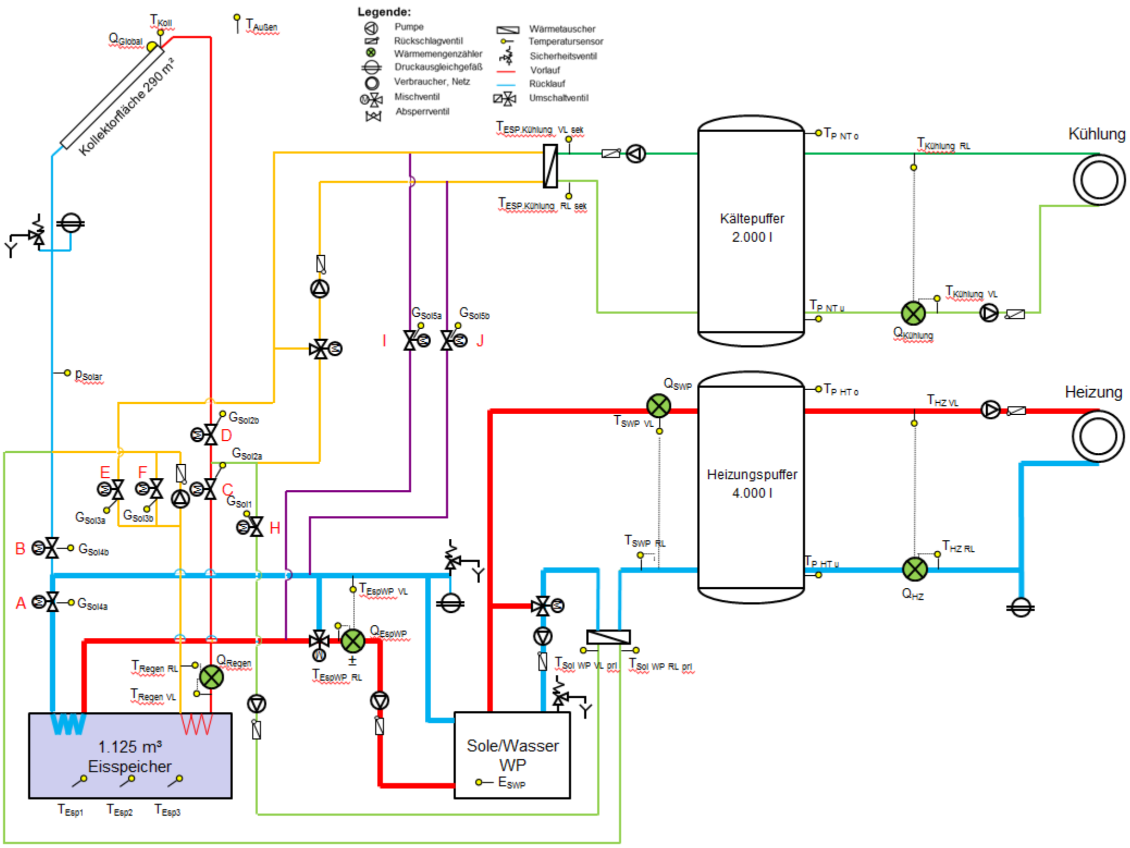


Figure 17: Ice Storage heating mode

3.3.3. Natural Cooling (Ice Storage Direct Cooling Mode):

This is one of the primary cooling modes, which directly use the Ice storage as a source for cooling without any input from the heat pump. Ice storage is overwhelmingly charged with ice or cooling energy by the end of winter season as energy in the form of heat is extracted by the heat pump during the Entzugsbetrieb mode that leads to freezing of water to ice. Moreover, regenerative heat exchanger of the ice storage is used during this operation to supply the cold buffer with cooling energy and dump its heat inside the ice storage. In this way, the ice storage is regenerated from outside to inside as the regenerative heat exchangers is one on the outer circumference of the ice storage. This mode is unique because it does not involve heat pump operation. Valves C and E are open during this mode. Heat exchanger is used to transfer the heat energy from the space that has to be cooled into the Ice storage which in turn is being charged for usage during the winter months. This mode can be operational until the temperature of ice storage raises to a specific temperature which makes the heat transfer very low and this mode ineffective.

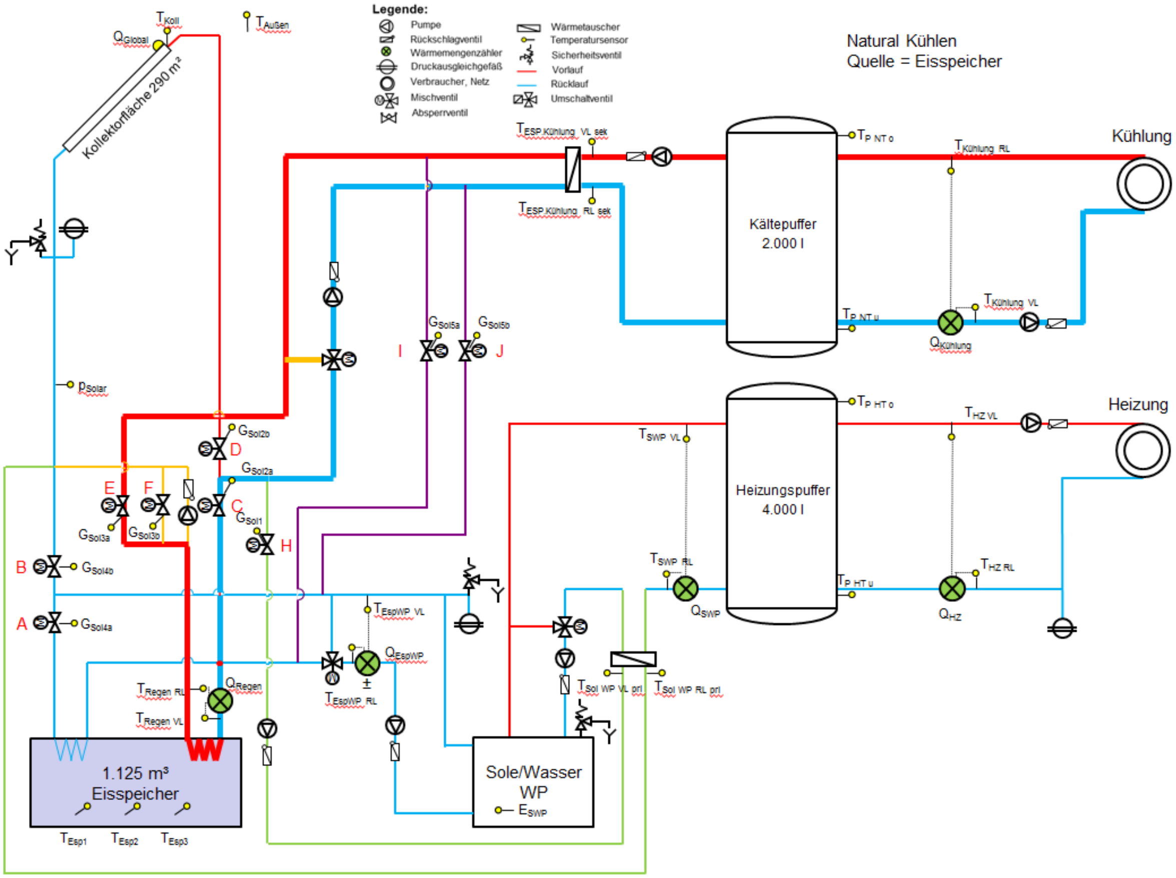


Figure 18: Natural Cooling Mode

3.3.4. AC RW Puffer (Heat Pump Cooling using Heating Buffer as a Heat Sink for the Heat Pump Condenser):

Active cooling involves electrical energy input from the heat pump for the cooling operation. Usually the difference between different active cooling modes is the heat sink for the heat pump condenser. In this case the heat from the cold buffer or kältepuffer is dumped into the heizungpuffer by the heat pump. For the active cooling mode, there are three heat sinks available for the heat pump which in this case is the hot buffer. The logic behind having this mode is to keep the hot buffer charged with heat in case there is any heating needed due to some unexpected cold days during the end of summer season. Valves I and J are open during this mode of operation.

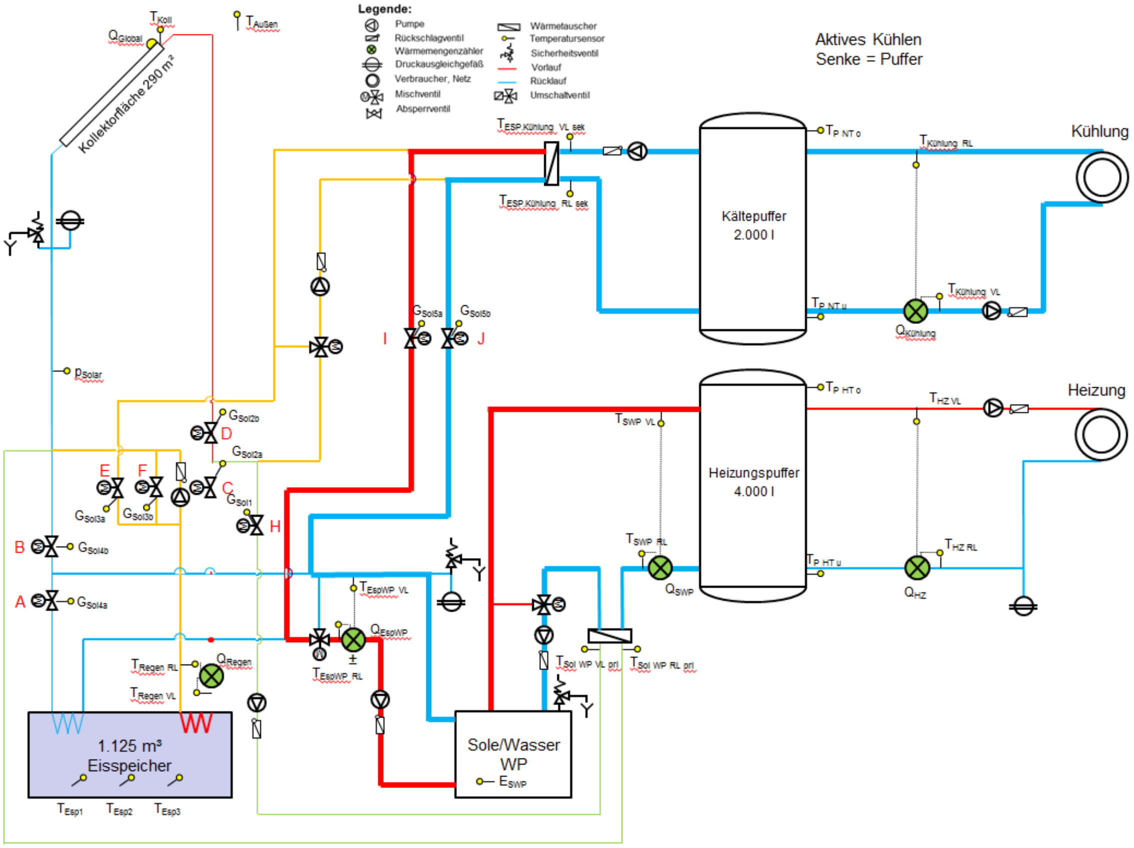


Figure 19: Active Cooling Using Hot Buffer as Sink

3.3.5. AC RW Kollector (Heat Pump Cooling using Solar Collector as a Heat Sink for the Heat Pump Condenser):

This mode is also active cooling mode which involves the solar collectors that serve as the heat sink for the heat pump condenser side. This mode is used when the hot buffer cannot be further charged with heat from the cold buffer so solar collectors in this case behave as air absorbers dissipating heat into the environment. This is one of the reasons for using special type of unglazed solar collectors that also are helpful in getting rid of access heat in the system without over heating of the collector pipes. Valves D and H are open in this case on the sink side of the heat pump while Valves I and J remain open as in other active cooling modes. This mode is usually expected to be operation during the end summer season when natural cooling cannot be done further. Figure below shows the schematic diagram for the operation of this specific mode with the flows highlighted.

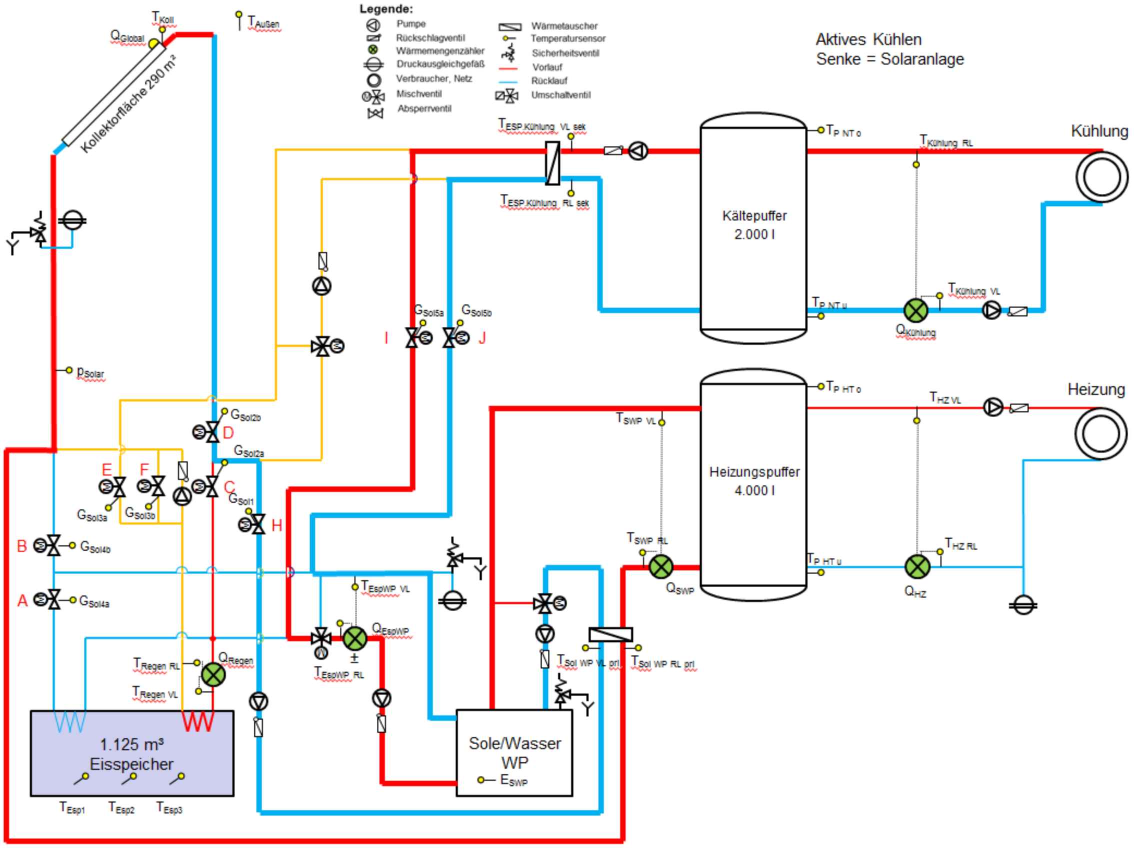


Figure 20: Active Cooling Using Solar Collector as Sink

3.3.6. AC RW EES (Heat Pump Cooling using Ice Storage as a Heat Sink for the Heat Pump Condenser):

This is third type of active cooling mode that uses ice storage as a heat sink for heat pump operation. Usually, Ice storage is used directly for cooling using the natural cooling mode but as the temperature of ice storage increases the heat transfer rate decreases due to decrease in temperature difference between HTF and the temperature of the cold buffer. So, in order to aid this process, heat pump kicks in and uses active cooling to charge up the kältepuffer with cooling energy and ice storage is used as a heat sink again which causes its temperature to rise further which is beneficial as this stored energy can be used later during the winter period for heating purposes. This operation is feasible only up to a certain limit of temperature defined by the manufacturer of the ice storage which put an end to this mode of operation when it decides that the conditions are not suitable for this mode to operate any further. Valves C, F and H are open to enable the connection between the regenerative heat exchanger of the ice storage and the heat pump while valves I and J remain open as for all other active cooling modes.

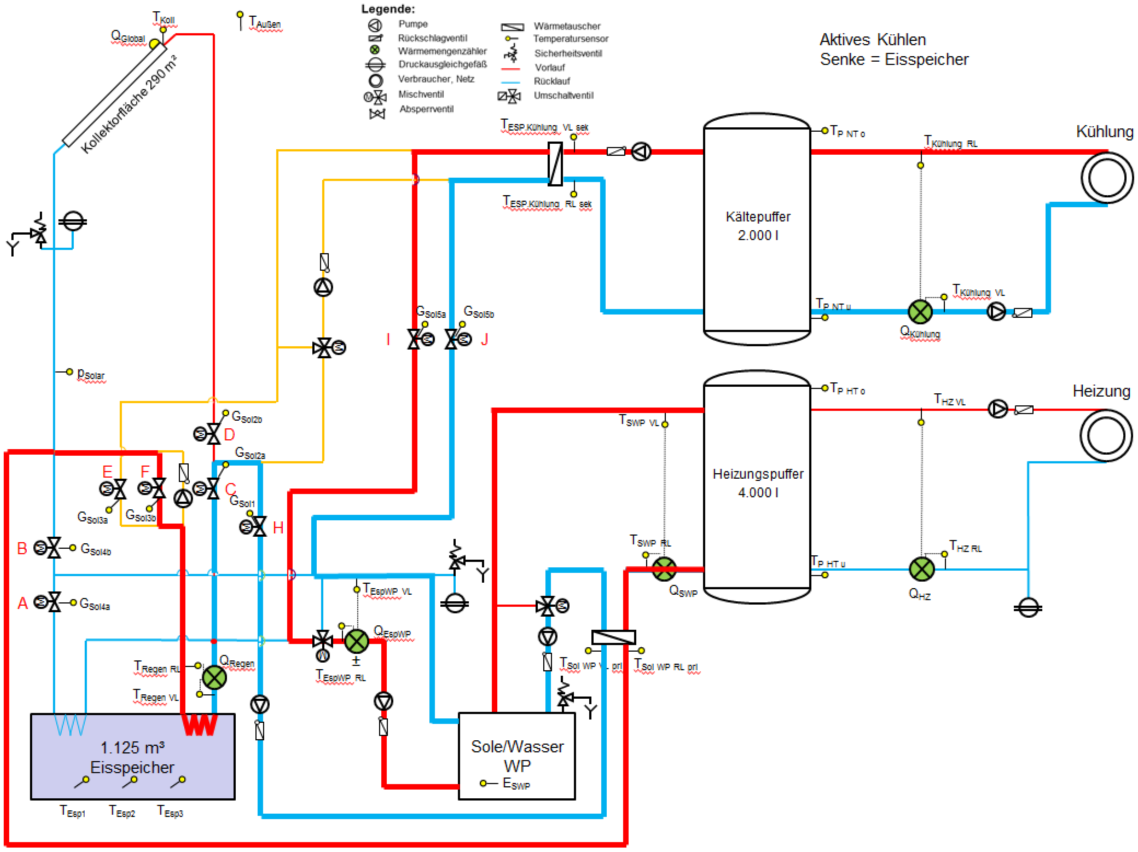


Figure 21: Active Cooling Using Ice Storage as Sink

3.3.7. Regeneration:

This is one of the two special modes used to regenerate heat in the ice storage using solar collectors/absorbers. So heat from the solar absorbers is taken to the ice storage which charges up with heat energy that can be supplied during the heating season. This mode is used in circumstances when ice storage is no further used for cooling purposes at the end of summer season or even during winter season when excess energy is available at the solar collector. During this operation, the ice storage operates like a normal thermal energy storage which is absorbing heat that can be later used when required. It should be noted that this mode is limited by the temperature of the ice storage which should not go above 28 °C as determined by the manufacturer due to compatibility issues with the heat pump and also other design and operational limitations of the ice storage. Valves C and D are open during this mode. Figure below represent the fluid flow in the circuit from solar collector to the ice storage and back.

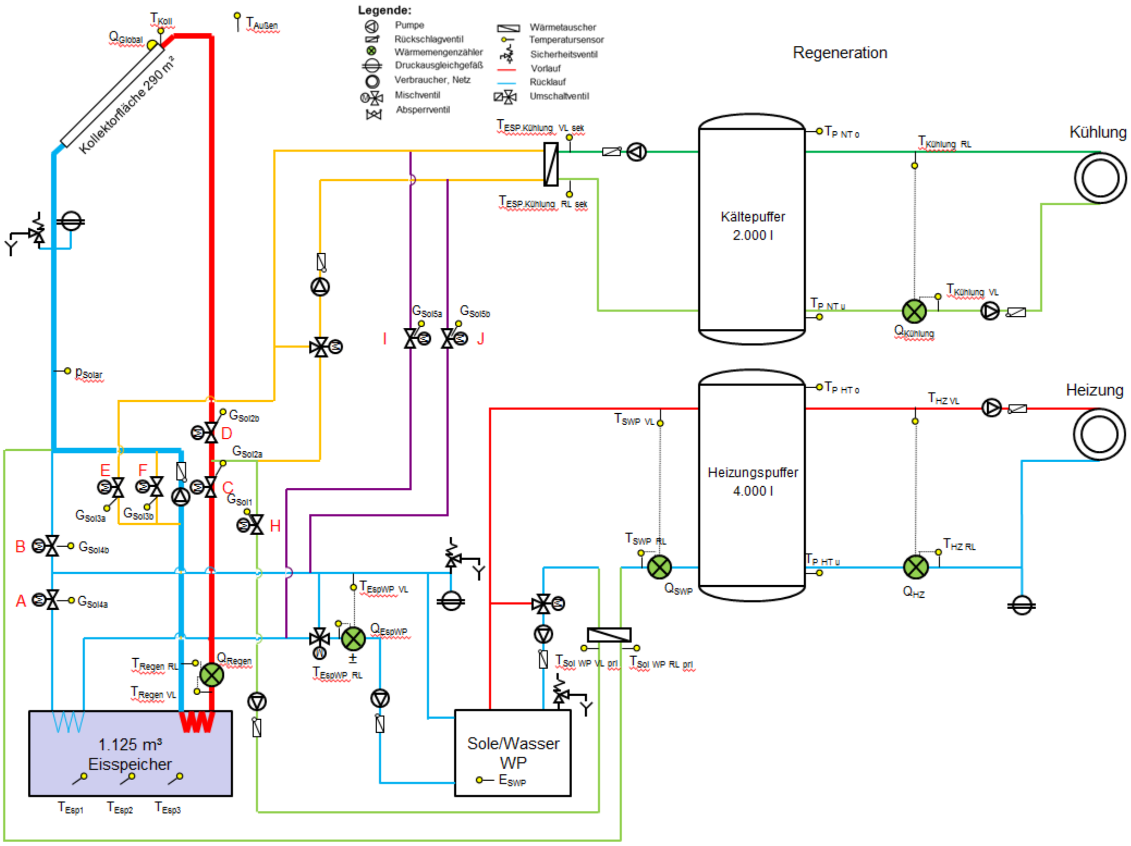


Figure 22: Regeneration Mode

3.3.8. Free Cooling:

Free Cooling is the other special mode of the two which also involve ice storage and the solar collectors/absorbers. The manufacturer of the ice storage system has set a design value for the temperature of the ice storage which is that it should not exceed 28°C. If the the temperature of ice storage must be lowered to keep it under design conditions, this mode is turned on. At night time, when the air temperature outside is lower, the heat from the ice storage is dumped into the air via the solar collectors. This can happen at the end of summer season. This is inverse operation of the regeneration mode in which we cool the absorbers and heat is dumped to the ice storage.

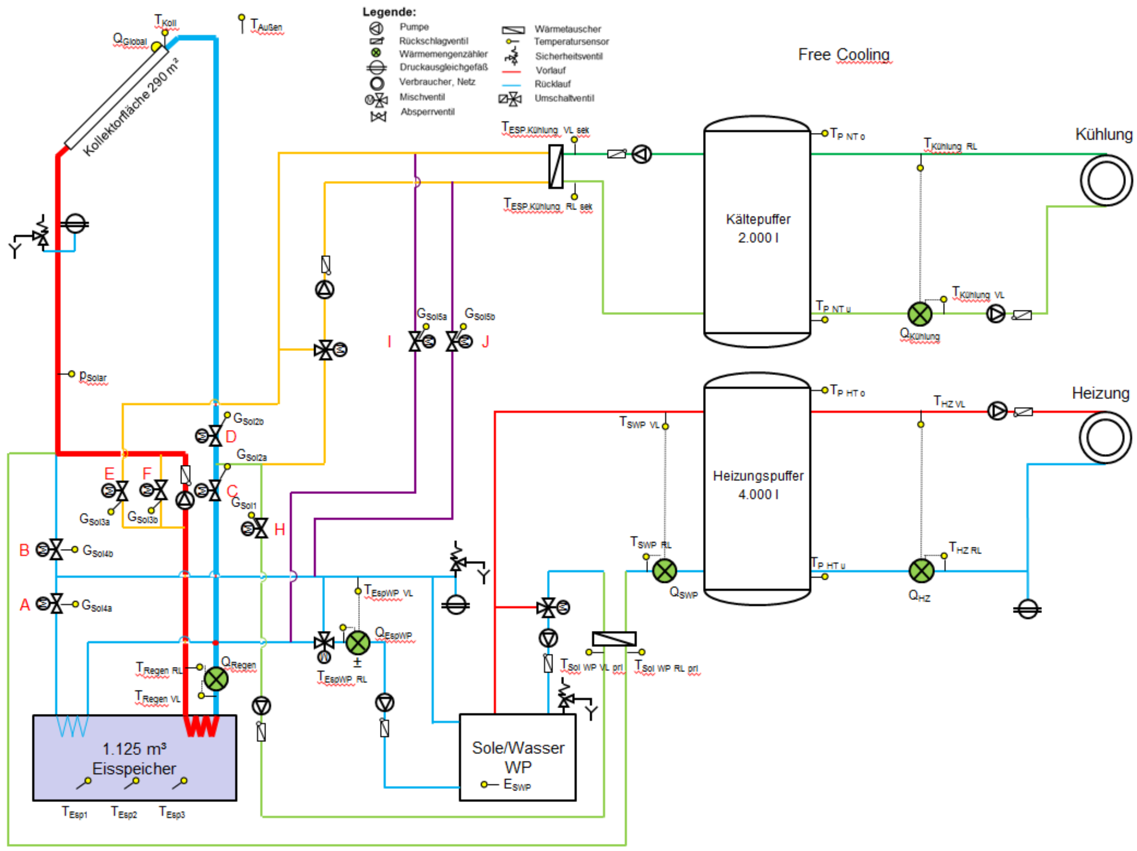


Figure 23: Free Cooling Mode

3.4. 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. Further details about the operation of the plant in different modes will be discussed in the next chapters.

Chapter 4: Results, Analysis & Discussion

4.1. 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 24 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.

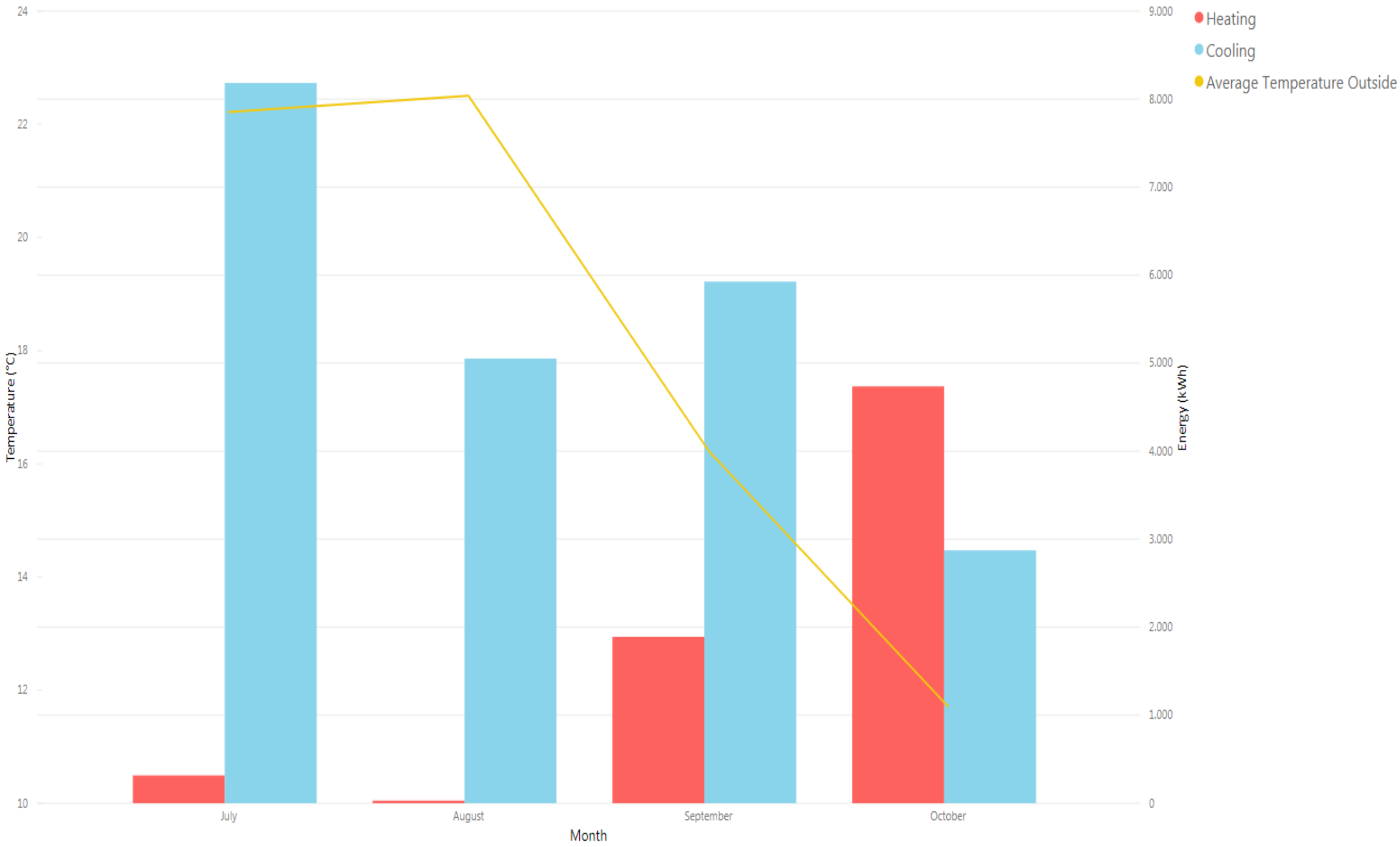


Figure 24: Monthly Heating and Cooling with Mean Outside Temperature

By the start of September, the outside temperature started to fall and there was a need for heating which increased in the start of October till the end of the analysis period within the scope of this thesis. It is observed that during the month of July and August, the outside temperature is comparatively higher due to which there is an increased cooling demand. While at the end of the analysis period, the heating demand increased due to lower temperatures outside. There are few instance of cooling even during September and October due to higher temperature outside. During the Months of July and August, the cooling system was in full operation. However, there were two instances when the cooling system was turned off and there was no supply on the source side of the cold buffer. The temperature in the cold buffer increased sharply to above 25 °C. It is assumed that the cooling system for the building was turned off due to holidays at both the instances.

Moreover, as mentioned in the previous chapter, 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.

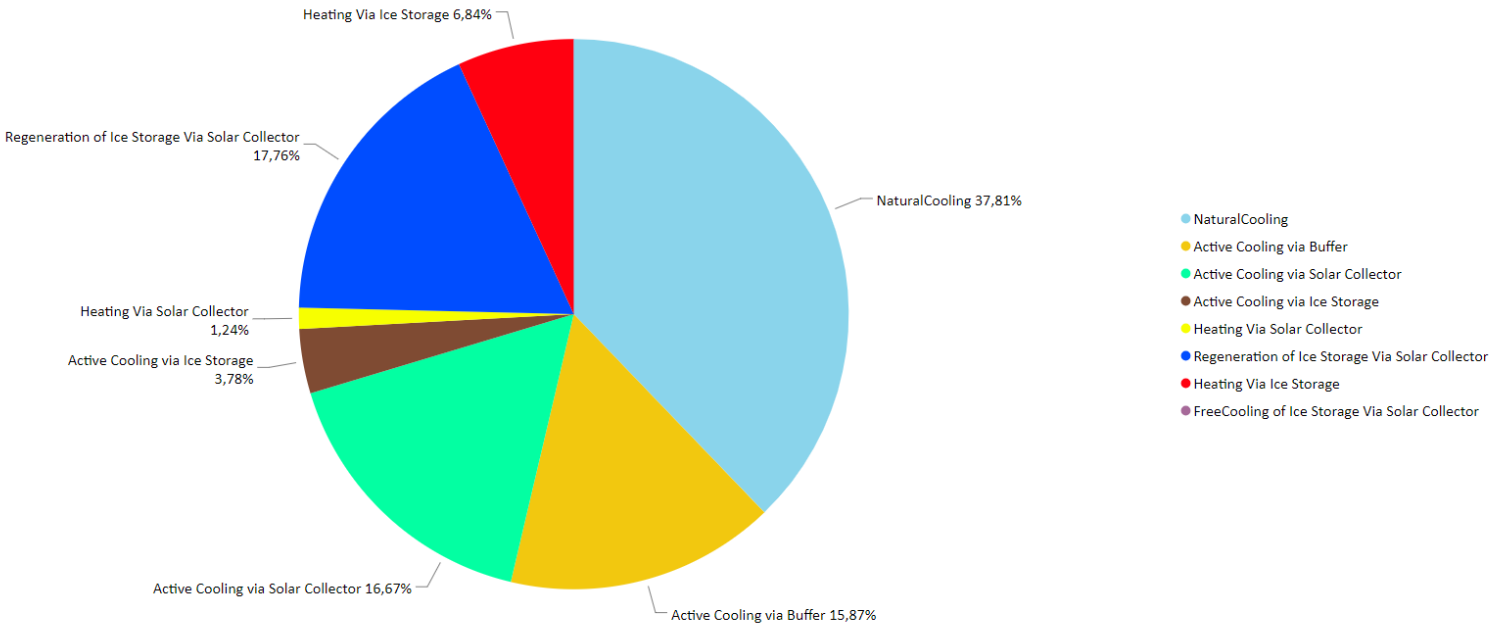


Figure 25: Different Operational Modes

Figure 25 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.

4.2. 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 26, 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.

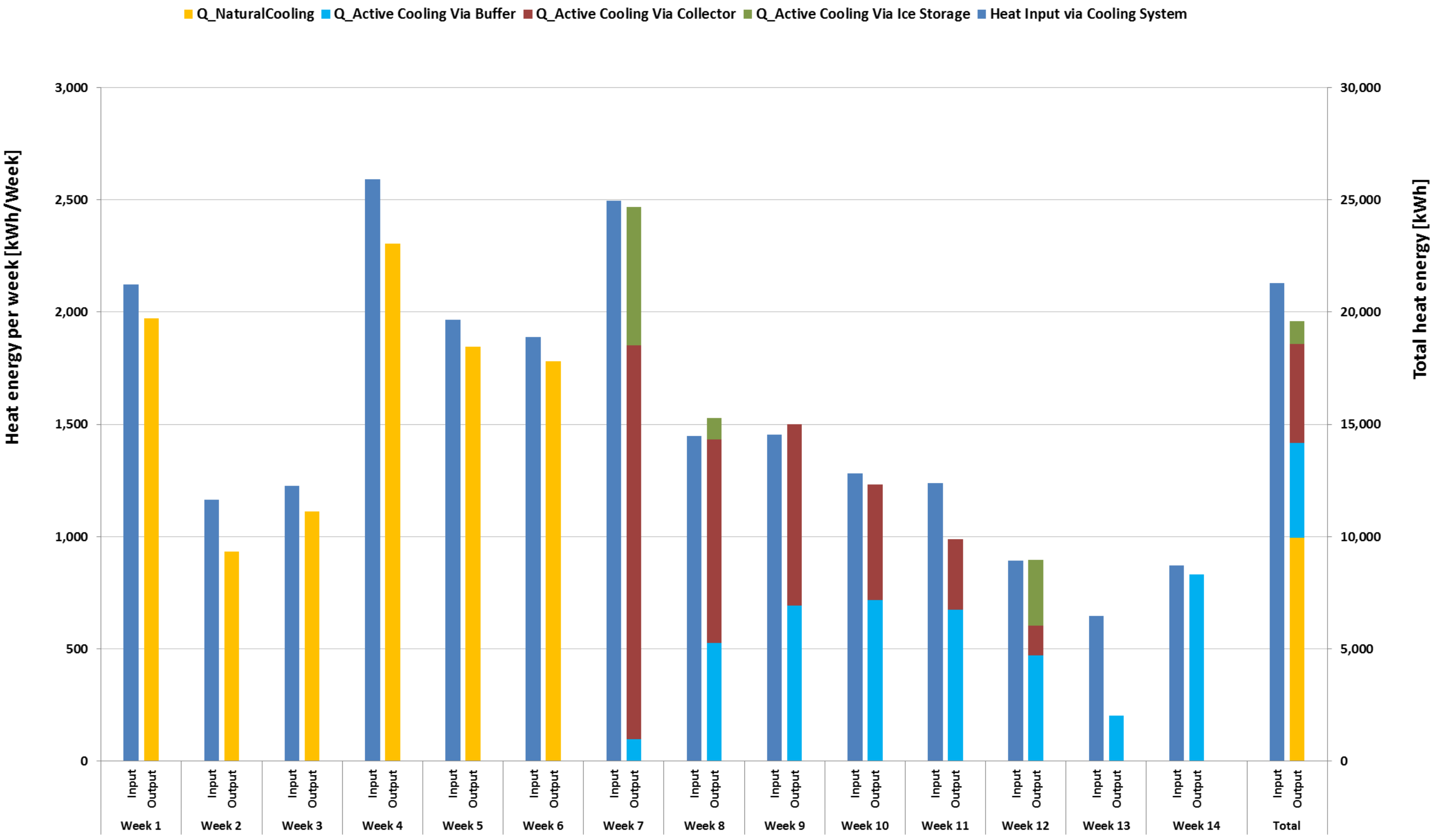


Figure 26: Weekly Energy Balance for Cooling

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 27, 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 a handsome amount of money going into electricity bills and also results in fractional CO_2 savings. These key aspects of this technology will be further analyzed later in this chapter.

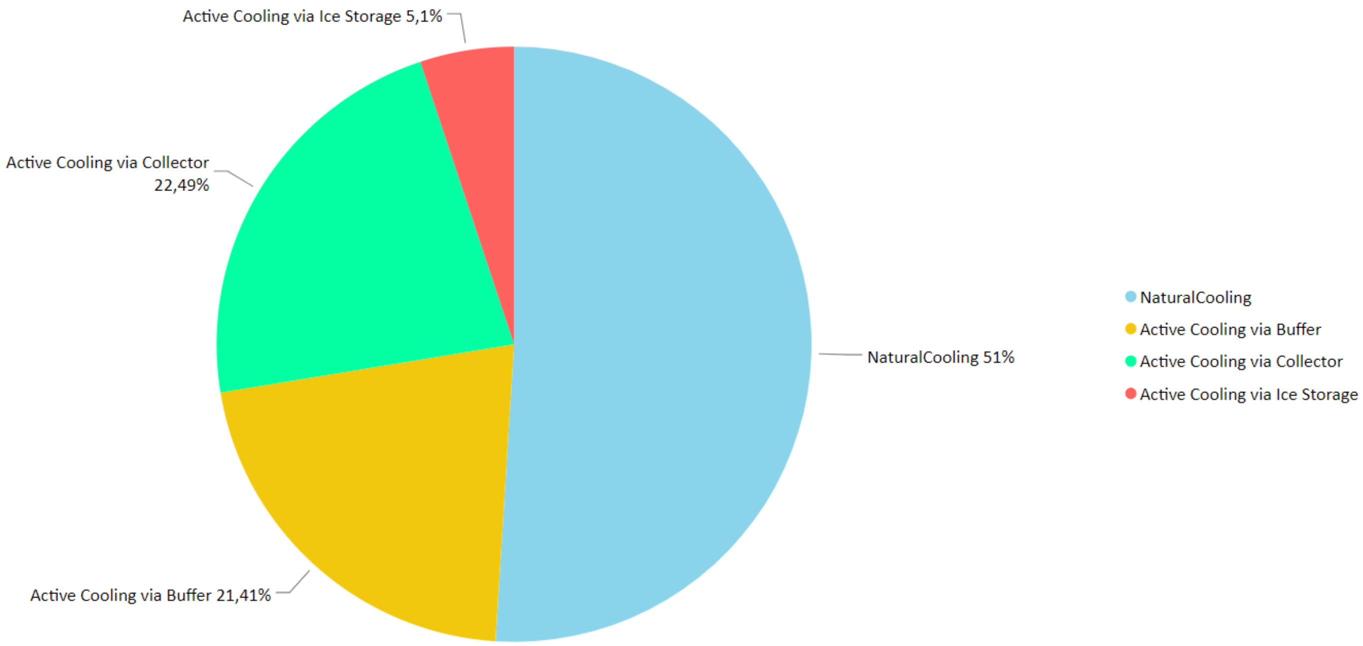


Figure 27: Different Cooling Modes

The behavior of the cold buffer is a crucial factor for the cooling supply system to decide whether the heat from the system should be taken out or not. Due to small size of the cold buffer, it is not able to act as a cold storage rather just as a buffer between supply and demand systems. Therefore, a lot of temperature fluctuations were observed. Further, it was observed that whenever the temperature inside the cold buffer tends to increase, there is an inflow of cooling supply from any source responsible during a particular operation mode. By mid-August, it was observed that as the natural cooling capacity of the ice storage started to deteriorate as the cooling supply temperatures begin to rise with more frequent demand for cooling.

4.3. Heating System Analysis

The system analyzed in this thesis comprised of heat pump, solar collectors and the ice storage also serve the purpose of heating during the winter season. In fact, for most of the applications of a combined system like this, to do heating was the primary driving force behind developing this kind of systems. Heat pump serves as the main driving component of this system while solar collector and ice storage serve as the heat sources for the heat pump. The heating system analyzed in this thesis used two different modes to generate heat primarily at the start of the winter season i.e. October. Heating system started working when the analysis period was about to end that is the reason why cooling operation is mostly the focus of the thesis. However, author of this thesis found it interesting to analyze how this transition period went from cooling to heating operation and what affect it had on the hot buffer tank which was also used for active cooling mode during the cooling operation and will also serve the heating needs during the winter season

However, during the monitoring period it was observed that there were some instances of heating during the cooling season that was not required as it affects the efficiency of the system. It was analyzed that this anomalous behavior was due to some problem in the control strategy that led to turning on of the heating circuit when the temperatures inside the building dropped by a few degrees during early mornings. Usually in the control strategy it is defined that the heating system should be off during peak summer months so that few instances like this of unnecessary heating can be avoided. It appears that this problem was rightly addressed by the operator of the system because this anomalous behavior didn’t occur after a few of such instances. Generally, by mid-October, the heating system was up and running and whenever there was need for heating, the hot buffer tank was supplied with heat and its temperature rose to the specific level required. Due to confidentiality issues, the time series graphs cannot be included in this thesis to fully understand the behavior of the heating system.

4.4. Analysis of the Ice Storage

Ice storage is one of the key components of this technology. As discussed in the previous section, 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 28. 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. After the natural cooling capacity of the ice storage was exploited, cooling was then done with the aid of heat pump but its share is mere 1000 kWh which is about 10% of the total cooling done using the ice storage. In addition, 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.

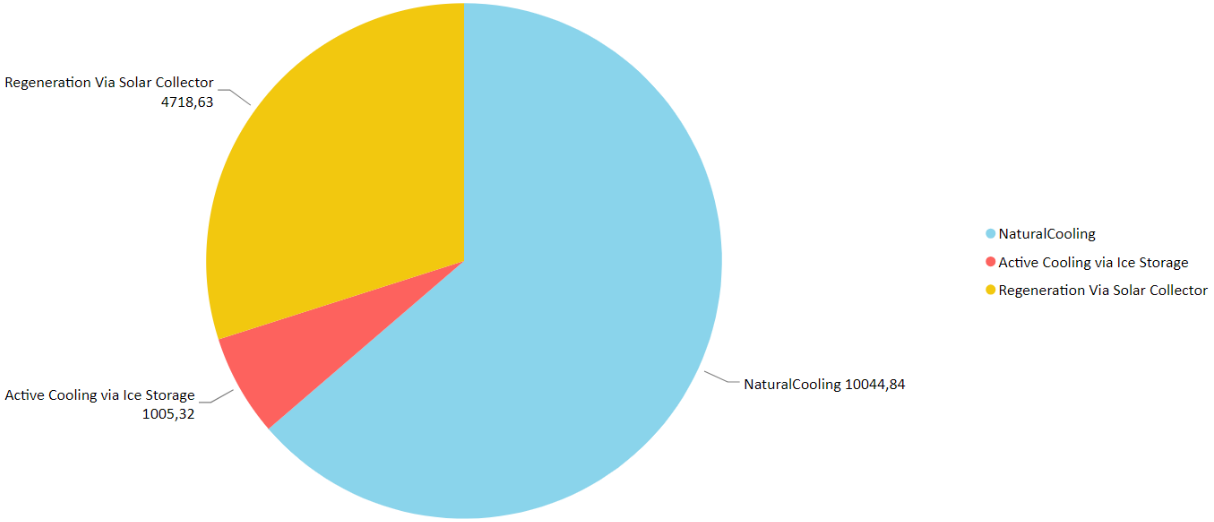


Figure 28: Energy Balance for Ice Storage

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 29. 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.

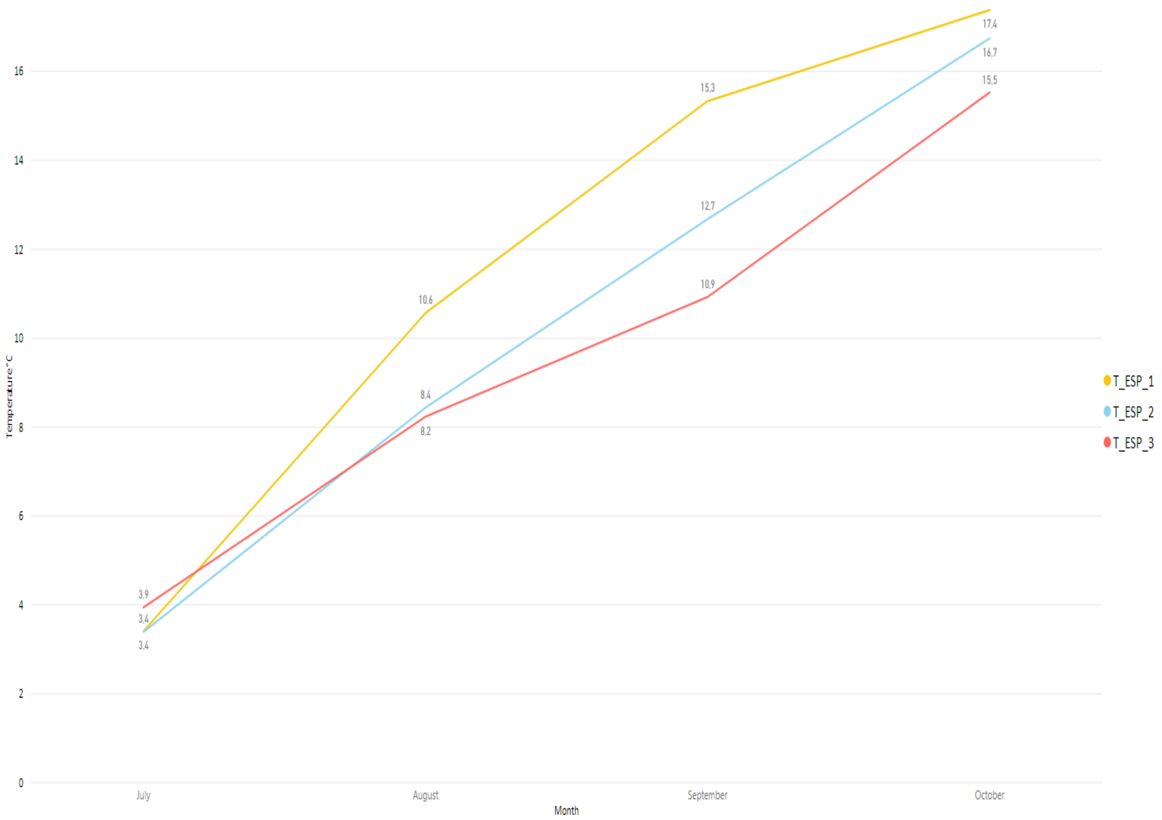


Figure 29: Temperature Variation inside Ice Storage

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 30 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 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.

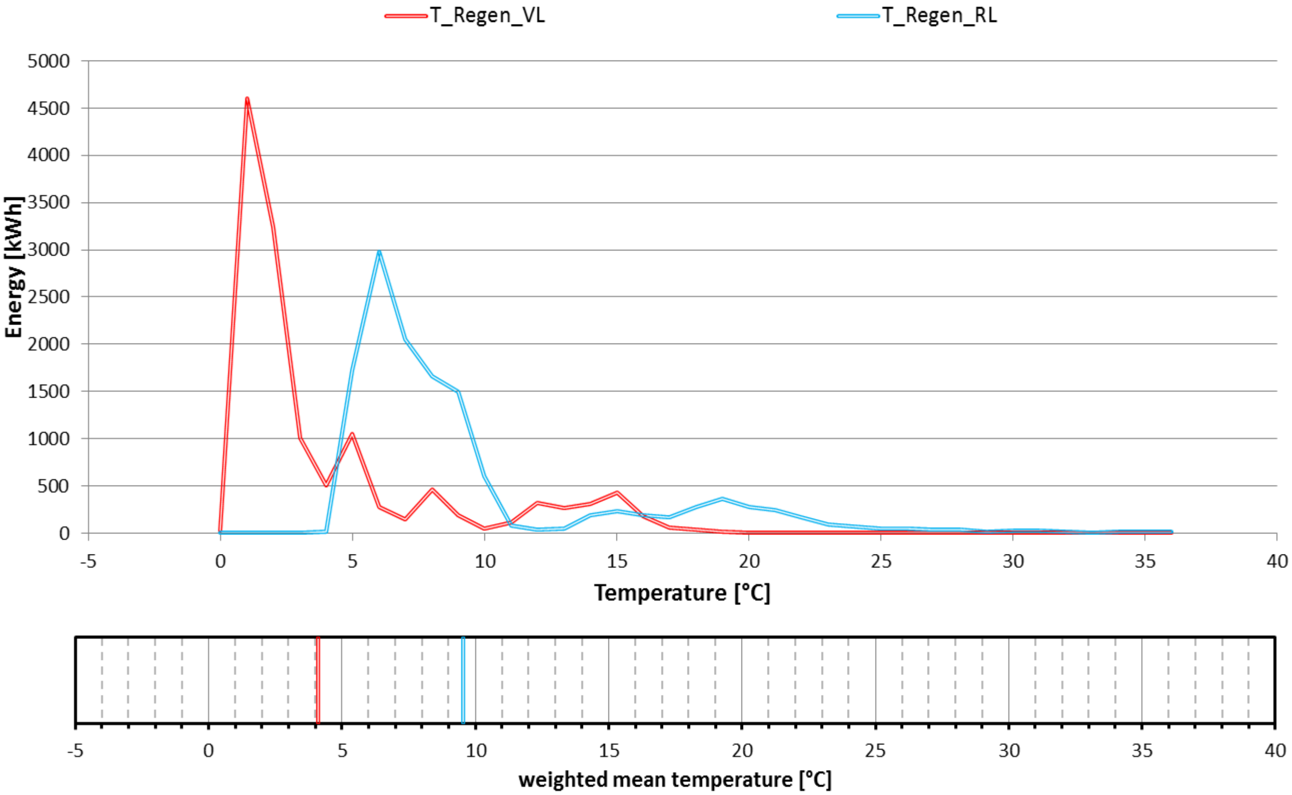


Figure 30: Energy Temperature Diagram for Input and Output Temperatures for the Ice Storage

4.5. 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.

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

As described earlier, IEA SHC Task44 defines SPF as the overall useful energy output to the overall driving final energy. For this particular system analyzed in this thesis, the SPF is determined both on component level and at system level. At component level, SPF is calculated for the heat pump on monthly basis and a calculated mean value for the whole duration it was in operation. The system boundary was defined over the heat pump with electricity as inflow and thermal energy as output from the system boundary.

Table 1 represents the monthly calculation of SPF for heat pump and mean value for the whole period of operation of the heat pump using equation 3. This calculation is also graphically represented in Figure 31.

Month	Electricity Input (kWh)	Thermal Output (kWh)	SPF	Mean inflow temperature (°C)	Mean outflow temperature (°C)
August	607.76	2807.76	4.62	24.88	26.2
September	1857.51	8297.51	4.47	34.95	40.84
October	1383.25	7409.27	5.36	29.87	34.25
Total	3,848.28	18,514.56	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 [7].

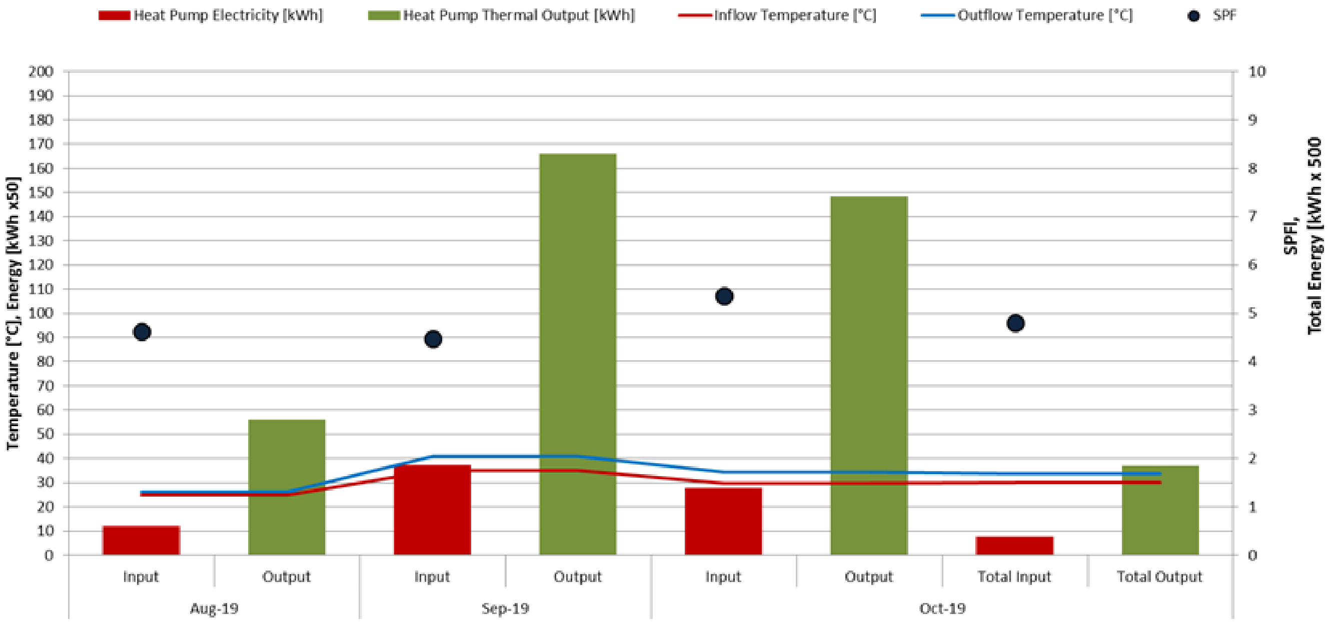


Figure 31: SPF, Input and Output Energy, Inflow and Outflow Temperature for Heat Pump

4.5.2. Solar Fraction

Solar fraction was defined in Chapter 2. Using equation 4, 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.

4.5.3. Waste Heat Utilization

Using equation 5, 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.

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

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.

4.5.4. Energy Density of Ice Storage

Energy density for the ice storage was calculated using the design temperatures provided by the manufacturers using equation 6:

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

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

4.5.5. Utilization of storage capacity

According to equation 7, 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.

4.5.6. Seasonal Performance Factor (SPF_{sys}) 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 (see Figure 32).

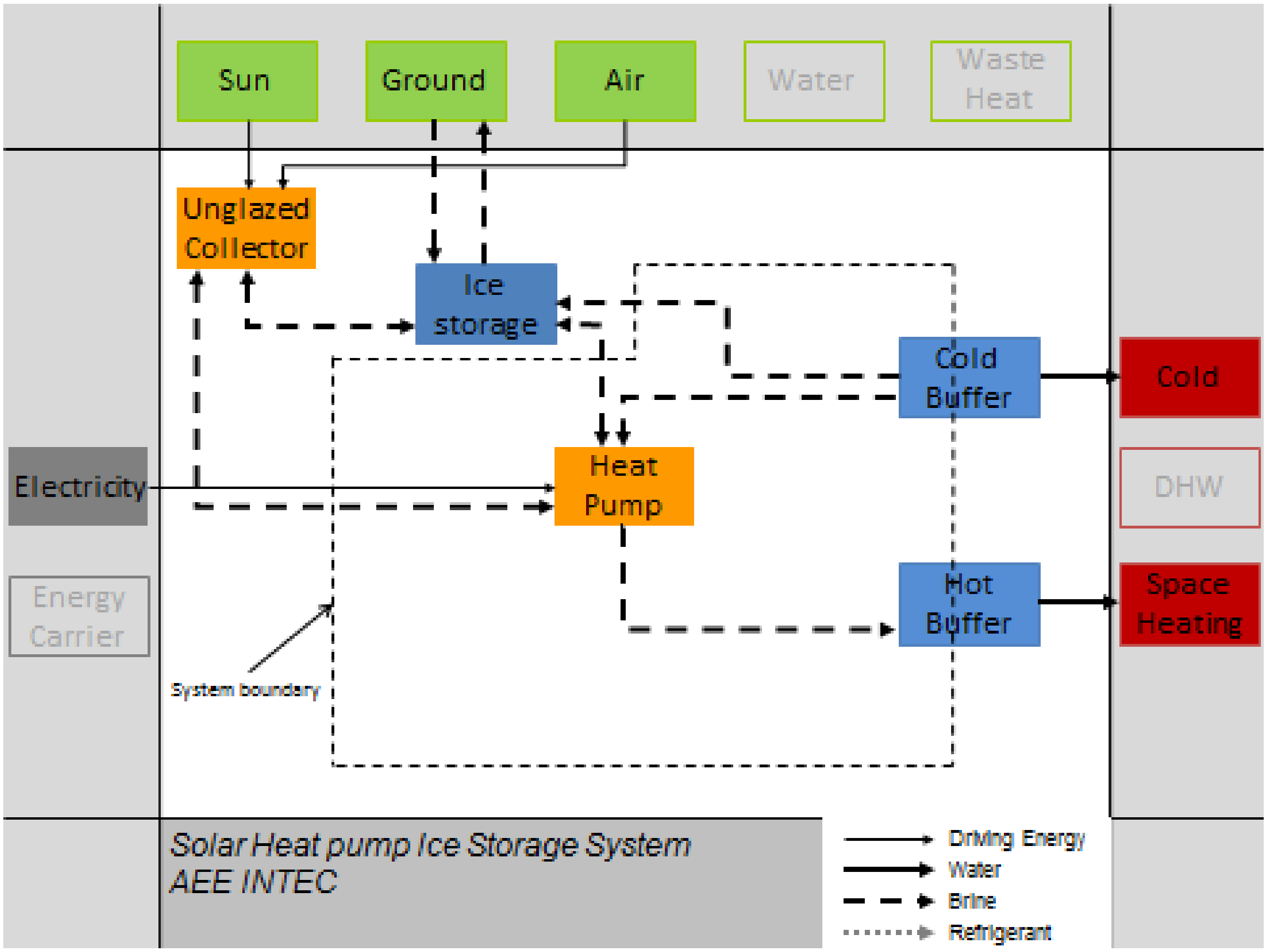


Figure 32: Boundary conditions for calculating SHP for system

Month	Total Electricity Input (kWh)	System Thermal Output (kWh)	SPF
July	408.778	8389.41	20.52
August	879.1044835	5054.26	5.74
September	2103.79654	8297.51	3.94
October	1784.355225	7605.86	4.26
Overall	5176.034248	29347.04	5.66

Table 2: SPF Calculation for the Whole System

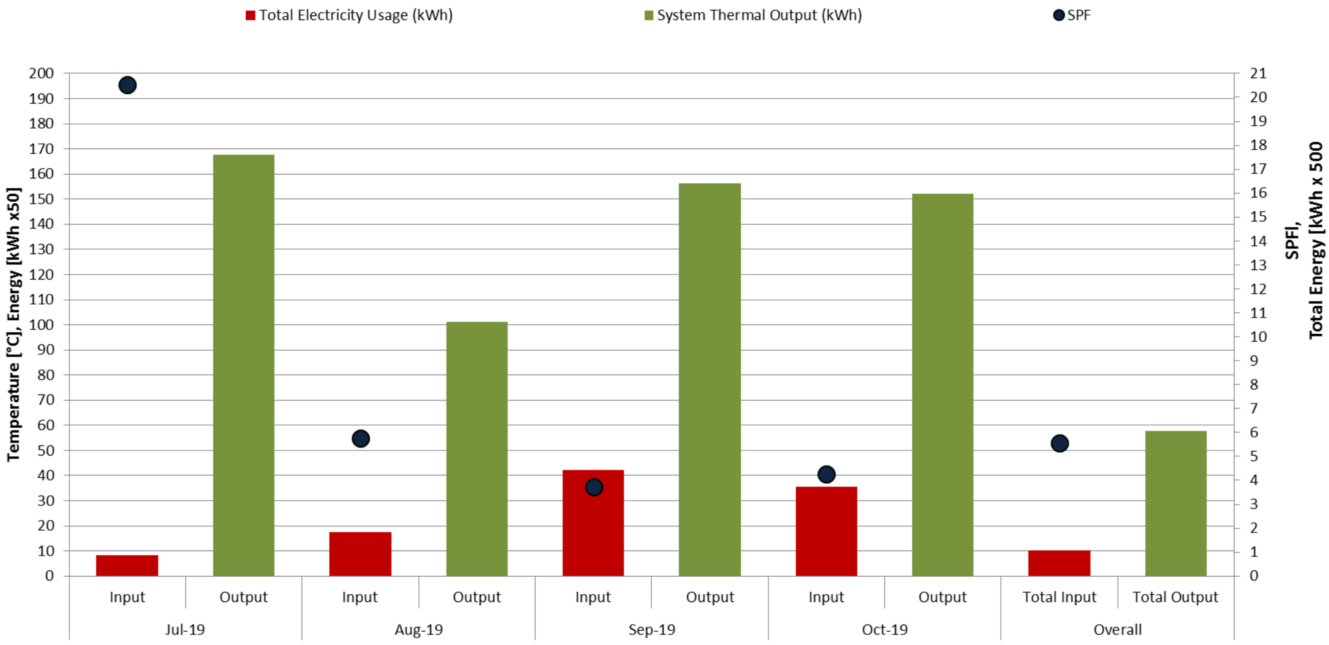


Figure 33: SPF, Input and Output Energy for Overall System

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 [43]. Although these results cannot be directly compared, they serve as a good reference for analysis done within the scope of this thesis.

4.5.7. Primary Energy Ratio and CO2 Emissions Reduction

After evaluating the system on other technical parameters, it is also important to analyze the ecological performance of the system and see if it's really worth it to use this technology for CO_2 emissions reduction. An evaluation was made based on performance evaluation figures devised by IEA SHC Task 44, defined in [4] and explained in the previous chapter.

4.5.7.1. 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. The calculation for PER_{NRE} was made using equation 9.

$CED_{NRE,el}$	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 [44]. 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.

4.5.7.2. 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 equation 10.

GWP_{el} (kg CO_2 equiv./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 CO2 Savings Using Natural Cooling

For calculating the fractional emission savings for the natural cooling mode, a heat pump reference system was chosen based on the manufacturer data sheet attached in Annex. 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.

4.5.7.3. 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 11 and the calculations are presented in Table 5.

GWP_{el} (kg CO_2 equiv./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 [45].

Chapter 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. The system was analyzed and evaluated for a time period of almost three and a half months, mostly summer season and starting autumn or winter season. 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.

Out of the main system components, of most interest 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 concept itself of using the phase change property of water for storing energy is unique and utilizing this characteristic requires right mathematical modelling and system design. 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. Most of the systems are designed to serve heating demand during the winter season as climate in Central Europe is continental. However, the climate is changing and the average temperature is rising very fast, with more hot days in summer including some record breaking weather statistics this year. This would certainly require air conditioning systems which can also serve purpose of cooling and at the same time, are more efficient, reliable and economical. The combined solar heat pump ice storage system analyzed in this thesis was also designed with heating as the main aim of this system indicated by the manufacturer Viessmann in the initial reports. It was interesting to see how a system designed with heating as primary focus performs during the cooling season. It turned out that ice storage was particularly effective during the whole cooling season specially peak summers. Primarily, it is also due to the fact that the system is currently overdesigned and will serve a larger need in the future as the building that now host the offices and the warehouse will also include a museum for music equipment. This fact is also indicated in the system analysis where ice storage is not fully utilized for the energy storage capacity it has and is continuously being regenerated by using solar collectors as a heat source. Sizing of the ice storage is still a hot topic among the researchers and companies manufacturing ice storages. Every company has different criteria for determining the size of the ice storage which was discussed in the first chapter of this thesis. 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.

Solar collectors used in this system are special feature of the system as there construction is very simple making them cheap in economic terms and they serve as air heat exchangers. Apart from the regeneration mode, within the scope and time duration of this thesis, solar collectors were mainly used as air heat exchanger for putting heat out of the system rather than supplying it. This feature is very much different from other type of solar heat pump systems where solar collectors are mainly used either as a direct source for heating up the buffer storage tank or as a source for the heat pump. Although, latter is true for this system also during the heating period but overall this is a unique aspect of this system.

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. There was one instant when an unusual heating was taking place but the operator of the system effectively and timely addressed it. 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.

Bibliography

[1] M. R. Fleiter, Tobias, Jan Steinbach, “Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables),” 2016.

[2] J. Henley, “Climate crisis blamed as temperature records broken in three nations | World news | The Guardian.” [Online]. Available: https://www.theguardian.com/world/2019/jul/24/summers-second-heatwave-set-to-break-records-across-europe. [Accessed: 31-Oct-2019].

[3] Heat Roadmap Europe, “Heating and Cooling. Facts and figures. The Transformation towards a low-carbon Heating & Cooling sector.,” no. June, 2017.

[4] J. C. Hadorn, *Solar and Heat Pump Systems for Residential Buildings*. 2015.

[5] J. Ruschenburg, S. Herkel, and H. M. Henning, “A statistical analysis on market-available solar thermal heat pump systems,” *Sol. Energy*, vol. 95, pp. 79–89, 2013.

[6] A. Mustafa Omer, “Ground-source heat pumps systems and applications,” *Renew. Sustain. Energy Rev.*, vol. 12, no. 2, pp. 344–371, 2008.

[7] D. Philippen, D. Carbonell, D. Zenhäusern, M. Granzotto, M. Haller, and S. Brunold, “High-Ice System development for high solar thermal gains with ice storage and heat pump,” 2015.

[8] S. M. Hasnain, “Review on sustainable thermal energy storage technologies, part II: Cool thermal storage,” *Energy Convers. Manag.*, vol. 39, no. 11, pp. 1139–1153, 1998.

[9] Stefan Minder, M. M. Roland Wagner, and T. Weisskopf, “Eisspeicher-Wärmepumpen-Anlagen mit Sonnenkollektoren Technologiestudie,” 2014.

[10] D. Carbonell, D. Philippen, M. Battaglia, and M. Y. Haller, “Cost energetic analyses of ice storage heat exchangers in solar-ice systems,” in *ISES Solar World Congress*

2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings, 2017, no. October 2018, pp. 2190–2201.

[11] R. Dott, C. Winteler, T. Afjei, and B. Hafner, "Key Facts for High Efficient Solar Ice Storage Heat Pump Systems," in *Clima2016*, 2016.

[12] C. Winteler, R. Dott, T. Afjei, and B. Hafner, "Seasonal performance of a combined solar, heat pump and latent heat storage system," in *Energy Procedia*, 2014, vol. 48, pp. 689–700.

[13] E. Frank and F. E. Gmbh, "IceCheck Auswertung solarer Eisspeicher-Systeme für Mehrfamilienhäuser in der Schweiz," 2019.

[14] R. Huber, "Planungszentrum Linth AG, Uznach Heizen und Kühlen mit saisonalen Energiespeichern, Solar-Luft-Absorbern und Sole-Wasser-Wärmepumpen, Erfolgskontrolle," 2015.

[15] D. Carbonell, J. Schmidli, D. Philippen, and M. Haller, "Solar-ice systems for multi-family buildings: hydraulics and weather data analysis," in *E3S Web of Conferences*, 2019, vol. 111, no. 201 9, p. 01013.

[16] I. Mojic, M. Y. Haller, B. Thissen, and E. Frank, "Heat pump system with uncovered and free ventilated covered collectors in combination with a small ice storage," *Energy Procedia*, vol. 48, pp. 608–617, 2014.

[17] I. Mojic, M. Y. Haller, B. Thissen, and E. Frank, "Wärmepumpen-Systeme mit selektiven unabgedeckten und frei belüftbaren abgedeckten Kollektoren als einzige Wärmequelle," in *OTTI Symposium Thermische Solarenergie, 23.-26. April 2013, Kloster Banz, Bad Staffelstein, OTTI e.V., Regensburg Wärmepumpen-Systeme*, 2013, no. April.

[18] R. Dott, M. Y. Haller, J. Ruschenburg, F. Ochs, and J. Bony, "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," in *Solar and Heat Pump Systems for Residential Buildings*, no.

October, 2013.

[19] D. Carbonell, M. Y. Haller, D. Philippen, and E. Frank, “Simulations of combined solar thermal and heat pump systems for domestic hot water and space heating,” *Energy Procedia*, vol. 48, pp. 524–534, 2014.

[20] D. Carbonell, M. Y. Haller, and E. Frank, “Potential benefit of combining heat pumps with solar thermal for heating and domestic hot water preparation,” *Energy Procedia*, vol. 57, pp. 2656–2665, 2014.

[21] C. Winteler, R. Dott, T. Afjei, and B. Hafner, “Seasonal performance of a combined solar, heat pump and latent heat storage system,” *Energy Procedia*, vol. 48, no. December 2014, pp. 689–700, 2014.

[22] C. Schmidt *et al.*, “Laboratory test procedures for solar and heat pump systems,” in *Solar and Heat Pump Systems for Residential Buildings*, 2015, pp. 103–130.

[23] A. Loose, S. Bonk, and H. Drück, “Investigation of Combined Solar Thermal and Heat Pump Systems - Field and Laboratory Tests,” in *EuroSun 2012*, 2012.

[24] M. Y. Haller *et al.*, “Solar and heat pump systems - summary of simulation results of the IEA SHC task 44/HPP annex 38,” 2014.

[25] D. Carbonell, D. Philippen, M. Granzotto, and M. Y. Haller, “Simulation of a solar-ice system for heating applications. System validation with one-year of monitoring data,” *Energy Build.*, vol. 127, pp. 846–858, 2016.

[26] M. Y. Haller, E. Bertram, R. Dott, T. Afjei, F. Ochs, and J. C. Hadorn, “Review of component models for the simulation of combined solar and heat pump heating systems,” *Energy Procedia*, vol. 30, no. December, pp. 611–622, 2012.

[27] D. Carbonell, D. Philippen, E. Frank, M. Granzotto, and M. Haller, “Simulation of Combined Solar Thermal, Heat Pump, Ice Storage and Waste Water Heat Recovery Systems. Design Criteria and Parametric Studies,” in *EuroSun 2014*, 2015, no. September, pp. 1–10.

[28] E. Bertram, P. Pärisch, and R. Tepe, “Impact of solar heat pump system concepts on seasonal performance-Simulation studies,” in *Proceedings of the EuroSun 2012*, 2012.

[29] D. Philippen, D. Zenhäusern, D. Carbonell, M. Granzotto, M. Haller, and S. Brunold, “Systemauslegung und Ökobilanzierung von Solarthermie- Wärmepumpen-Heizungen mit Eisspeichern und,” in *OTTI Symposium Thermische Solarenergie, 6.-8. Mai 2015, Kloster Banz, Bad Staffelstein*, 2015, p. 8640.

[30] D. Carbonell, D. Philippen, M. Y. Haller, and S. Brunold, “Modeling of an ice storage buried in the ground for solar heating applications. Validations with one year of monitored data from a pilot plant,” *Sol. Energy*, vol. 125, pp. 398–414, 2016.

[31] J. Goeke, “Wärmeübertragung in Eisspeichern und Energiegewinne aus dem Erdreich,” *Bauphysik*, vol. 41, no. 2, pp. 96–103, 2019.

[32] D. Philippen, D. Carbonell, M. Battaglia, B. Thissen, and L. Kunath, “Validation of an Ice Storage Model and Its Integration Into a Solar-Ice System,” in *EuroSun 2018 Conference Proceedings*, 2019, no. May 2019, pp. 1–12.

[33] D. Carbonell, D. Philippen, M. Battaglia, and M. Y. Haller, “Cost energetic analyses of ice storage heat exchangers in solar-ice systems,” in *ISES Solar World Congress 2017 - IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry 2017, Proceedings*, 2017, no. January, pp. 2190–2201.

[34] “Welcome to Python.org.” [Online]. Available: https://www.python.org/. [Accessed: 31-Oct-2019].

[35] “Spyder :: Anaconda Cloud.” [Online]. Available: https://anaconda.org/anaconda/spyder. [Accessed: 31-Oct-2019].

[36] “Spyder Website.” [Online]. Available: https://www.spyder-ide.org/. [Accessed: 31-Oct-2019].

[37] E. Frank and M. Haller, “Systematic Classification of Combined Solar Thermal and

Heat Pump Systems," in *Proceedings of the EuroSun 2010 Conference, Sep. 29 - Oct. 1, Graz, Austria Systematic*, 2016, pp. 1–8.

[38] J. A. Palyvos, "A survey of wind convection coefficient correlations for building envelope energy systems' modeling," *Appl. Therm. Eng.*, vol. 28, no. 8–9, pp. 801–808, 2008.

[39] "Eisspeicher als innovative Energiequelle | Viessmann." [Online]. Available: https://www.viessmann.at/de/wohngebaeude/waermepumpe/eis-energiespeicher.html. [Accessed: 31-Oct-2019].

[40] G. A. Lane, *Solar heat storage: Latent heat materials*. 1983.

[41] R. Itten, R. Frischknecht, M. Stucki, P. Scherrer, and I. Psi, "Life Cycle Inventories of Electricity Mixes and Grid," *Paul Scherrer Inst.*, no. June, pp. 1–229, 2014.

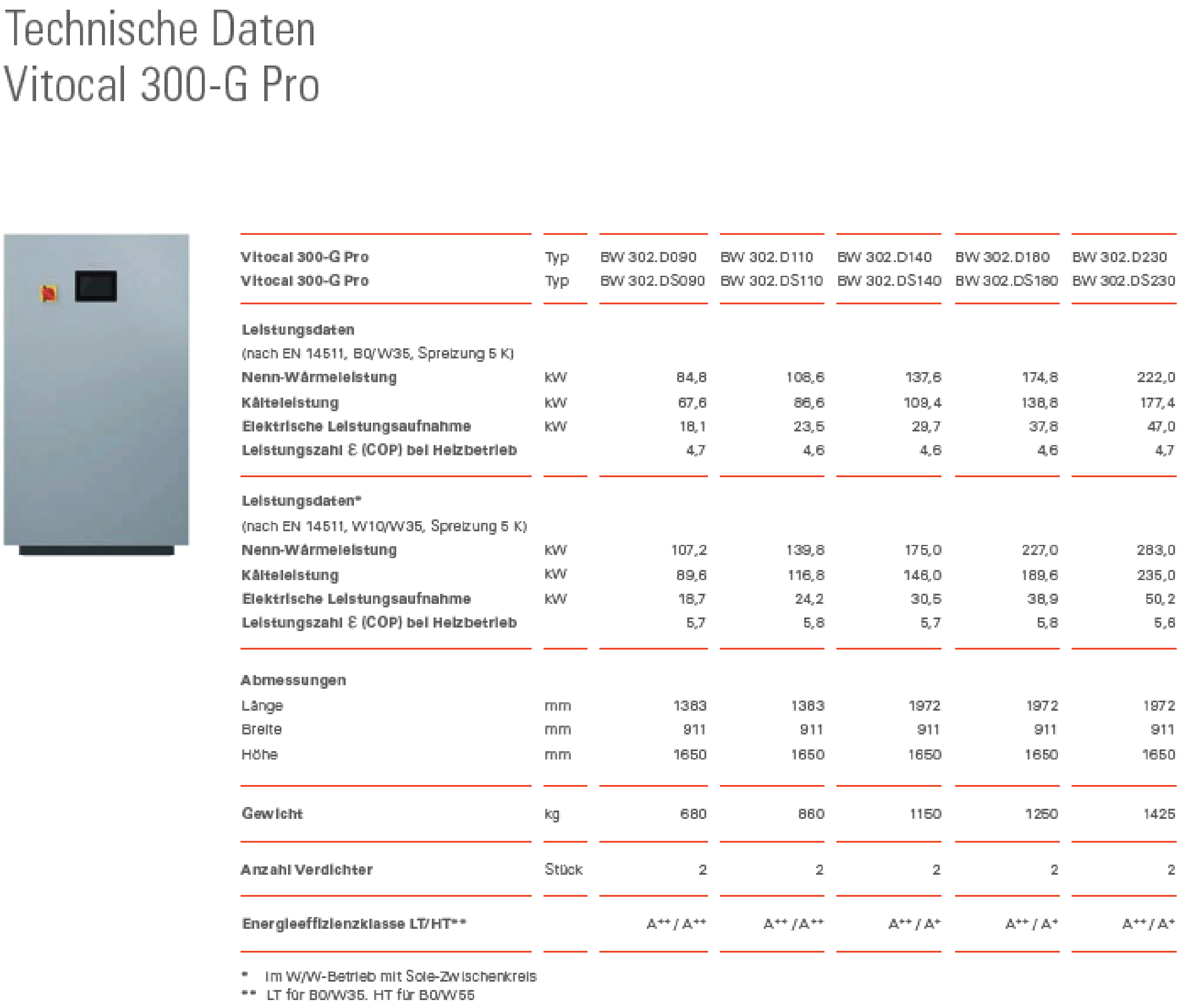
[42] "ecoinvent." [Online]. Available: https://www.ecoinvent.org/. [Accessed: 31-Oct-2019].

[43] J. Desmedt, H. Hoes, and N. Robeyn, "Experiences on sustainable heating and cooling with an aquifer thermal energy storage system at a Belgian hospital," no. August, p. 8, 2007.

[44] Ö. I. für Bautechnik, "OIB Richtlinien 6: Energieeinsparung und Wärmeschutz," *OIB-330.6-026/19*, 2019. [Online]. Available: https://www.oib.or.at/sites/default/files/richtlinie_6_12.04.19_1.pdf. [Accessed: 31-Oct-2019].

[45] S. Allen, "Carbon Footprint of Electricity Generation," *383*, 2011. [Online]. Available: www.parliament.uk/post. [Accessed: 31-Oct-2019].

Appendix

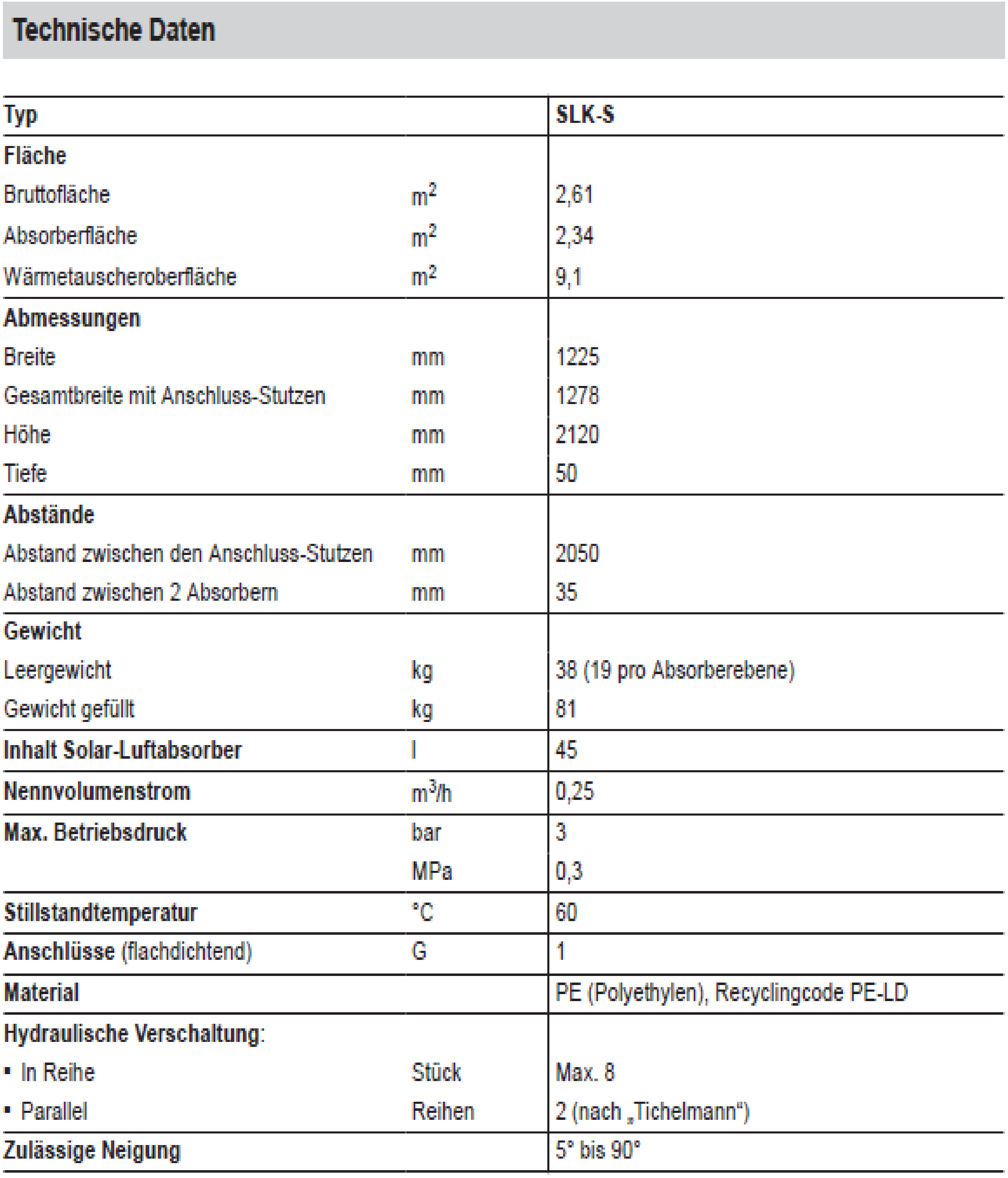


Technische Daten
Vitocal 300-G Pro

Vitocal 300-G Pro Vitocal 300-G Pro	Typ Typ	BW 302.D090 BW 302.DS090	BW 302.D110 BW 302.DS110	BW 302.D140 BW 302.DS140	BW 302.D180 BW 302.DS180	BW 302.D230 BW 302.DS230
Leistungsdaten						
(nach EN 14511, B0/W35, Spreizung 5 K)						
Nenn-Wärmeleistung	kW	84,8	106,6	137,6	174,8	222,0
Kälteleistung	kW	67,6	86,6	109,4	136,8	177,4
Elektrische Leistungsaufnahme	kW	18,1	23,5	29,7	37,8	47,0
Leistungszahl ε (COP) bei Heizbetrieb		4,7	4,6	4,6	4,6	4,7
Leistungsdaten*						
(nach EN 14511, W10/W35, Spreizung 5 K)						
Nenn-Wärmeleistung	kW	107,2	139,8	175,0	227,0	283,0
Kälteleistung	kW	89,6	116,8	146,0	189,6	235,0
Elektrische Leistungsaufnahme	kW	18,7	24,2	30,5	38,9	50,2
Leistungszahl ε (COP) bei Heizbetrieb		5,7	5,8	5,7	5,8	5,8
Abmessungen						
Länge	mm	1383	1383	1972	1972	1972
Breite	mm	911	911	911	911	911
Höhe	mm	1650	1650	1650	1650	1650
Gewicht	kg	680	860	1150	1250	1425
Anzahl Verdichter	Stück	2	2	2	2	2
Energieeffizienzklasse LT/HT**		A++ / A++	A++ / A++	A++ / A+	A++ / A+	A++ / A+

* Im W/W-Betrieb mit Sole-Zwischenkreis
** LT für B0/W35. HT für B0/W55

App 1: Technical data sheet for the heat pump (Source: Viessmann)



Technische Daten

Typ		SLK-S
Fläche		
Bruttofläche	m^2	2,61
Absorberfläche	m^2	2,34
Wärmetauscheroberfläche	m^2	9,1
Abmessungen		
Breite	mm	1225
Gesamtbreite mit Anschluss-Stutzen	mm	1278
Höhe	mm	2120
Tiefe	mm	50
Abstände		
Abstand zwischen den Anschluss-Stutzen	mm	2050
Abstand zwischen 2 Absorbern	mm	35
Gewicht		
Leergewicht	kg	38 (19 pro Absorberebene)
Gewicht gefüllt	kg	81
Inhalt Solar-Luftabsorber	l	45
Nennvolumenstrom	m^3/h	0,25
Max. Betriebsdruck	bar	3
	MPa	0,3
Stillstandtemperatur	°C	60
Anschlüsse (flachdichtend)	G	1
Material		PE (Polyethylen), Recyclingcode PE-LD
Hydraulische Verschaltung:		
▪ In Reihe	Stück	Max. 8
▪ Parallel	Reihen	2 (nach „Tichelmann“)
Zulässige Neigung		5° bis 90°

App 2: Technical data sheet for the Solar Collector (Source: Viessmann)