SEASONAL PERFORMANCE OF A COMBINED SOLAR, HEAT PUMP AND LATENT HEAT STORAGE SYSTEM

Christian Winteler; Ralf Dott; Thomas Afjei

Institut Energie am Bau, Fachhochschule Nordwestschweiz FHNW, St. Jakobs-Strasse 84, CH-4132 Muttenz, Switzerland

ABSTRACT

This paper investigates the seasonal performance of a combined solar, heat pump and latent heat storage system for dwellings. This combination could provide a viable alternative to common brine-water heat pump systems with a borehole heat exchanger. (BHX). Since the latent heat storage, or ice storage, is filled with pure water, it can also be used in (but is not limited to) places where a BHX is prohibited, e.g. water protection areas. The aim of this work is to find and evaluate given system configurations for three different annual heat demands that reach seasonal performance factors (SPF) comparable to those of BHX heat pump systems, i.e. SPF ~ 4.0.

A simulation study using MATLAB®/SIMULINK® and the CARNOT Blockset is conducted. Technologies considered in the simulation study are a brine-water heat pump, unglazed solar collectors as source for the heat pump and a buried ice storage that serves as alternative source for the heat pump and is regenerated by the collectors. Unglazed collectors use solar irradiation and ambient heat (via convective heat exchange) for heat generation. Additionally, thermal coupling of the ice storage to the surrounding soil which also contributes to the regeneration of the system is considered. The simulation models of this system have been validated with laboratory and field test data. The heat generated by the heat pump is used for space heating and domestic hot water preparation of single family houses with different heat loads which have been defined in the framework of IEA SHC Task 44 / HPP Annex 38 "Solar and heat pump systems". To obtain the desired SPF for each building type the power output of the heat pump with the corresponding size of the collector field is varied.

For each building a configuration is found that yields a SPF ~ 4.0. A high SPF can only be reached as long as no backup heating is needed, which means, that the ice storage should never be completely discharged, i.e. completely frozen. This requires significant contributions from the solar collector, especially during the heating period.

Keywords: heat pump, solar heat, latent heat, ice storage

INTRODUCTION

The turnaround in energy policy demands energy supply systems to use predominantly renewable energy sources. Heat pumps in combination with solar energy are key technologies for heat generation for space heating and domestic hot water in buildings. Currently the most effective heat sources for heat pumps are borehole heat exchangers. Recently systems with large ice storages have been promoted as equally efficient at comparable cost without the need for deep drilling and the associated authorization and risks. Furthermore, ice storages can also be installed in areas where deep drilling is not possible or prohibited, even in water protection areas since the ice storage is filled with pure water.

Aim of this study is to investigate the seasonal performance of a combined solar, heat pump and ice storage system for buildings with different heat loads and compare it to the average seasonal performance factor of systems with borehole heat exchangers of ~ 4.0.

METHOD

The simulation study is conducted using MATLAB®/SIMULINK® [1] and the CARNOT Blockset [2]. Technologies considered in the simulation study are a brine-water heat pump, unglazed solar collectors as source for the heat pump and a buried ice storage that serves as alternative source for the heat pump and is regenerated by the collectors. Unglazed collectors use solar irradiation and ambient heat (via convective heat exchange) for heat generation. Furthermore, thermal coupling of the ice storage to the surrounding soil which also contributes to the regeneration of the system is considered. The heat generated by the heat pump is used for space heating and domestic hot water preparation of a single family house (SFH) which has been defined in IEA HPP Annex 38 / SHC Task 44 "Solar and heat pump systems" (A38T44) as reference heat load, c.f.[3]. Therein, three building types called SFH15, SFH45 and SFH100 are defined, where the numbers refer to the insulation quality and therewith the space heat demand of 15 kWh/m^2/a, 45 kWh/m^2/a or 100 kWh/m^2/a as described in detail in [4]. The implementation of these buildings in the presented simulation environment differs from the reference which can lead to an increase in the heat demand due to a different space heating control. However, the aim of the study is not to perfectly match the heat load to the reference, but to investigate the behaviour of the heat generation system for different system configurations.

Reference conditions

The reference conditions of A38T44 are applied using the following options for all systems:

- moderate climate of Strasbourg, a French city in central Europe
- a simplified domestic hot water (DHW) tapping profile of only three tappings per day (07:00, 12:00 and 19:00) corresponding to an average draw off of 140 l/d at 45 °C or 5.845 kWh/d (2133 kWh/a). The seasonal variation of the DHW energy demand is approximated with a sine-curve variation of the cold water temperature.

Domestic hot water preparation is delivered by a boiler with attached mixing valve to adjust the fixed tapping temperature and heated only by the heat pump.

The heat delivery system for space heating in SFH15 and SFH45 is a floor heating system, in SFH100 a radiator. The required flow temperatures needed to satisfy the heat demands are 30 °C for the SFH15 building, 34 °C for the SFH45 and 48 °C for the SFH100 building.

There is a range of heat pump models intended by the manufacturer for the solar ice storage system with thermal capacities of 6, 8, 10 and 13 kW. To study the behaviour of the heat generation system in combination with the aforementioned reference buildings, a heat pump is chosen for each building such that its thermal capacity exceeds the design heat load of the building (1.8 kW, 4 kW and 7.3 kW for SFH15, SFH45 and SFH100 respectively).

The heating characteristic of the heat pump controller defines the space heating return flow temperature as a function of the outdoor temperature. The heating characteristic is set such that the room temperature is kept around 20 ± 0.5 °C. If necessary, DHW preparation has priority over space heating.

Solar thermal absorber modules are installed on a south facing roof at an inclination of 40°. The collector area for the buildings SFH15 and SFH45 amounts to approximately 10 m^2, for building SFH 100 to 20 m^2.

Applied tools and parameter data sets

All simulations are performed with MATLAB®/SIMULINK® in combination with the CARNOT Blockset, an extension for the calculation and simulation of thermal components of heating systems. All simulation results are annual values from July to July with 300 days preconditioning, corresponding to one full heating period. Heat loads are simulated with the simple house model from the CARNOT Blockset, parametrized according to the building definitions from the IEA HPP Annex 38 / SHC Task 44. The Isocal solar ice system [5] consists of Isocal SLK-S pipe absorber modules and an Isocal SES ice storage.

The absorber is modelled as described in [6] and parametrized according to the data in [5]. Effects of condensation as well as freezing/frosting are not taken into account. The model has been validated through laboratory tests both with and without irradiation. For the brine/water heat pump the generic heat pump model from the CARNOT Blockset is used with performance data of Viessmann Vitocal 300 G BW series models [7] BW 301.A06 (6 kW) and BW 301.A08 (8 kW). The storage tank model is a CARNOT multiport model with specifications of a Viessmann Vitocell 100-V CVW [8]. All simulation models and applied parameter data sets have furthermore been validated through field test measurement data.

Schematic

Figure 1 shows a schematic depiction of the system and the hydraulic connections. The solar thermal absorber and the ice storage both serve as heat source for the heat pump. The buried ice storage is not insulated and can exchange heat with the surrounding soil. Additionally, the absorber also supplies heat for the regeneration of the ice storage. The heat pump is the sole supplier of heat for space heating as well as for domestic hot water preparation. The electric heater serves as backup in case the source temperature drops below the minimum operating temperature of the heat pump.

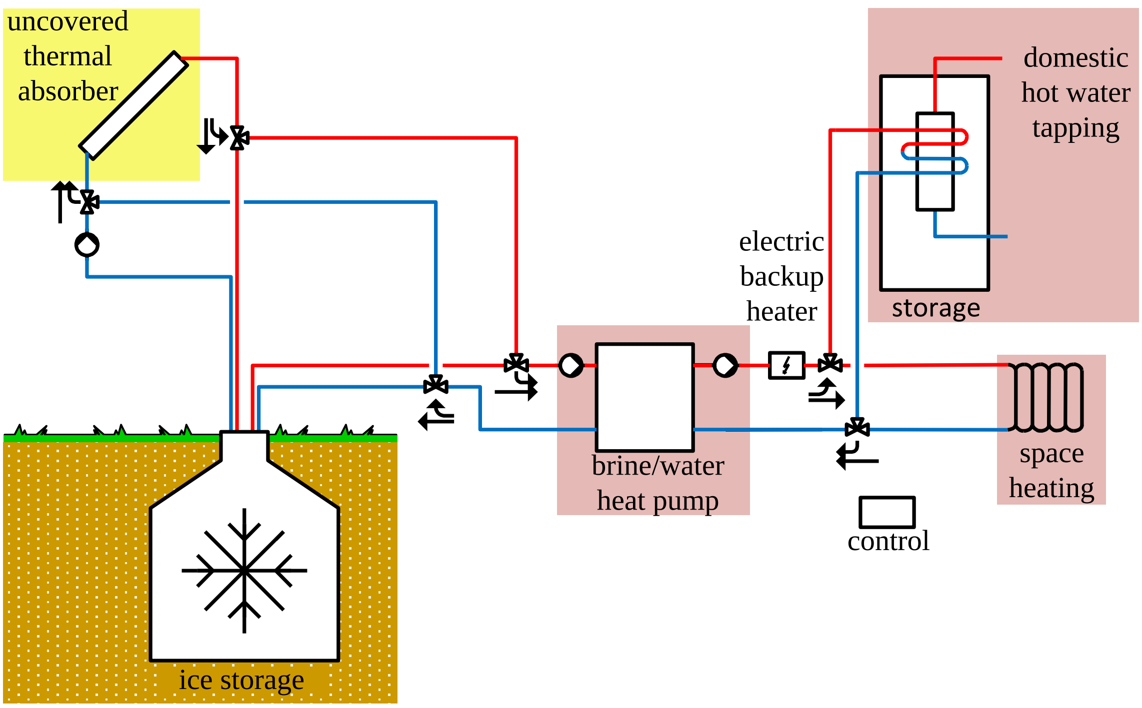

Figure 1 System and hydraulic scheme

RESULTS

A selection of results for the three chosen systems is presented in Figure 2 and Table 1. Therein, the following results are shown:

- The total generated heat for space heating and domestic hot water preparation in kilowatt-hours (kWh), divided into the different heat sources for the heat pump: electricity, solar collector or ice storage. The contribution from the ice storage is subdivided into a solar and a ground heat part, depending on how the heat extracted from the ice storage is restored. Since heat exchange between ice storage and ground works in both ways, the displayed value denotes the net annual energy balance. The latent heat contribution cannot be displayed here since its annual energy balance is zero.
- The total electric energy consumption of the whole heating system including all components in kWh.
- The seasonal performance factor (SPF) of the heat generation system as quotient of heat generated by the heat pump divided by the electricity consumption of the heat pump, the heat pump control, the pump between collector and ice storage, the pump for the heat pump source and the electric backup heater.

The variant SFH15, representing a building with very high energetic quality, has the lowest heating energy generation of 5'260 kWh. The major heat source for the heat pump is the solar absorber, providing 2'908 kWh of the 4'267 kWh needed. The rest of the energy is supplied by the ice storage, which in turn is regenerated by the absorber. On average the temperature of the ice storage is higher than the temperature of the surrounding ground. This excess heat is transferred from the ice storage to the ground which is indicated by the negative contribution in Figure 1. The SPF of 3.73 is slightly below the expected 4.0.

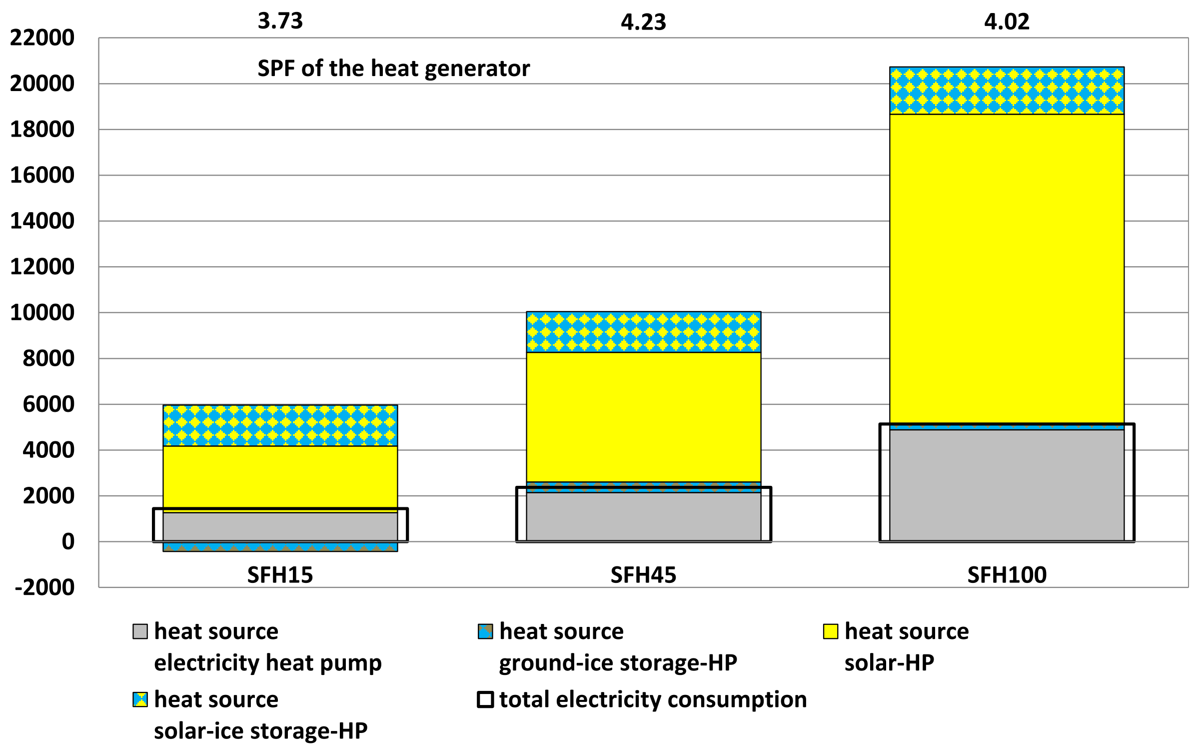

Figure 2 System simulation results for the three building types

The variant SFH45 represents a renovated building with good thermal quality of the building envelope that also satisfies current legal requirements. From the total 9'731 kWh of generated heat, 7'351 kWh are used for space heating. The predominant heat source for the heat pump is the solar absorber. Its contribution of 5'654 kWh to the total heat demand of 7'906 kWh is significantly larger than the 2'252 kWh extracted from the ice storage. On an annual balance the ice storage is not only recharged by the absorber, but also extracts 467 kWh heat from the surrounding ground. The thermal capacity of the heat pump of 6 kW matches the design heat load of the building quite well, resulting in the highest SPF of 4.23 among the presented simulations.

A38T44 building type	Solar absorber surface in m^2	Thermal power of heat pump in kW	Total generated heat in kWh	Design flow/return temperature in °C	SPF of heat generator	Total generator electricity consumption in kWh	Electricity consumption of auxiliaries in kWh
SFH15	10	6	5'260	30/25	3.73	1'412	150
SFH45	10	6	9'731	34/29	4.23	2'301	161
SFH100	20	8	20'249	48/38	4.02	5'040	158

Table 1 System simulation results for the three building types

The variant SFH100 represents a non-renovated existing building and has therefore the highest heat demand. From the total 20'249 kWh of generated heat 17'681 kWh are used for space heating. The 20 m^2 of thermal collectors deliver 13'549 kWh of heat as source energy for the heat pump. The remaining 2'298 kWh of source energy are supplied by the ice storage. The annual balance of the ice storage shows 233 kWh of heat that are extracted from the surrounding ground, the rest is provided by the collector. The heat generator reaches an SPF of 4.02.

DISCUSSION

For all three buildings the heat demand for space heating is significantly higher than the reference values given in [4]: 21 kWh/m^2/a for SFH15, 52.5 kWh/m^2/a for SFH45 and 126 kWh/m^2/a for SFH100. The main reason for this difference is the fact, that no thermostatic valves regulating the mass flow are used in the heat delivery system. This in turn leads on average to higher room temperatures and therefore more heat losses. However, the focus of this work is to study the performance of the solar ice storage system, i.e. the heat generation system, for different heat loads and not the optimal reproduction of the reference heat loads. The authors are well aware that this aspect could be optimized in future studies.

The most important result is that for all three buildings the solar ice system reaches an SPF close to or above 4.0. With a value of 3.73 the SFH15 variant is the only one with an SPF below 4.0. There are two main reasons for this discrepancy:

1. The heat pump thermal capacity of 6 kW is a factor 2-3 larger than the design heat load which leads to a lower SPF of the heat pump alone.

2. The fraction of electricity consumed by auxiliary systems (here the heat pump control, the pump between collector and ice storage, the source pump of the heat pump and the electric backup heater), 150 kWh, to total generator electricity consumption, 1'412 kWh, is around 11 % which leads to a rather large reduction of the SPF when extending the system boundary from the heat pump alone (SPF 4.17) to the heat generator (SPF 3.73).

From the range of available heat pumps intended for this system by the manufacturer, with thermal capacities of 6 kW and above, it is obvious that the ice storage system is not primarily designed for buildings with very low space heat loads like SFH15 (1.8 kW). In this context an SPF of 3.73 is still a remarkable result.

The SFH100 variant reaches an SPF of 4.02 which is only slightly above the desired value of 4. In this variant the heat pump SPF is reduced, because higher flow temperatures are needed to meet the heat load than in the variants with floor heating, see c.f. Table 1. To obtain these temperatures the heat pump needs more electricity which in turn reduces the SPF.

The highest SPF is reached for the SFH45 variant where the thermal capacity of the heat pump is close to the building heat load and heat is delivered at moderate temperatures with a floor heating system.

CONCLUSIONS

The study shows, that the solar ice system generates heat efficiently for different heat loads. It reaches SPF > 4 for buildings with moderate (SFH45) to high (SFH100) space heat demands with space heating or radiator heat delivery systems. The system is not primarily intended for buildings with very low heat loads (SFH15) but reaches a SPF close to 4 nevertheless.

ACKNOWLEDGEMENTS

The authors are grateful for the project advising and funding by the Swiss Federal Office of Energy SFOE in the frame of the project SOFOWA. They acknowledge the support of the component manufacturers Viessmann Werke GmbH & Co. KG and isocal HeizKühlsysteme GmbH. The project contributes to the IEA SHC Task 44 / HPP Annex 38 “Solar and heat pumps”. The permission of Meteotest for using Meteonorm climate data for simulations within the IEA SHC Task 44 / HPP Annex 38 is gratefully acknowledged.

REFERENCES

1. Matlab®/Simulink® Version R2011b, The Mathworks, Inc.
2. CARNOT Toolbox für Matlab/Simulink Ver. 5.2, August 2012
3. M. Y. Haller, R. Dott, J. Ruschenburg, F. Ochs und J. Bony: The Reference Framework for System Simulations of the IEA SHC Task 44 / HPP Annex 38, 2011
4. R. Dott, M. Y. Haller, J. Ruschenburg, F. Ochs und J. Bony: Reference Buildings Description of the IEA SHC Task 44 / HPP Annex 38, 2011
5. Das Wärmequellensystem SE 12 - Informationsblatt, isocal HeizKühlsysteme GmbH, Friedrichshafen, Deutschland, 2012
6. E. Frank, Modellierung und Auslegungsoptimierung unabgedeckter Solarkollektoren für die Vorerwärmung offener Fernwärmenetze, Kassel University Press, 2007
7. Data set for Viessmann Vitocal 300-G BW series , in Planungsunterlagen für Wärmepumpen - Ausgabe 05/2012, Viessmann Deutschland GmbH, Allendorf, Germany, 2012
8. Datenblatt Viessmann Vitocell 100-V Typ CVW - 06/2009, Viessmann Deutschland GmbH, Allendorf, Germany, 2009