

Daniel Philippen, Daniel Carbonell, Mattia Battaglia, Michel Haller
Institut für Solartechnik SPF
Hochschule für Technik Rapperswil HSR
Oberseestrasse 10, CH-8640 Rapperswil
daniel.philippen@spf.ch
www.spf.ch

Eisspeicher in der Forschung und im praktischen Einsatz (in English)

Zusammenfassung

Eisspeicher können zur Speicherung von Niedertemperaturwärme und als Wärmequelle von Wärmepumpen eingesetzt werden. Zum Entzug der Latentwärme im Eisspeicher können unterschiedliche Wärmetauscherarten verwendet werden. Eine Auswahl solcher Wärmetauscher (Kapillarmatten („ice-on-coil“) und Plattenwärmetauscher ohne Enteisungsfunktion) wurde mit Labormessungen untersucht, wobei sich gezeigt hat, dass Kapillarmatten einen niedrigeren und über den gesamten Vereisungsvorgang stabileren Wärmedurchgangskoeffizienten haben. Der Vergleich zweier Konzepte für Solar-Eis-Heizungen zeigt, dass das Eisspeichervolumen dann deutlich verringert werden kann, wenn sehr niedrige Soletemperaturen (-8 °C) am Einlass des Verdampfers erlaubt sind. Diese Niedertemperatursysteme benötigen keine Zusatzheizung und können Systemjahresarbeitszahlen (SPF_{SHP+}) bis 6 erreichen. Solar-Eis-Heizungen mit grossen Eisspeichern können mit Komponentengrössen, wie sie in Einfamilienhäusern installiert werden können, SPF_{SHP+} über 7 erreichen. Eine Solar-Eis-Heizung wird vorgestellt, die in einem Neubau mit $2'050\text{ m}^2$ Energiebezugsfläche installiert wurde und voraussichtlich einen SPF_{SHP+} von 4.2 erreicht. Die unverglasten Kollektoren des Neubaus können als alleinige Wärmequelle für die Wärmepumpe bis zu einer Minimaltemperatur von -10 °C eingesetzt werden.

Summary

Ice storages allow the storing of solar heat in a compact volume for the later use as source for a heat pump. Different heat exchanger concepts can be used for ice storages to extract the latent heat. Measurement results for a selection of these heat exchanger concepts (capillary mats (ice-on-coil), and flat plate without de-icing) were presented, showing that capillary mats have lower but more stable heat transfer coefficients while extracting latent heat. A comparison of solar-ice systems shows that a relevant reduction of ice storage volume can be realized with concepts that allow for temperatures on the source side of the heat pump down to -8 °C . These low temperature heat source systems still reach SPF_{SHP+} around 6 without a need for a backup heater. Solar-ice systems with larger ice storage volume can reach SPF_{SHP+} above 7 with component sizes that are feasible for single family houses. A solar-ice system was realized in a new building with $2'050\text{ m}^2$ heated floor area providing heat for space heating and domestic hot water with an anticipated SPF_{SHP+} of 4.2. The system is designed in a way that the ice storage stores solar heat seasonally and the unglazed collector field can be used as low temperature source for the heat pump down to a temperature of -10 °C .

Use of ice storages in heating systems

Ice storages have been used for many decades in the cooling industry and for air-conditioning of buildings [1]. For this kind of application ice storages are optimized for the provision of high cooling power in industrial processes and for the dispersal of cooling loads for air-conditioning over the day in order to reduce chiller needs at times of peak electricity cost. Different requirements are necessary when ice storage systems are used to provide space heating and domestic hot water in buildings and possibly also space cooling. In this case it is of high importance that the storage has low investment costs, is easy to install, and needs minimal maintenance. In contrast to peak cooling applications, a reduction of the capacity of the heat pump and shaving of peak loads are not relevant.

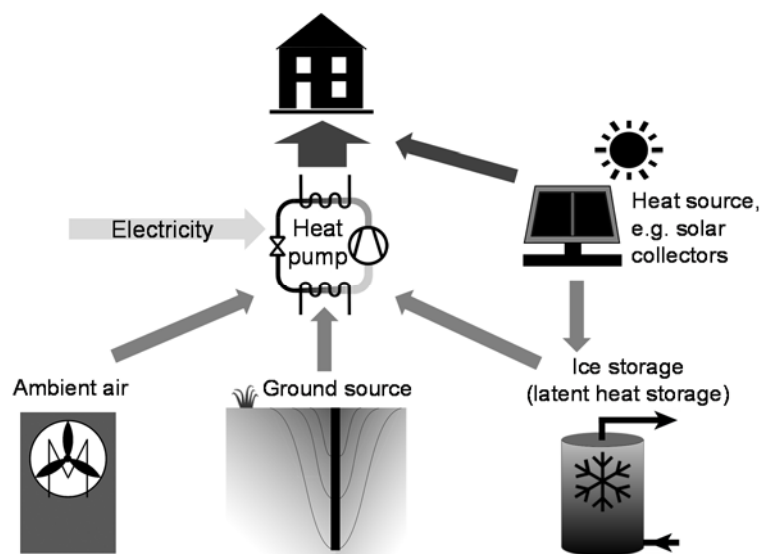


Figure 1: Principle use of an ice storage as heat source for a heat pump in a solar-ice system. The ice storage is used alternatively to ambient air or ground source.

In combination with e.g. solar collectors an ice storage is an alternative heat source compared to ambient air or ground source (see Fig. 1). Usually, the heat pump extracts the sensible and latent heat via heat exchangers that are immersed into the storage water. To be able to extract the latent heat of water, the heat transfer fluid needs to circulate below 0 °C through the heat exchangers and therefore an antifreeze mixture must be used. When the surface temperature of the heat exchanger drops below the freezing point of water, ice is formed on the heat exchanger. By this process of building up ice, latent heat of the storage water is extracted.

By freezing water, a high amount of heat can be extracted: per kilogram of water 333 kJ (0.093 kWh) are released during this 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. From these numbers it can be derived 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.

In general, the following characteristics of ice storages are of interest for solar thermal and heat pump heating systems:

- The use of phase change enthalpy in the ice storage leads to a high volumetric storage capacity, i.e. relatively small-sized ice storages can store a large amount of heat.
- Ice storages have low heat losses during operation at low storage temperatures, and can even gain heat if the storage is colder than the surroundings.
- If the ice storage is installed outside the building (especially if buried in the ground) a thermal insulation of the walls of the ice storage may not be necessary.
- The impact on-site is low compared to other heat sources for heat pumps like boreholes or air heat exchangers (no potential restrictions or risks like for boreholes and no visual or acoustic impacts like for air-source heat exchangers).
- The regeneration of the ice storage with solar heat at a low temperature level leads to additional solar gains in times during which the solar heat cannot be used directly for space heating or domestic hot water preparation.
- Low temperature heat sources like waste heat of e.g. exhaust air or waste water can deliver heat for melting the ice.
- If the ice formed in winter is stored until summer or if the building has both heating and cooling demands, the storage can be used as a heat sink for free cooling.
- The system design allows flexibility, i.e. lack of roof area can be compensated by larger ice storage volume and vice versa.

Overview of heat exchanger types for ice storages

Several heat exchanger concepts for extracting the latent heat from ice storages can be used. Each concept has to ensure that the ice layer on the specific heat exchanger reaches thicknesses that are appropriate for the concept and do not result in too low source temperatures for the heat pump. In principle, two strategies exist for the design of heat exchangers for ice storages:

(a) Large heat exchanger, homogeneously distributed throughout the whole storage volume. Depending on the extraction power of the heat pump and on the specific characteristics of the heat exchanger, a maximum ice layer thickness ranging from several centimeters to a few decimeters is usually allowed. This maximum ice thickness determines the distribution of the heat exchanger in the storage volume. The following heat exchanger types are commonly used:

- Coils or capillary mats typically made of plastic that are mounted on a supporting structure ("Ice-on-coil type", suppliers are e.g. Viessmann/Isocal, Fafco Switzerland, Conso-lar, Calmac).
- Flat heat exchanger plates mounted on a supporting structure. Each plate includes channels for the circulation of heat transfer fluid. Materials are plastic or stainless steel (supplier e.g. Energie Solaire, MEFA, BITHERM).
- Spheres made of plastic filled with water (ice balls). The ice storage is filled with the spheres and brine is pumped through the gaps between the spheres (supplier e.g. Cris-topia).

(b) Small heat exchanger in or outside the storage with prevention of ice formation on the heat exchanger or active removing of ice from the heat exchanger surface:

- Ice slurry machines that can be mounted outside the storage. On a compact heat exchanger either water is sub-cooled and freezes after being released into the ice storage or ice is directly formed on the heat exchanger, continually scraped away by a mechanic device, and washed into the storage [2] (Supplier e.g. Mayekawa Intertech).
- Falling water film: the storage water is sprayed over a heat exchanger mounted above an open storage. The storage water freezes on the heat exchanger which is periodically de-iced thermally by a hot gas [3]. This system is known as an ice harvesting system.
- Flat immersed heat exchanger plates made of stainless steel. The plates are mounted vertically at the bottom of the storage and have a low height compared to the water level. The plates are periodically de-iced thermally by low-grade heat [4].

From the above mentioned systems only the homogeneously distributed concepts are established in the solar and heat pump heating market.

Comparison of several kinds of heat exchangers for ice storages

An experimental analysis of several heat exchangers for ice storages was carried out in the SFOE project IceEx. The aim was to compare different heat exchanger concepts in terms of efficiency and cost with the goal to define the cost effective heat exchanger type and area needed for solar heating applications.

The scheme of the experimental set-up is shown in Fig. 2. The insulated storage is filled with 2 m³ of tap water. The heating and cooling is provided by a chiller with approximately 6 kW heating and cooling power. Pt100 temperature sensors are installed inside the storage for measuring the temperature at different heights and at the inlet/outlet of the heat exchangers. An ultrasonic sensor is used to measure the height of the water level and to derive the total fraction of ice inside the storage. A volume flow sensor is installed and the volume flow is regulated by a PID control.

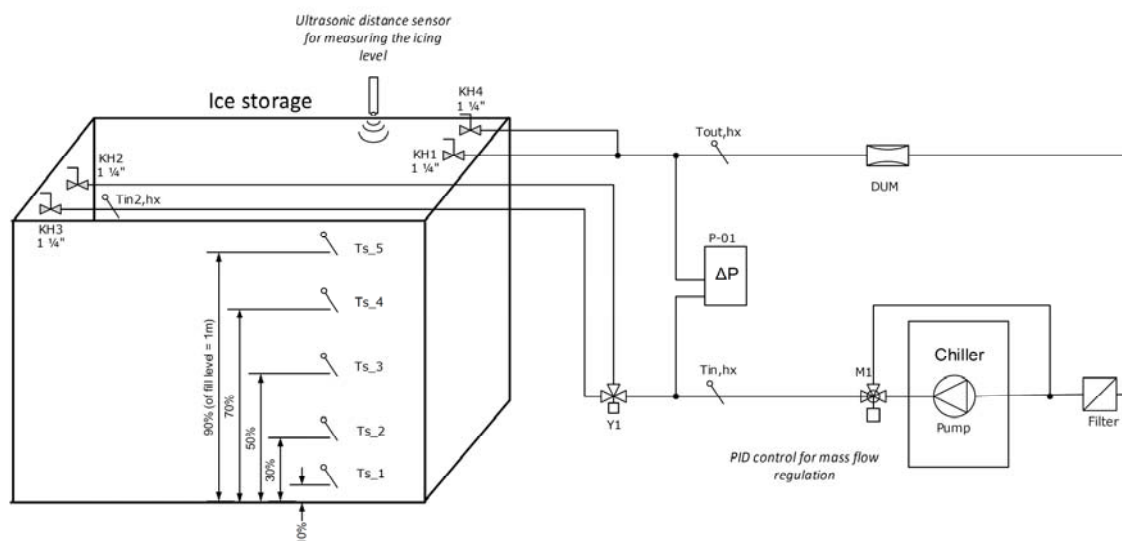


Figure 2: Experimental set-up for lab-testing of different heat exchangers in an ice storages with 2 m³ water volume.

Different heat exchangers were experimentally evaluated in the lab. Preliminary results of ice-on-coil (as capillary mats, CM) and two flat plate heat exchangers (FP) are presented.

Two capillary mats were tested (so called G and S-type, Fig. 3 a & b) that are made with the same kind of tubes and material with large header pipes for the inlet and outlet on top. The G-type has 22% more heat exchanger area than S-type, but the S-type can be mounted with half the time approximately. In both designs, the mats have been connected in parallel to the distribution pipes and are tested with 16 or 8 heat exchanger sub-units. In total, four capillary mat combinations have been tested as shown in Table 1.

Two different flat plate heat exchangers have been tested. One was made of stainless steel (SS) and the other of polypropylene (PP, Fig. 3 c). Data of these heat exchangers is given in Table 2.

Tab. 1: Heat exchanger data for capillary mats.

Type	n_{hx} [-]	n_{tubes} [-]	L_{tube} [m]	d_i [mm]	d_o [mm]	A_{hx} [m ²]	x_{tubes} [mm]	x_{hx} [mm]
G-16	16	64	1.96	2.75	4.25	30.75	30	30
S-16	16	96	0.98	2.75	4.25	24.06	20	60
G-8	8	64	1.96	2.75	4.25	15.38	30	60
S-8	8	96	0.98	2.75	4.25	12.03	20	120

Tab. 2: Heat exchanger data for flat plates.

Type	n_{hx} [m]	L_{hx} [m]	H_{hx} [-]	A_{hx} [m ²]	x_{hx} [mm]
SS-10	10	1.854	0.834	30.93	100
SS-8	8	1.854	0.834	24.73	125
SS-6	6	1.854	0.834	18.55	167
PP-10	10	1.875	0.860	32.25	100
PP-8	8	1.875	0.860	25.80	125



a)



b)



c)

Figure 3: Examples of heat exchangers (a) 16 S-type capillary mats (b) 8 G-type capillary mats and (c) 8 polypropylene flat plates.

The following processes were tested in the experiments: sensible heating and cooling, solidification, cycles of icing and melting, and melting. The set-temperatures of the chiller during the different modes were in the range of 40 °C to -10 °C. Two mass flow rates were used for the experiments: 1'000 and 2'000 l/h.

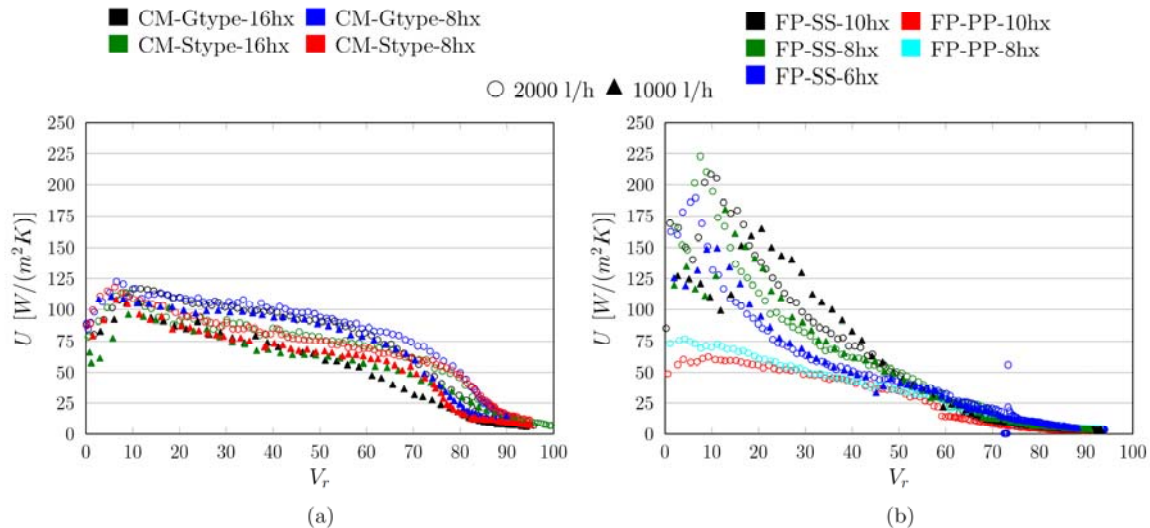


Figure 4: Overall heat transfer coefficient as a function of the ice fraction for the solidification sequence (a) Capillary mats (CM) and (b) Flat plates (FP) made of stainless steel (SS) or polypropylene (PP) with different numbers of heat exchanger sub-units.

The overall heat transfer coefficient (U) is shown as a function of the ice fraction (V_f) in Fig. 4 for CM (left) and FP (right). It can be observed that the U -values for CM are lower for small ice fractions compared to FP but more stable over the whole range of ice fraction. The U -values of the stainless steel FP are large at the beginning of the solidification sequence but drop to low levels already after 50 % ice fraction. The polypropylene FPs show the lowest U -values. For CM, considering the ideal case of ice growing on a single tube, the higher thermal resistivity of the ice layer when ice grows is partially compensated by the increasing surface area of the ice around the tube. Therefore, the heat extraction power in W remains relatively constant when ice grows on a cylinder [5] until a certain thickness is reached respectively until ice of neighboring tubes gets into contact with each other.

While in all ice storages on the market that are known to us, the maximum ice fraction allowed is far below 100 %, in our lab tests ice fractions close to 100 % did not cause any destructive effects on the casing. This allows for a higher use of latent heat capacity per volume of ice storage and thus also allows for reducing size and costs.

The measurement results have been used for validating the ice storage model for the different heat exchanger concepts. Based on the developed ice storage model an optimization of the heat exchanger area in the ice storage as a function of the design of the heat exchanger concept will be done with annual simulations. Moreover a costs analyses will be performed.

Solar-ice systems: Effect of component sizes on the efficiency for specific system designs

The integration of an ice storage into a heating system can be done in different ways in terms of hydraulic connections and heat sources that are used for loading the ice storage. In solar-ice systems the ice is melted by heat from solar collectors. Further (low) temperature heat sources like waste heat might be used for the melting as well.

To assess the electric efficiency of heat pump systems in general and in particular of solar-ice systems the System Performance Factor (SPF_{SHP+}) calculated as described in [6] can be used:

$$SPF_{SHP+} = \frac{Q_{DHW} + Q_{SH}}{P_{el}}$$

Where Q_{DHW} and Q_{SH} is the useful heat per year delivered to the building as domestic hot water and space heat respectively, and P_{el} is the electricity demand per year of the whole heating system including the circulation pump of the heat distribution system.

Several examples of research work on solar-ice systems can be found in the literature. In [7] simulations for the Viessmann/Isocal system using climate data and system boundaries different from the ones used here were carried out. For the SFH45 building of Task44/Annex38 a seasonal performance factor of 4.2 was reached. In [8] simulation results for a solar-ice system with different heating loads of the building are shown. The seasonal performance factor reached 4.8. In [9] different solar-ice system in the field are listed that reach maximum SPF_{SHP+} around 3.5.

In the following, results from system simulations of two different system concepts are compared:

- **High-T-systems:** a concept where the system is designed in a way that the brine temperature always remains above -3 °C . The reason behind this is that heat exchangers are used in the ice storage that have to be de-iced when the brine leaving them is colder than -3 °C , and part of the brine is always pumped through the ice storage when the heat pump is in operation. The solar-ice system is designed for reaching highest SPF_{SHP+} . The simulations of the High-T-System were done within the SFOE project High-Ice [10]. Results are shown for glazed collectors.
- **Low-T-systems:** here the collector field can be used as a heat source for the heat pump without the simultaneous operation of the ice storage and/or the ice storage has heat exchangers that are not de-iced. As a result, the brine source may reach very low minimum temperatures. In the simulations -8 °C inlet temperature was set as minimum and unglazed collectors are used to ensure high solar gains and heat gains from ambient air when used as a source for the heat pump.

In the High-Ice project the solar-ice system was implemented in single family houses (SFH) with different heating demands and weather data. A backup (electric rods) is simulated and switched on if the heating demand cannot be covered by the heat pump. This is the case when the ice storage is completely iced and the actual heat gain of the collector field is not sufficient to run the heat pump.

The definition of the simulated building is based on the IEA SHC Task44 /Annex38 boundary conditions (building SFH45: see [11] and [12]). The building has a low temperature heat distribution system with flow and return temperatures of 35 and 30 °C respectively at nominal conditions. The heated floor area is 140 m², the space heating demand 59 kWh/(m²a) for the climate of Zurich. The domestic hot water (DHW) is tapped at temperatures of 45 °C and 55 °C. The average tapping amount is 140 l/d. This corresponds to 2133 kWh/a or 15.2 kWh/a per m² of heated building area. Results of the system simulations are presented for the climate of Zurich.

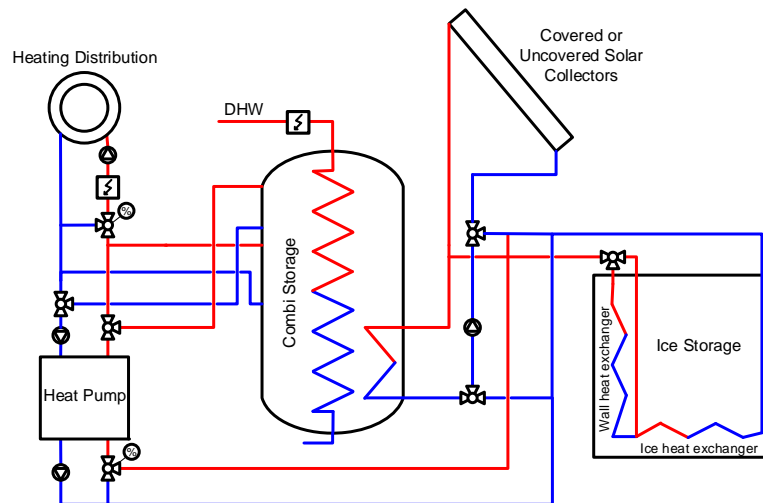


Figure 5: Hydraulic scheme of the analysed solar-ice heating system.

The system performance SPF_{SHP+} of the High-T-system (in green, Fig. 6) ranges from 2 to approximately 7. High-T-systems that need no backup reach SPF_{SHP+} of 5.8 to 7.2, depending on the component sizes. Smallest High-T-systems without need for backup have sizes e.g. of 30 m³ ice storage and 20 m² glazed collectors or 15 m³ and 35 m², and reach SPF_{SHP+} of 5.8 and 6.3 respectively.

For Low-T-systems (in black, Fig. 6) the backup can already be avoided with much smaller volumes for the ice storage. The Low-T-systems can reach high SPF_{SHP+} up to approx. 6.0. As their unglazed collectors have a lower efficiency during summer, the maximum SPF_{SHP+} that were observed are lower than for the High-T-systems. The Low-T-systems can avoid backup and reach an SPF_{SHP+} of 5.0 already with an ice storage size of 6 m³ and unglazed collectors with 25 m² total area. The use of low temperatures on the evaporator side allows for running the heat pump with the collectors as the only source. This greatly reduces the time when the ice storage is fully iced and thus the use of the electrical backup. A lower COP of the heat pump for running with collectors at very low temperatures, instead of using the ice storage at 0 °C, is compensated by the lower need of the electrical backup.

For both system concepts the potential to increase the SPF_{SHP+} is high if the increase of sizes of storage volume or collector area leads to reduced backup usage. When the electricity demand of the backup reaches values near zero, the increase is smaller but still significant. However, results of a life cycle assessment of these solar-ice systems show that a further increase of system sizes after the demand of the backup reaches zero is not beneficial [10].

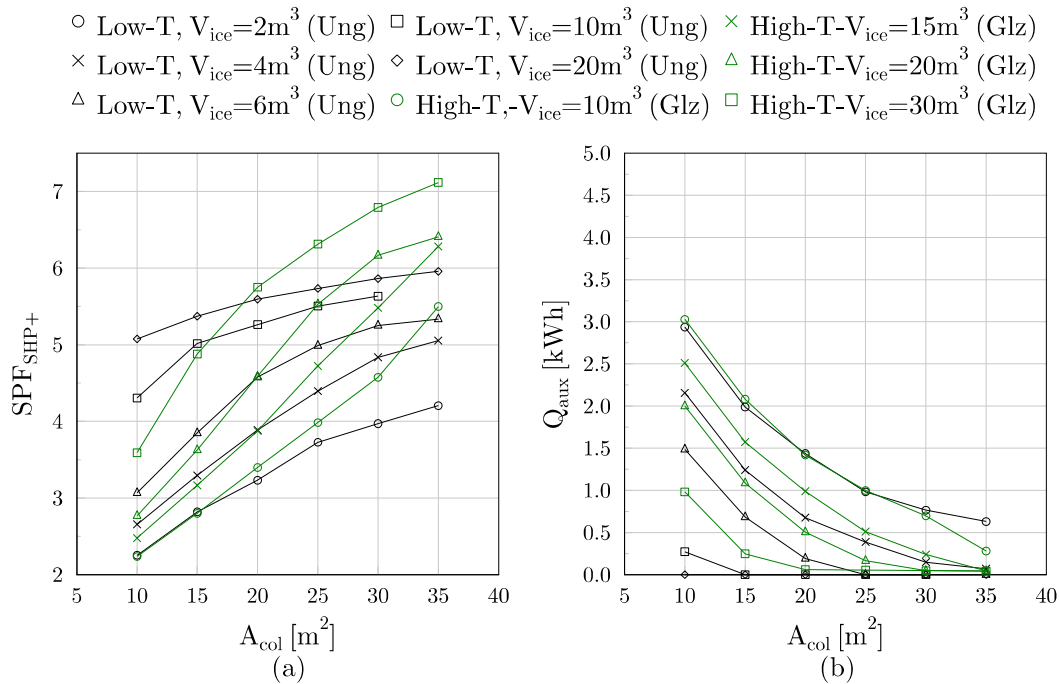


Figure 6: Seasonal performance factors (left) and electrical backup (right) of High- and Low-T-systems with varying ice storage volume (V_{ice}) and collector area for building SFH45. Un-glazed (Ung) respectively glazed (Glz) collectors are simulated.

P&D-Lattenhofweg: A solar-ice system with de-icing concept

In March 2017 a solar-ice system was set into operation which was integrated into a new building with 2'050 m² of heated floor area realized by the Elektrizitätswerk Jona-Rapperswil AG (EWJR). The heating system was designed and will be monitored by SPF Institut für Solartechnik in the frame of an SFOE Pilot and Demonstration Project.



Figure 7: New building with 2'050 m² of floor area which is supplied with heat by the solar-ice system.

The building is characterized by a mixed use with 7 apartments, offices and a business enterprise. The total heat demand, including domestic hot water, is expected to be 91 MWh per year. The specific demand for space heat is 32 kWh/(m²a). The space heat is delivered via floor

heating and radiant ceiling panels with flow/return temperatures of 35 °C and 28 °C, respectively. A heat pump with thermal power of 22.5 kW (one compressor) and 45 kW (two compressors) at B0/W35 is installed.

A novelty of this building is an ice storage of 210 m³ volume that is integrated into the shell of the building. This storage is situated at the basement adjacent to the underground car park. 42 heat exchangers with height of 62 cm are installed at the bottom with a total heat exchanger area of 114 m² (both sides of the flat plates taken into account). The ice storage is used as seasonal storage for the solar heat and it is unloaded by the heat pump in the heating season. However, loading of the ice storage is done regularly during winter if solar low grade heat is available which is often the case as high temperatures cannot be reached often with the unglazed collectors that are installed.

On the flat roof a maximum of 120 m² unglazed collectors could be installed, i.e. 1.3 m² per MWh/a total heat demand. In the system simulations shown in the chapter above this ratio is around 2.4 without need for backup for the Low-T-system. Hence, the realized solar-ice system had to be designed in a way that on the one hand a maximum of heat can be extracted from the small collector area by low brine temperatures and on the other hand the ice storage volume had to be increased to 210 m³ (2.3 m³/MWh versus 0.57 m³/MWh for the Low-T-system) for seasonal storing of solar heat. The heat exchangers in the ice storage are based on the above mentioned de-icing concept, which ensures high source temperatures for the heat pump near 0 °C while extracting latent heat and ensures low investment costs.

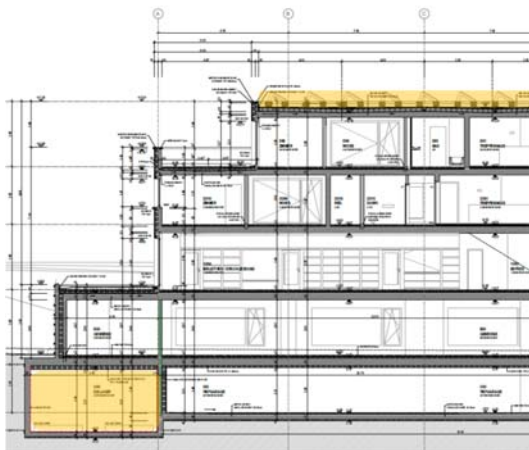


Figure 8: Left: Part of the section of the building. Highlighted are the ice storage next to the underground car park and the collector field on the flat roof. Right: Photo of the ice storage with 210 m³ volume before filling. At the bottom heat exchangers are installed that can be de-iced.

The solar collectors are the only heat source for the building. When using one of the two evaporators, the collector field can serve as sole source. In this operation mode, a minimum inlet temperature of the brine entering the evaporator of -10 °C is accepted. As a consequence of low temperatures of the brine, a high efficiency of the solar collectors is reached and also heat from the ambient can be gained as the collectors are unglazed. When the heat pump runs with both compressors the collectors and the ice storage are used as sources in parallel. The simulations show that due to the use of the collectors as low temperature source a high specific solar yield

of 640 kWh/(m²a) can be expected. The solar-ice system is designed in a way that an SPF_{SHP+} of 4.2 can be reached.

Acknowledgments

The SPF likes to thank the Swiss Federal Office of Energy for financing our work within the frame of the projects High-Ice, IceEx, and the P&D project Lattenhofweg. Our thanks go also to the company EWJR AG for mandating the development of a solar-ice system currently in the frame of the P&D project Lattenhofweg.

References

- [1] ASHRAE, 2007. Handbook : HVAC Applications. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- [2] T. Abrahamsson, S. Jonson, and K.-O. Lagerkvist (1981). Heat from solar energy and air with storage in water and ice, The Bramhult project in Boras. Swedish Council for Building Research in Stockholm, Sweden.
- [3] H. Mehling, L. Cabeza, (2008). Heat and cold storage with PCM: an up to date introduction into basics and applications. Berlin Heidelberg: Springer-Verlag.
- [4] D. Philippen, M.Y. Haller, W. Logie, M. Thalmann, S. Brunold, E. Frank, 2012. Development of a heat exchanger that can be de-iced for the use in ice stores in solar thermal heat pump systems, in: Proceedings of EuroSun, International Solar Energy Society (ISES), Rijeka and Opatija, Croatia.
- [5] D. Carbonell, D. Philippen, M.Y. Haller, E. Frank, 2015. Modeling of an ice storage based on a de-icing concept for solar heating applications. Solar Energy 121, 2–16.
- [6] I. Malenkovic, S. Eicher, J. Bony, (2012). Definition of main system boundaries and performance figures for reporting on SHP systems. IEA-SHC Task44 Subtask B.
- [7] C. Winteler, R. Dott, T. Afjei, B. Hafner, 2014. Seasonal performance of a combined solar, heat pump and latent heat storage system. Energy Procedia 48, 689–700. Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013).
- [8] C. Trinkl, W. Zörner, V. Hanby, 2009. Simulation study on a domestic Solar/Heat pump heating system incorporating latent and stratified thermal storage. Journal of Solar Energy Engineering 131, 041008.
- [9] S. Minder, R. Wagner, M. Mühlebach, T. Weisskopf, Eisspeicher-Wärmepumpen-Anlagen mit Sonnenkollektoren, Weisskopf und Partner im Auftrag des Bundesamts für Energie, Schlussbericht 15. September 2014.

- [10] D. Philippen, D. Carbonell, D. Zenhäusern, M. Granzotto, M. Haller, S. Brunold, High-Ice; System development for high solar thermal gains with ice storage and heat pump - Final Report, <http://www.bfe.admin.ch/php/modules/enet/streamfile.php?file=000000011293.pdf&name=000000291052>
- [11] R. Dott, M.Y. Haller, J. Ruschenburg, F. Ochs, J. Bony, (2012). The reference framework for system simulation of the IEA SHC Task44/HPP Annex 38: Part B : Building and space heat load. Technical Report IEA-SHC Task44 Subtask C.
- [12] M.Y. Haller, R. Dott, J. Ruschenburg, F. Ochs, J. Bony, (2012). The reference framework for system simulation of the IEA SHC Task44/HPP Annex 38: Part A : General simulation boundary conditions. Technical Report IEA-SHC Task44 Subtask C.