

Solar-ice systems for multi-family buildings: hydraulics and weather data analysis

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Abstract.

Dynamic simulations using the TRNSYS environment were used to assess the potentials of solar-ice systems for multi-family buildings in Switzerland. The goals of this paper were: i) to analyze and quantify the effects of different hydraulics in the primary loop (solar collectors, ice storage and heat pump), ii) to determine the energetic performance of solar-ice systems for multi-family buildings and iii) to assess the influence of the chosen weather data on the system performance. Simulations were carried out for a range of collector areas of 1.5 m²/MWh to 2.5 m²/MWh and for ice storage volumes of 0.4 m³/MWh to 0.6 m³/MWh being MWh the total yearly heat demand.

An averaged increase of the Δ SPF of 26 % was obtained by using direct solar heat in the warm storage. Adding the possibility to use solar heat for heat pump evaporator, increased the SPF_{SHP+} by 31 %. Simulations of eight cities in Switzerland using cold, warm and normal weather data sets from SIA were carried out. Results for Davos and Locarno achieved the best results with averaged SPF_{SHP+} of 7.4 and 6.3 respectively. Simulations for the rest of the cities achieved averaged SPF_{SHP+} in the range of 3.8 to 4.5. The use of cold weather data respect to the normal one defined by the SIA standard led to an average decrease of the SPF_{SHP+} of 25 %. The use of a warm weather data led to an increase of the SPF_{SHP+} of 5 %.

1 Introduction

A general increase of system efficiency by raising the share of renewable energy in the building sector is necessary to reach the ambitious targets of the European Commission by 2050 [1]. Heat pumps are becoming a well-known technology to increase the share of renewable energy. Heat pumps can use air, ground, waste water or solar energy as heat source for the heat pump. In this paper, the combination of solar thermal and heat pump systems with ice storages, the so-called solar-ice systems will be investigated for multi-family houses. Solar-ice systems are an alternative to air and ground-source heat pump systems and have the potential to be more efficient by reducing the use of electricity. As opposed to the air and ground-source systems, solar-ice systems do not need space for air heat exchangers or for drilled boreholes around or below the building. This is an advantage when fossil based heating systems are replaced in existing buildings in urban areas and might be important for the reduction of CO₂-emissions, especially for large refurbished buildings. Solar-ice systems are becoming more and more popular in the Swiss and German market. However, designing a solar-ice system for a specific building is challenging due to the interactions between the main components of the system like collector field, ice storage (heat exchangers), and heat pump. The main components are strongly influencing each other in terms of energy flows. Hence, only very experienced planners are able to design and install solar-ice systems that work efficiently and do not

need an extensive optimization phase after commissioning. Different ways of how solar heat is provided to the other components are offered on the market. However, possible advantages or disadvantages of different hydraulic connections have not yet been analyzed in a systematic way. As a consequence, it is difficult for the market participants to make proper decisions when assessing the different solar-ice system concepts.

Solar-ice systems are competing with other heat pump based systems such as air source or ground source heat pump systems. Therefore, finding reference conditions to compare these solutions is of importance. Usually dynamic simulations software such as TRNSYS or Polysun use Meteonorm as a source for weather data. However, the selection of the weather data is crucial in order to estimate the performance of solar-ice systems, since these systems rely on the energy extracted from the collector field (from solar and air) as the only heat source. Results presented in [3] showed an increase of 25 % on the average system efficiency (SPF_{SHP+}) using real data for 11 years compared to the climatic data obtained from Meteonorm in Zurich for one year. As an order of magnitude this means that 0.5 m² collector area per MWh of total heat demand could be reduced to achieve the same SPF_{SHP+} . In a single family home in Zurich this represents a saving of 5 m² of collector area corresponding to a 8 % reduction of the total system investment cost. Ground source heat pumps on the other hand are not significantly affected by the weather differences between different years in the same location. Thus, for a fair comparison between the systems, appropri-

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ate weather data should be used. Within this paper, the influence of the selected weather data will be analyzed using SIA weather data [7] in Switzerland based on cold, normal and warm years.

2 Methodology

Dynamic simulations using the simulation environment TRNSYS-17 [4] were used to assess the potentials of solar-ice systems. A reference multi-family building was defined and climatic conditions from different locations in Switzerland were used for the analyses. The basic components to model a solar-ice system are: collectors, heat pump, ice storage, sensible thermal storage, building, and system control. The ice storage model was based on ice-on-capillary heat exchangers, which was presented and validated in [5]. The remaining component models were provided in [2], where a complete solar-ice system based on a de-icing concept was validated with a one year monitoring data of a pilot plant located in Jona, Switzerland. The control explanation for non de-icing solar-ice concepts, as the ones used in this paper, can be found elsewhere [6].

The time step of the yearly simulations was set to 120 seconds. As a verification process several systematic checks were done for all simulations. Heat balances are calculated for all individual components, hydraulic loops and also from the system perspective. The convergence criteria from TRNSYS is set to $5e-4$, which allows to achieve heat imbalances always below 1 % with respect to the total heat demand.

2.1 Possible hydraulic integration

The solar-ice systems that are sold on the market or analyzed in the literature can be classified by the way the solar heat is used. Besides the common use of regenerating the ice storage, solar heat can be used directly to load the warm storage (direct heat mode) or to work in series with the heat pump providing heat to the evaporator (series mode). These combinations lead to four principle system concepts shown in Figure 1. Viessman (Isocal) sells a system with non-selective unglazed collectors with designs according to Hyd-IceHp. Consolar has a system for single family houses with hybrid collectors and a hydraulic according to Hyd-IceTes. Energie Solaire SA offers systems with Hyd-IceTes and Hyd-IceHpTes hydraulics together with their selective uncovered collectors. Comparisons between these hydraulics are necessary to quantify the benefits of adding hydraulic possibilities.

The main energy source of the system is the solar radiation. Some additional energy is extracted from the air, especially when uncovered collectors are used. The authors are only aware of one system installed in the field using covered collectors [15] and therefore all simulations provided in this work are obtained using uncovered collectors. One of the objectives of this paper is to quantify the benefits of the use of solar direct heat and therefore the use of thermal collectors with selective coatings is of important. In this paper, uncovered selective collectors made

of stainless steel have been used for all simulations. Part of the total solar radiation is transformed by the collectors to useful heat for the system. This energy is transferred, either to the heat pump if series operation is active (Hyd-IceHp and Hyd-IceHpTes), to the ice storage (all hydraulics integration), or to the combi-storage (Tes) if the use of solar direct heat is possible (Hyd-IceTes and Hyd-IceHpTes). When the heat pump is running, two operation modes are possible: i) the heat pump uses the solar energy directly as a heat source in a series operation mode (Hyd-IceHp and Hyd-IceHpTes) or ii) the heat pump uses only the ice storage as its direct source (all systems). If none of these heat sources are available, which means that the ice storage is full of ice and the solar radiation and the ambient temperature are very low, the temperature of the heat pump evaporator drops below the minimum value allowed and the heat pump stops. In this case, a direct electric back-up, implemented as two electric rods located in the combi-storage at DHW and SH positions, is used.

2.2 Weather data

In order to systematically assess the influence of the different weather data profiles from the same location and also to assess the behaviour with different locations, the SIA weather data was used. The SIA weather data uses the standard SN EN ISO 15927-4, to generate a collection of so called *Design Reference Years*. This collection is based on measurement data from the years 1984 to 2003. It contains weather data of 40 different locations in Switzerland, each with an extreme warm, an extreme cold and a normal design reference year as described in [7]. From all of these, eight locations have been chosen in order to cover most of the weather types in the inhabited regions of Switzerland: Basel (BAS), Bern (BER), Davos (DAV), Geneva (GEN), Zurich (KLO), Lucern (LUZ), Locarno (OTL) and St. Gallen (STG).

2.3 Collector area and ice storage volume sizes

Dynamic system simulations were carried out for a set of ice storage volumes of $0.4 \text{ m}^3/\text{MWh}$, $0.5 \text{ m}^3/\text{MWh}$ and $0.6 \text{ m}^3/\text{MWh}$ and a set of collector areas of $1.5 \text{ m}^2/\text{MWh}$, $2 \text{ m}^2/\text{MWh}$ and $2.5 \text{ m}^2/\text{MWh}$, where the MWh unit refers to the yearly heat demand. This size range was shown to be cost competitive while achieving system performances in the range of ground source heat pump systems for single family houses [6]. However, companies such as Viessman (Isocal), tend to size the ice storage as $1 \text{ m}^3/\text{MWh}$ for single family homes and well above $2 \text{ m}^3/\text{MWh}$ for multi-family buildings using as source non-selective plastic collectors that are used more as air heat exchangers than as solar collectors. Others, such as Energie Solaire SA, tend to size the ice storage with values around $0.2 \text{ m}^3/\text{MWh}$ making use of a high collector field in the range of $2.5 \text{ m}^2/\text{MWh}$.

The absolute values of collector area in m^2 and ice storage volume in m^3 depend on the total heat demand in MWh, which in turn depends on the location and weather data selected (warm, normal and cold). For obtaining the

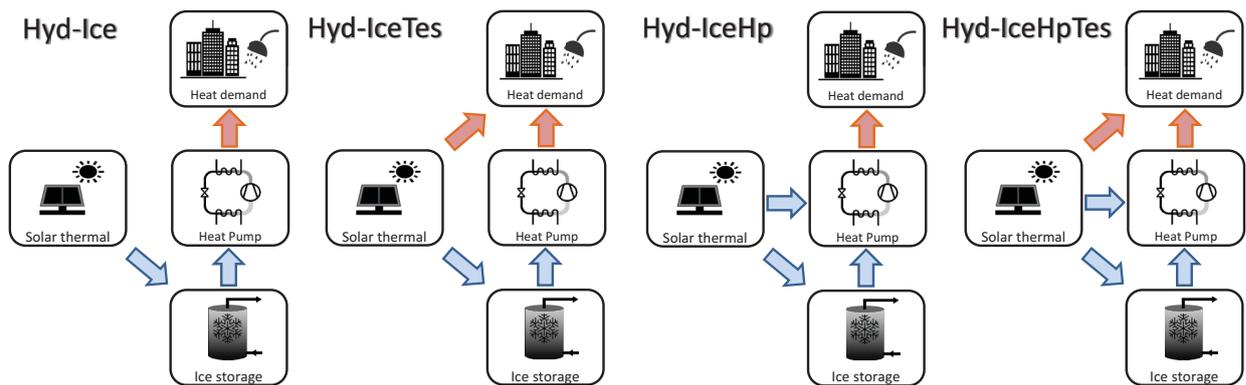


Fig. 1. Principle concept of solar-ice systems. The arrows show the heat fluxes that are on different temperature levels, i.e. red and blue for high (>30 °C) and cold (<10 °C) respectively.

absolute sizes of the collector area and ice storage volume, the relative sizes are multiplied to the yearly heat demand using the specific weather data. Therefore, the absolute sizes of collector area in m² and ice storage volume in m³ are different for the cold, warm and normal data sets for each location.

2.4 Performance indicators

The main performance indicator for the systems is the System Performance Factor calculated as described in [8]:

$$SPF_{SHP+} = \frac{Q_{DHW} + Q_{SH}}{P_{el,T}} = \frac{Q_D}{P_{el,T}} \quad (1)$$

Q is the yearly heat demand and P_{el,T} the yearly electricity consumption of the heating system. The subscripts SHP, DHW, SH and D stand for solar and heat pump, domestic hot water, space heating, and total demand respectively.

The yearly electricity consumption is calculated as:

$$P_{el,T} = P_{el,pu} + P_{el,hp} + P_{el,cu} + P_{el,back-up} + P_{el,pen} \quad (2)$$

where the subscripts pu, hp, cu, aux and pen refer to circulation pumps, heat pump, control unit, back-up and penalties respectively. The symbol "+" in the SHP+ from Eq. 1 refers to the consideration of the heat distribution circulating pump in the electricity consumption. Therefore, the system performance indicator used in this work includes all circulation pumps of the system and also all thermal losses/gains from storages and piping. Penalties for not providing the heating demand at the desired comfort temperature are calculated according to [9]. P_{el,back-up} is the energy used from the direct electric back-up system. This back-up is implemented with two electrical rods for DHW and SH in the storage. The back-up is switched on when the temperature of the brine at the inlet of the evaporator drops below -8 °C. This is the case when the ice storage is at its maximum allowed ice fraction and the energy gained in the collector field is not sufficient (night or foggy times with low ambient temperatures).

In order to compare results from one simulation with a particular set-up to a reference (ref) case, the relative increase of SPF_{SHP+} is used:

$$\Delta SPF = 100 \cdot \frac{SPF_{SHP+} - SPF_{ref}}{SPF_{ref}} [\%] \quad (3)$$

3 Description of space heating and domestic hot water demands

3.1 Reference building

A multi-family house (MFH), as described in [10], was used as reference building for the simulations. It has an energy reference area (A_E) of 1205 m² that consists of common areas and three residential floors with a total of six apartments. Further key figures of the reference building are the ratio of the thermal building envelope to the energy reference area of 1.3 and the window share in relation to A_E of 25 %. A depiction of the building can be seen in Fig. 2. The zones and internal loads correspond to the specifications of the data sheet SIA 2024 [11]. The building was modelled as a solid structure and the building envelope was designed in such a way that the heating requirement meets the Swiss *Minergie* standard for sustainable buildings, with mechanical ventilation that has a heat recovery efficiency of 80 %. It has a standard heating demand of 29 kWh/(m² a) for the reference weather station Zurich SMA. The results obtained with a detailed building model from IDA-ICE were used to fit a simplified building model using the SIA standard [12]. The TRNSYS building model used is a modified version of [13] as described in [3].

3.2 DHW profile

A DHW profile was created using the Load Profile Generator software [14]. A single profile for each of the six apartments were considered:

- Couple under 30 years old, both at work.

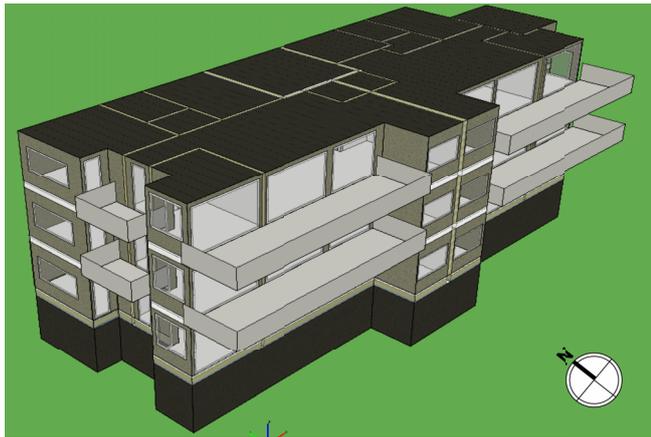


Fig. 2. IDA ICE model view of the reference building.

- Family with two children (14-16), one at work, one at home.
- Family both at work, two children (9-12).
- Retired couple, both at home.
- Shift worker couple.
- Family, two children (6-12), both parents at home.

The six single profiles of the apartments were merged to one DHW profile including an annual tapped consumption of 16.9 MWh at a delivery temperature of 35 °C. Fig. 3 shows the DHW draw-off profile for the first week of the year. The DHW demand is in the order of 16 kWh per m² of heated surface area. A scaling factor of the consumption in l/h was applied to use 45 °C as delivery temperature. Circulation losses were included such that the minimum return temperature of the circulation loop was 53 °C. These temperatures were chosen to fulfill the standards that will be used in Switzerland in a near future. The pipe length from the circulation loop has been defined such that the circulation losses were around 33 % of the DHW demand. In total, the DHW demand including circulation losses accounted for 23 kWh/m².

4 Results

4.1 Analyses of hydraulic configurations

All simulations from this section were carried out using the multi-family building described in section 3.1 located in Zurich with 49.5 MWh of total heating demand for SH and DHW. The normal year from the SIA data [7] for the Klotten weather station was used to represent Zurich. Results using different hydraulic configurations are shown in Fig. 4. Results were obtained using the sets of 1.5 m²/MWh, 2 m²/MWh and 2.5 m²/MWh collector area and 0.4 m³/MWh, 0.5 m³/MWh and 0.6 m³/MWh ice storage volume.

Fig. 4 shows that the higher the possibilities allowed by the hydraulic integration, the higher the SPFSHP+. Thus, Hyd-Ice achieves the lowest performances with an median SPFSHP+ of 2.45. Adding direct solar heat to Hyd-Ice leads

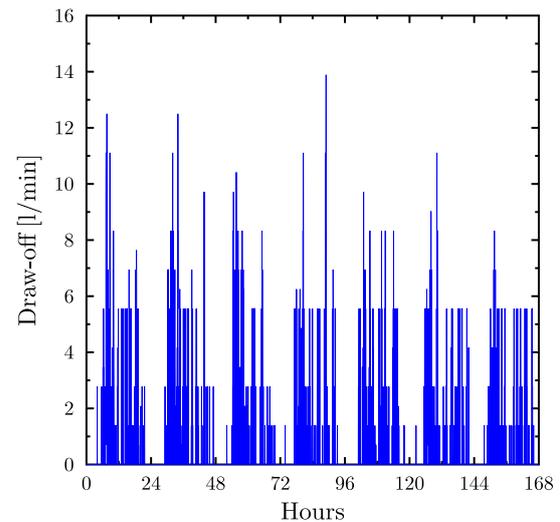


Fig. 3. Example of one week of the DHW draw-off profile of the multi-family house.

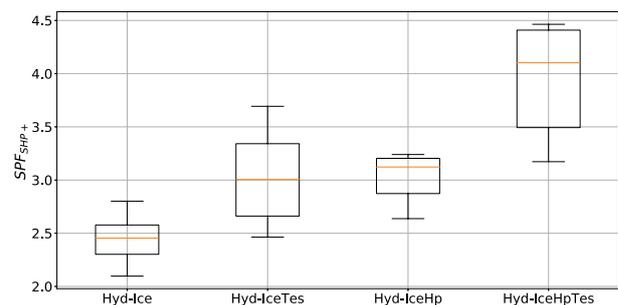


Fig. 4. System performances for ice storage volumes of 0.4 m³/MWh to 0.6 m³/MWh and collector areas of 1.5 m²/MWh to 2.5 m²/MWh for the different hydraulic configuration in the city of Zurich with the normal year defined in SIA.

to Hyd-IceTes with a median SPFSHP+ of 3.0. Adding series operation to the Hyd-Ice leads to the Hyd-IceHp with a median SPFSHP+ of 3.1. Adding solar direct heat to Hyd-IceHp leads to the Hyd-IceHpTes with a median SPFSHP+ of 4.1. These results show an average increase of the system performance ΔSPF in the range of 22 % to 31 % for adding solar direct heat and 27 % to 36 % for considering series operation to the heat pump. In total, from the Hyd-Ice to the Hyd-IceHpTes, there is an average improvement of 67 %. Thus, an appropriate implementation of the hydraulic is of high importance. These results have been obtained using uncovered selective collectors. In future works it would be of interest to include simulations using non-selective uncovered collectors.

The sensitivity of the SPFSHP+ on the collector area for each hydraulic set up is shown in Fig. 5. Results for the

simulated range show a quite linear behavior. The linear fit has been shown in the graphs as an order of magnitude to quantify the increase of the SPF_{SHP+} (slope of the linear fit) by increasing the collector area. As can be observed in Fig. 5, the slope of the linear fit increases by adding more possibilities of using the solar heat. It ranges from 0.48 for the Hyd-Ice to 1.24 for the Hyd-IceHpTes for an ice storage volume of $0.4 \text{ m}^3/\text{MWh}$ and from 0.5 to 1.03 for an ice storage volume of $0.6 \text{ m}^3/\text{MWh}$. As an example, considering that in Zurich the yearly heat demand is 49.5 MWh for the normal weather data, a slope of 1.24 for the Hyd-IceHpTes means that it is possible to increase the SPF_{SHP+} from 3 to 4 by adding $0.8 \text{ m}^2/\text{MWh}$, i.e. by adding 40 m^2 of collector area.

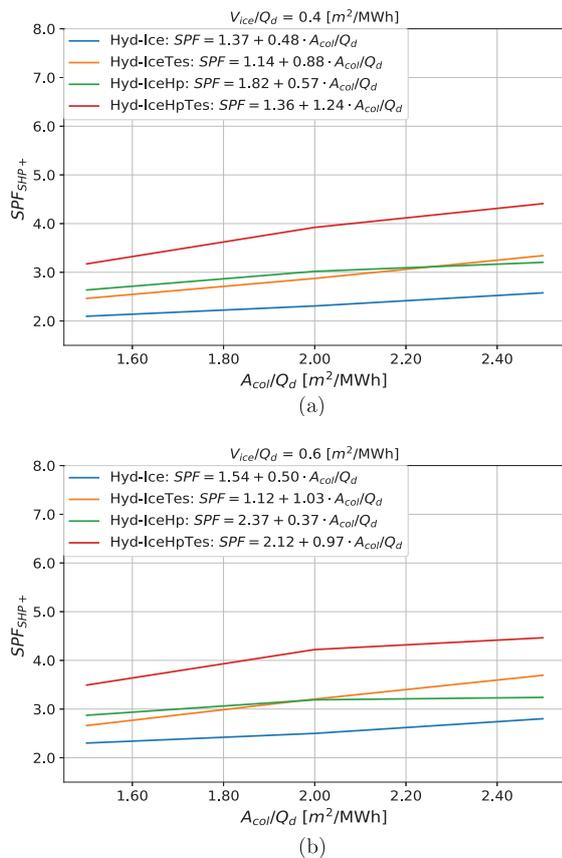


Fig. 5. System performance as function of collector area and different hydraulic configurations for ice storage sizes of (a) $0.4 \text{ m}^3/\text{MWh}$ and (b) $0.6 \text{ m}^3/\text{MWh}$.

4.2 Analysis of weather data

4.2.1 Influence of locations

As described in section 2.2, the SIA standard [7] has derived three kinds of weather data, i.e. cold, warm and normal, for 40 weather stations in Switzerland. In this section, results for eight cities are presented: Basel (BAS), Bern (BER), Davos (DAV), Geneva (GEN), Zurich (KLO), Lucern (LUZ), Locarno (OTL) and St. Gallen (STG). Results for the simulated ranges of $1.5 \text{ m}^2/\text{MWh}$ to $2.5 \text{ m}^2/\text{MWh}$ and $0.4 \text{ m}^3/\text{MWh}$ to $0.6 \text{ m}^3/\text{MWh}$ using cold, warm and normal weather data sets are shown in Fig. 6 for each location.

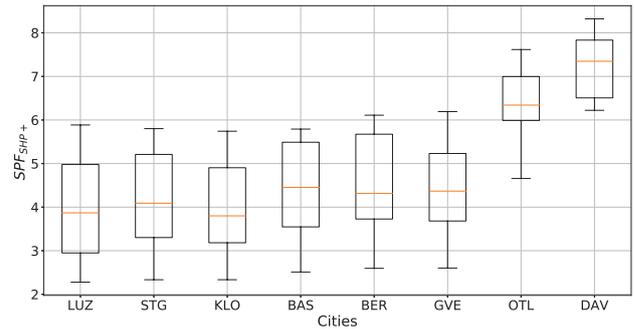


Fig. 6. System performance as a function of location for all the simulated ranges of $1.5 \text{ m}^2/\text{MWh}$ to $2.5 \text{ m}^2/\text{MWh}$ and $0.4 \text{ m}^3/\text{MWh}$ to $0.6 \text{ m}^3/\text{MWh}$ using cold, warm and normal weather data sets.

Davos (DAV), which is located in the Swiss Alps and characterized by having very cold and sunny winters, shows the best performance of all simulated locations. All simulations from Davos show system performances well above 6, reaching SPF_{SHP+} above 8 for warm years and a median SPF_{SHP+} of 7.4 (orange line in Fig. 6). These SPF_{SHP+} clearly outperform any other heat pump based system. However, simulated results are overestimated, since snow on the collectors has not been considered. Therefore, these results are only valid if snow is removed periodically. The second best results are obtained for Locarno, which is south of the Alps. It has high solar radiation in winter and warmer temperatures compared to the other cities with SPF_{SHP+} ranging from 4.7 for cold years, up to 7.6 for warm years with a median SPF_{SHP+} of 6.3. The SPF_{SHP+} for the remaining cities are on the same order of magnitude and significantly lower than those obtained in Davos and Locarno with a median SPF_{SHP+} in the range of 3.8 to 4.5.

All simulations shown in Fig. 6 have been presented in Fig. 7 using the total winter (December, January, February) irradiation reaching the collector area ($H_{T,winter}$) on the x-axis. Results correlate relatively well using winter irradiation on the collector plane as independent variable for each weather data set i.e., cold, normal and warm and for each ice storage volume. Notice that each irradiation value has three points on the vertical representing the $4 \text{ m}^3/\text{MWh}$, $5 \text{ m}^3/\text{MWh}$ and $6 \text{ m}^3/\text{MWh}$ ice storage volumes used.

4.2.2 Influence of warm, normal and cold data sets

Simulation results for all cities for an ice storage volume of $0.4 \text{ m}^3/\text{MWh}$ and a collector area of $2 \text{ m}^2/\text{MWh}$ are shown in Fig. 8 for cold, normal and warm years. The SPF_{SHP+} is shown in Fig. 8(a) and the relative increase of the system performance ΔSPF is shown in Fig. 8(b). Blue bars show the ΔSPF between using the cold and the normal weather data, and red bars show the ΔSPF between using the warm and the normal weather data. Using the cold instead of the normal year leads to an average decrease of the ΔSPF for

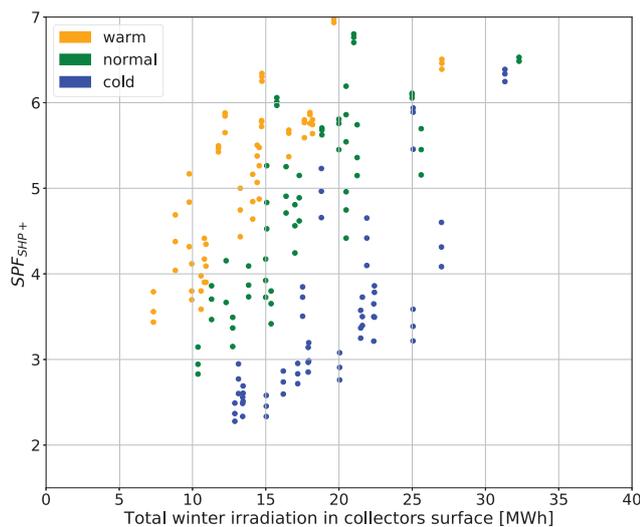


Fig. 7. System performance as a function of the winter irradiation on the collector surface for the 8 different cities, collector areas of 1.5 m²/MWh, 2.0 m²/MWh and 2.5 m²/MWh and ice storage volumes of 0.4 m³/MWh, 0.5 m³/MWh and 0.6 m³/MWh.

all cities of 25 %. Using the warm compared to the normal year, leads to an average increase of the Δ SPF of 5 %.

The selection of the warm or the cold years are based on temperature levels, while solar-ice systems are mainly influenced by the winter solar irradiation. Table 1 shows the yearly and winter solar radiation for some cities as well as the total heat demand as function of the weather data used. Davos has a very high solar radiation in winter and in the cold year is even higher than in the normal year. Geneva has also a higher irradiation in winter compared to the normal year. This partially explains why in Geneva the use of a warm year leads to a worse SPF_{SHP+} compared to the one obtained with the normal year.

Table 1. Global yearly horizontal irradiation (H_0) and global winter horizontal irradiation ($H_{0,w}$) for some cities and weather data files, as well as total heat demand.

City	Type	H_0 [kWh/m ²]	$H_{0,w}$ [kWh/m ²]	Q_D [MWh]
Davos (DAV)	warm	1397	164	56
	normal	1353	159	72
	cold	1296	173	90
Zurich (KLO)	warm	1226	103	38
	normal	1103	105	49
	cold	966	95	65
Geneva (GVE)	warm	1302	92	34
	normal	1275	117	43
	cold	1091	100	58
Bern (BER)	warm	1232	107	39
	normal	1179	119	49
	cold	994	106	66

The large difference between the SPF_{SHP+} obtained using normal and cold years, suggest that the tendency of planners of using cold years to size the system in worst case scenarios will lead to an oversize of the complete system with the corresponding additional cost. Instead, it would

be more helpful to size the system and assess its performance using an average-synthetic year that would represent a long period of time, e.g. a decade. It is not clear yet if the normal weather data of the SIA can be used to represents the long term performance of solar-ice systems. In future works, comparisons of simulations using real weather data for a decade and the normal, cold and warm weather data will be provided.

5 Conclusions

Dynamic system simulations using TRNSYS were used to assess the influence of the hydraulic configurations and of the weather data sets used in solar-ice systems for multi-family buildings.

The effects of using solar heat directly in the warm storage and the possibility to use solar heat as source for the heat pump evaporator (series operation) were quantified for the city of Zurich. Four hydraulic configurations were simulated: Hyd-Ice, Hyd-IceTes, Hyd-IceHp and Hyd-IceHpTes using a collector area of 1.5 m²/MWh, 2.0 m²/MWh and 2.5 m²/MWh and an ice storage volume of 0.4 m³/MWh, 0.5 m³/MWh and 0.6 m³/MWh per MWh of yearly heating demand. The average SPF_{SHP+} obtained for this simulated range was 2.45 for Hyd-Ice, 3.0 for Hyd-IceTes, 3.1 for Hyd-IceHp, and 4.1 for Hyd-IceHpTes. Adding solar direct heat to the thermal storage provided an average Δ SPF of 26 %. Adding series operation, i.e. the possibility to use solar heat for heat pump evaporator, led to an average Δ SPF of 31 %. Adding both possibilities, i.e. from Hyd-Ice to Hyd-IceHpTes lead to an average Δ SPF of 67 %. Regarding the weather data, it was shown that the chosen weather data for each location had a large influence on the system performance. An increase of 5 % on the SPF_{SHP+} was obtained by using the warm weather data in comparison to the use of the normal one. A decrease of 25 % on the SPF_{SHP+} was obtained by using the cold weather data in comparison to the use of the normal one. Therefore, attention must be paid to the selected weather data for sizing the system.

Simulations of eight cities in Switzerland with collector areas in the range of 1.5 m²/MWh to 2.5 m²/MWh and ice storage volumes in the range of 0.4 m³/MWh to 0.6 m³/MWh using cold, warm and normal weather data sets were carried out. From all the eight cities simulated Davos and Locarno showed the best results with median SPF_{SHP+} of 7.4 and 6.3 respectively. The rest of the cities achieved averaged SPF_{SHP+} in the range of 3.8 to 4.5. Results were observed to correlate with the winter solar radiation. The high solar radiation in winter periods of Locarno and Davos was the main reason of the high performance achieved in these locations. However, results from Davos shown here were overestimated due to the non-consideration of snow on the collectors. The real performance would depend on the frequency of snow removal.

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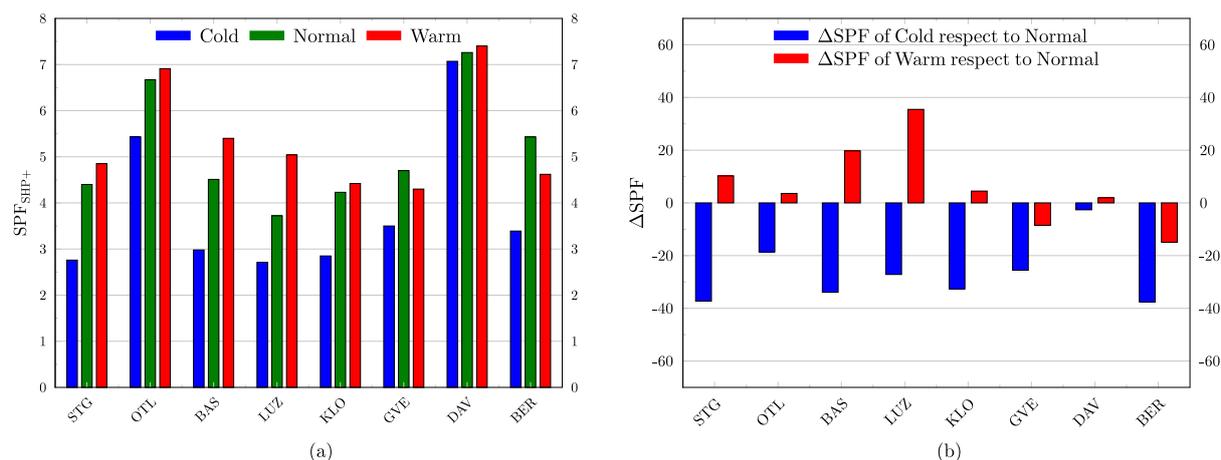


Fig. 8. Influence of cold, normal and warm weather data sets on system performance for all cities for $0.4 \text{ m}^3/\text{MWh}$ and $2 \text{ m}^2/\text{MWh}$

the project Big-Ice.

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