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Energy Procedia 30 (2012) 562 – 570

Energy Procedia

SHC 2012

System evaluation of combined solar & heat pump systems

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Abstract

This paper evaluates combined solar and heat pump systems for dwellings with the focus on direct or indirect use of solar irradiation and generic system configurations. The dynamic simulation study covers systems ranging from pure direct solar heat generation with seasonal heat storage over combined solar and heat pump systems to a pure air/water heat pump system and contributes to the International Energy Agencies Heat Pump Program Annex 38 / Solar Heating and Cooling Task 44 "Solar and Heat Pump Systems". The simulation results show characteristics of the applied configurations and their suitability for a particular design focus.

Selection and/or peer-review under responsibility of PSE AG

Keywords: Solar heat; photovoltaic; heat pump; system evaluation

1. Introduction

Future energy supply systems need to support the transition from a mainly fossil to a predominantly renewable energy generation. The heat generation for space heating and domestic hot water in buildings plays an important role. Therein solar energy systems as well as heat pumps are key technologies. This study investigates combinations of solar heat and heat pump systems striving for high renewable energy shares in systems that are still robust and can be realized with a reasonable technical effort at affordable cost.

Aim of the paper is a juxtaposition of the described heat generation systems that use the roof as part of the building envelope to generate energy and to show their individual characteristics and respective strength and weaknesses. The paper deals with heating systems for space heating and domestic hot water preparation that use solar irradiation or ambient heat as energy source combined with heat pumps. The

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Selection and/or peer-review under responsibility of PSE AG
doi:10.1016/j.egypro.2012.11.066

work has been conducted in the frame of the International Energy Agencies (IEA) Heat Pump Program (HPP) Annex 38 / Solar Heating and Cooling (SHC) Task 44 "Solar and Heat Pump Systems" (A38T44) [1].

2. Methods

The system evaluation is conducted as simulation study based on actually best available technologies. Later on, a laboratory measurement of a promising system configuration will support this theoretical work, but is not subject of this paper. Technologies considered in the simulation study are the direct and indirect use of solar irradiation for heat generation as well as photovoltaic (PV) to produce electricity. The generated heat is used for space heating (SH) and domestic hot water preparation (DHW) of a single family house (SFH) which has been defined in IEA SHC Task 44 / HPP Annex 38 "Solar and heat pump systems" as reference heat load, c.f. [2]. 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 [3]. Direct use of solar heat means here the direct support of heat at the required temperature for the heat demand; indirect use means the use of solar irradiation as heat source for the heat pump.

2.1. Selected systems for comparison

The selected systems for comparison range from a pure direct use of solar irradiation by solar thermal collectors (SC) for heat generation and seasonal heat storage, thus requiring highly efficient components to overcome the seasonal mismatch of solar irradiation and heat demand in the building, over combined systems using either glazed collectors for direct use and unglazed thermal absorbers (SA) as heat source for the heat pump or high efficient selective absorbers (sel. SA) for both direct and indirect use. Furthermore systems that only use solar absorbers with brine buffer as cold storage as heat source for a heat pump are evaluated and compared to a classical air/water heat pump (A/W-HP) system.

The reference conditions of the IEA HPP Annex 38 / SHC Task 44 (A38T44) are applied using the following options for all variants:

- moderate climate of Strasbourg, a French city in central Europe [2], [4]
- the defined domestic hot water tapping profile, which is adapted from EU mandate M/324 [2]
- either the reference building definition SFH 15 with a total heat demand of 4'607 kWh/a for space heating and domestic hot water or the SFH 45 building with a total heat demand of 8'609 kWh/a [3]

Domestic hot water preparation is delivered in all variants of the simulation study instantaneously by a direct-flow-through external heat exchanger that is heated by the storage.

A south oriented and 45° inclined roof surface has been defined as possible area of up to 50 m^2 that could be covered either by solar thermal absorber area or photovoltaic panel area or photovoltaic-thermal absorber area (PVT) or a mixture of the named components. The photovoltaic generators in this simulation study supply the generated electricity to the grid. Furthermore all consumed electricity is taken from the grid. Hence, no electricity storage is considered, only the annual balance of electricity generation and consumption are evaluated. The authors are well aware of the different handling of thermal and electric energy storage in this study, but concentrate on the system design for thermal energy supply and consider the photovoltaic generated electricity as potential use of the remaining roof area.

2.1.1. Variant 1 & 6 – direct solar heat generation

The variants 1 and 6 focus on a maximum direct solar thermal heat generation, resulting in a minimum demand of externally supplied end energy from the electric grid (c.f. Fig. 1). This could be reached by a large collector field of 50 m^2 high efficient, covered flat plat collectors and a well stratified storage of 10 m^3. An air/water heat pump supplies the remaining heat demand to the storage. Since the thermal collectors cover the whole given roof surface, no space is left for photovoltaic electricity generation. In variant 1 the system is applied to the SFH45 building of A38T44, in variant 6 to the SFH15 building.

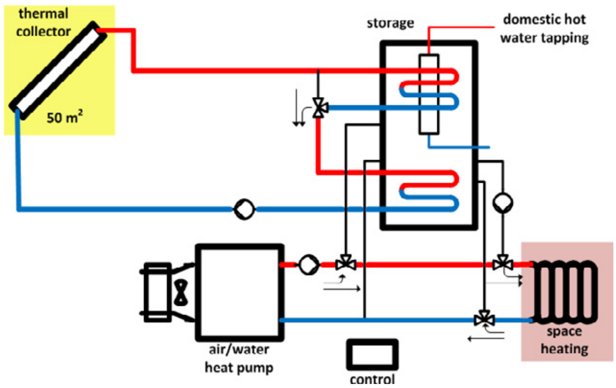

Fig. 1. System and hydraulic scheme of variant 1 and variant 6

2.1.2. Variants 2, 3 & 4 – heat pump and photovoltaic

The variants 2 to 4 use only an air/water heat pump to supply heat for space heating and domestic hot water (c.f. Fig. 2). A photovoltaic generator uses the whole applicable roof surface of 50 m^2 for electricity generation. There is no direct coupling of the PV and the heat pump. Variant 2 uses the SFH45 building with a storage tank of 900 liters, variant 3 and variant 4 the SFH15 building with a storage tank of 750 liters. Variant 4 is identical to variant 3 except that the climate data of Strasbourg are changed in a way that all outdoor temperatures that were below 0 °C are set to 0 °C ($T\_ODA \geq 0$°C). The variant 4 has been chosen to show the effect of a minimum source temperature of 0 °C that is one effect originating from an ice storage on the source side of the heat pump, since at the moment a validated ice storage model has not been available for the system simulation environment.

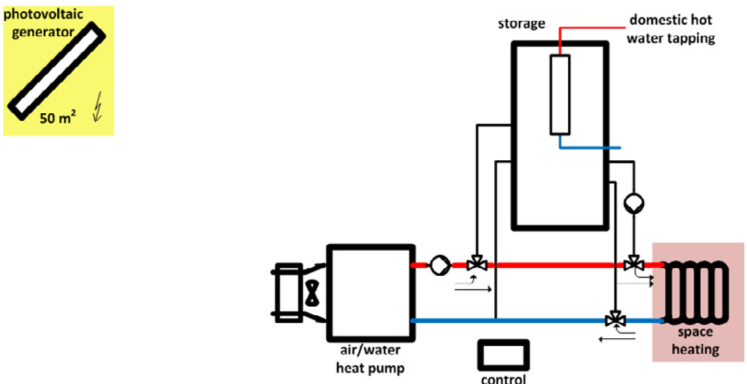

Fig. 2. System and hydraulic scheme of variant 2, 3 and 4

2.1.3. Variant 5 – small solar thermal side-by-side with photovoltaic

The variant variant 5, shown in Fig. 3, combines a smaller solar thermal system with an air/water heat pump and photovoltaic electricity generation applied to the SFH15 building of A38T44. 8 m^2 of covered flat plate collectors supply heat for space heating and domestic hot water to a 900 liter storage tank. An air/water heat pump additionally supplies heat as backup system. The remaining 42 m^2 roof surface are used for a photovoltaic generator.

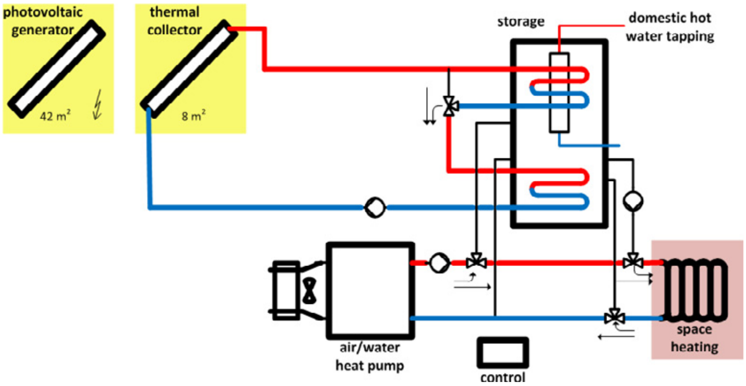

Fig. 3. System and hydraulic scheme of variant 5

2.1.4. Variant 7 & 8 – uncovered thermal absorber with heat pump

In the variants 7 and 8 (c.f. Fig. 4) an uncovered thermal absorber is used as only heat source for a brine/water heat pump (B/W-HP) and furthermore supplies heat directly to the storage tank. The systems are applied to the SFH15 building of A38T44. The absorber covers the whole given 50 m^2 of roof area. It supplies as much heat as possible directly to the 4 m^3 storage tank and feeds the 600 liter brine buffer (B-ST) on the source side of the heat pump. In variant 7 a standard uncovered plastic absorber (SA) is used whereas variant 8 uses an uncovered selective coated metal absorber (sel. SA). Since the whole given roof area is covered with the thermal absorber, no photovoltaic generator is considered.

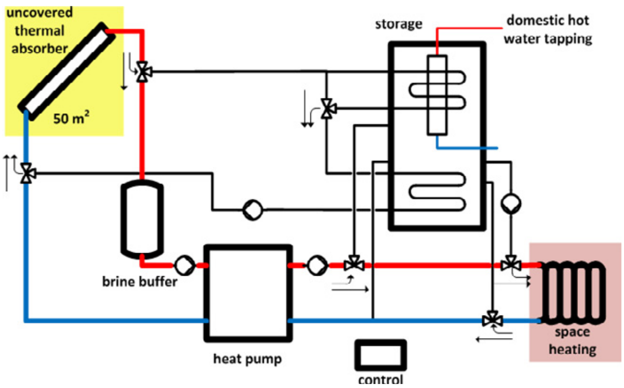

Fig. 4. System and hydraulic scheme of variant 7 and variant 8

2.1.5. Variant 9 – uncovered photovoltaic thermal absorber with heat pump

Variant 9, shown in Fig. 5, uses a photovoltaic thermal absorber as heat source, which generates in 50 m^2 roof area as well electricity as low temperature heat. Variant 9 is hydraulically identical to variant 7 and 8 except of the absorber technology.

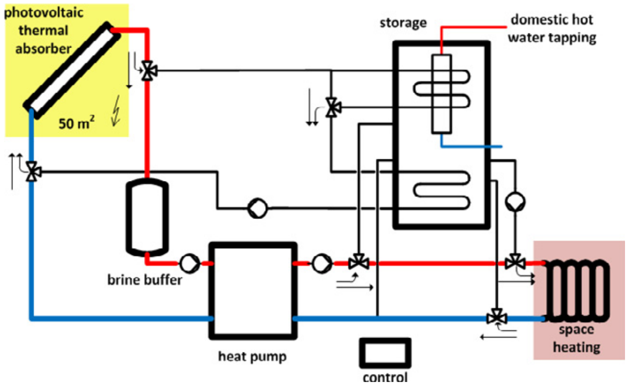

Fig. 5. System and hydraulic scheme of variant 9

2.2. Applied tools and parameter data sets

The simulation study has been conducted with the software Polysun [5]. All simulation results are annual values with between 92 and 180 additional simulation days for preconditioning. The applied heat loads are taken from the definition in the IEA HPP Annex 38 / SHC Task 44 by the supplied load profiles template for Polysun [6] of A38T44. The used flat plate collector data set is the generic collector data set named "flat plate collector, premium quality" [5]. The storage tank model uses generic storage data with typical insulation thicknesses between 20 mm (e.g. for the heat pump source buffer in variants 7 to 9) up to 200 mm (e.g. for the 10 m^3 seasonal storage tank in variant 1 & 6). For the air/water heat pump, performance data of a Viessmann Vitocal 350 A AWHI 351.A10 [7] are used. For the brine/water heat pump the data set "brine/water heat pump: heat pump 10 kW" [5] is taken. The photovoltaic generator is calculated with the "Photovoltaic polycrystalline PV module" which is identical to the one used in the PVT modules, which is taken from the data set "Photovoltaic thermal absorber: PVT collector 2" [5].

3. Results

A selection of the simulation results for the nine chosen system variants is presented in Figure 6 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);
- the share of directly solar generated heat of solar collectors or absorbers at useful temperature levels supplied to the storage tank in percent of the total generated heat for space heating and domestic hot water preparation;
- the seasonal performance factor of the heat pump (SPF) as quotient of generated heat by the heat pump divided by the electricity consumption of the compressor, the heat pump control and the circulating pump or fan consumption caused by heat pump internal pressure drops;
- the total electricity consumption of the whole heating system including all components in kWh;
- the total photovoltaic generated electricity on the AC-side of the inverter in kWh.

The variants variant 2 and 3 operate as heat pump only system without a solar thermal support. The consequence is the highest total electricity consumption of 3’231 kWh for variant 2 with the SFH45 building and 1’888 kWh for variant 3 with the lower space heating demand of SFH15. Hence, the better insulation of SFH15 leads to a reduction of 1’343 kWh in the total electricity consumption and with the same PV generated electricity this leads furthermore to a 1’343 kWh higher surplus in renewable electricity of totally 4’862 kWh for variant 3.

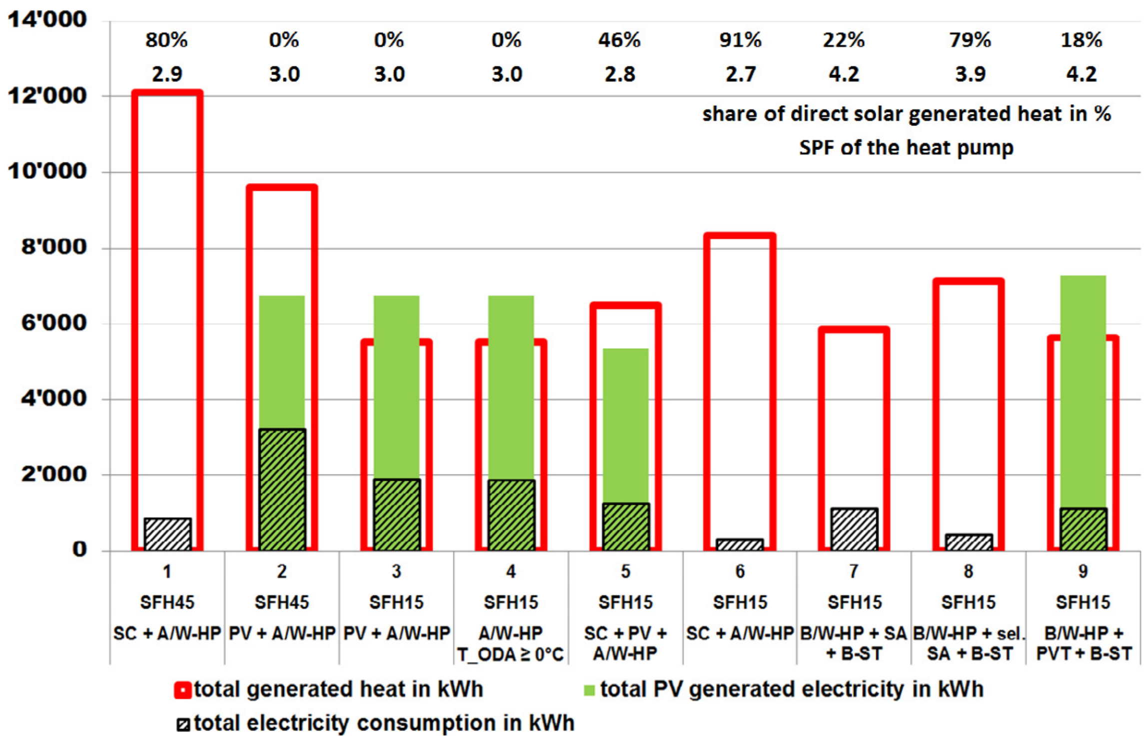

Fig. 6. System simulation results for all nine variants

Going to variant 1 and variant 6 with a focus of direct solar heat generation from the above mentioned heat pump only systems in variant 2 and variant 3, leads on the first sight to a significantly higher amount of total generated heat. Hence, changing for the SFH45 building from variant 2 to variant 1 results in an increase of 2’530 kWh or 26% for the total amount of generated heat, and for the SFH15 building changing from variant 3 to variant 6 results in an increase of 2’817 kWh or 51%. On the other hand the total electricity consumption is reduced even stronger from 1’888 kWh to 296 kWh for the SFH15 building - the lowest electricity consumption overall, and for the SFH45 building from 3’231 kWh to 846 kWh. This shows clearly that the focus on direct solar generated heat, with shares of 80% for the SFH45 and 91% for the SFH15, leads to the smallest electricity consumption and thus highest system efficiency. But, since all the roof surface is covered with high efficient solar thermal collectors, no surplus PV electricity could be generated.

Table 1. System simulation results for all nine variants

variant	A38T44 building	Comment	Solar absorber surface in m^2	PV area in m^2 / nominal capacity in kW_{peak}	total generated heat in kWh	Share of direct solar generated heat	SPF of the heat pump	Total electricity consumption in kWh	Total PV generated electricity in kWh
1	SFH45	SC + A/W-HP	50	0 / 0	12’127	80%	2.9	846	0
2	SFH45	PV + A/W-HP	0	50 / 7.2	9’597	0%	3.0	3’231	6’750
3	SFH15	PV + A/W-HP	0	50 / 7.2	5’516	0%	3.0	1’888	6’750
4	SFH15	A/W-HP T_ODA ≥ 0°C	0	50 / 7.2	5’514	0%	3.0	1’867	6’750
5	SFH15	SC + PV + A/W-HP	8	42 / 5.8	6’494	46%	2.8	1’268	5’354
6	SFH15	SC + A/W-HP	50	0 / 0	8’333	91%	2.7	296	0
7	SFH15	B/W-HP + SA + B-ST	50	0 / 0	5’843	22%	4.2	1105	0
8	SFH15	B/W-HP + sel. SA + B-ST	50	0 / 0	7’133	79%	3.9	403	0
9	SFH15	B/W-HP + PVT + B-ST	50	50 / 7.2	5'640	18%	4.2	1'126	7'278

A combination of PV and a smaller solar thermal collector area of 8 m^2 side-by-side and an A/W-HP in variant variant 5 shows similar effects as can be seen for pure heat pump plus PV or direct solar heat plus additional heat pump. Due to the direct solar heat use, the generated heat increases compared to variant 2 to 6’494 kWh and the total electricity consumption decreases to 1’268 kWh. With a smaller remaining PV area also the electricity surplus decreases, but only slightly, to 4’086 kWh.

The variants 7 to 9 show the result of uncovered absorbers that supply heat directly and are furthermore used as the only heat source for a heat pump. In variant 7, an uncovered plastic absorber of 50 m^2 supplies a smaller amount of heat directly at useful temperatures with 22% of the total generated heat, which is mainly preheating at the lower part of the storage tank. But, since the total amount of generated heat is with 5’843 kWh only 327 kWh higher than the heat pump only system variant 3, the total consumed electricity decreases to 1’105 kWh compared to variant 3. But it is still significantly higher than the high efficient direct solar system variant 6, which consumes 296 kWh. Applying a selective coated metal absorber to the otherwise same system in variant 8 leads with 7’133 kWh to a higher amount of generated heat compared to variant 7, but delivers with 79% a high amount of this heat directly from the absorber and hence reduces the total electricity demand to a low amount of 403 kWh. Both systems variant 7 and variant 8 do not leave space for photovoltaic electricity generation and are thus net consumers.

Variant 9 shows the results for a combined photovoltaic-thermal absorber that produces as well electricity as low temperature heat. The results of variant 9 are similar to the one of the plastic absorber in variant 7 for the thermally caused balances with a total generated heat of 5’640 kWh and a total electricity consumption of 1’126 kWh. But the PVT modules produce with one absorber also electricity and since they are operated at lower temperatures due to the heat extraction, the total amount of generated electricity increases by 528 kWh compared to the heat pump only system with PV in variant 3 to 7’278 kWh. The remaining surplus of renewable electricity is with 6’152 kWh the highest amount of the here presented system solutions.

4. Conclusions

The simulation study shows the main characteristics of heating systems supplying space heat and domestic hot water with combined heat pump and thermal or electric solar systems. A system with only a heat pump as heat generator (variant 2 to 4) leads to the smallest amount of heat losses, and thus meets the heat demand best. Because of the smaller efficiency of a heat pump compared to a solar thermal system, it consumes the highest amount of electricity, but leaves the defined roof area free for PV generated electricity and thus leads to the second highest amount of renewable surplus electricity. A system with focus on directly solar generated heat (variant 1 and 6) leads to the highest amount of generated heat and hence heat losses, but is at the same time the smallest but for the defined roof surface still net electricity consumer. It has to be emphasized that this system implements as only system seasonal energy storage, in this case heat storage. Systems, where photovoltaic and solar thermal collectors share the roof side-by-side like in variant 5, could be seen from an overall point of view as interpolation between only heat pump and focus on direct solar heat generation systems. Using a solar absorber as only heat source for the heat pump leads to a significantly higher system efficiency if solar heat is also delivered directly, whether it is a smaller amount only as low temperature heat for preheating by a non-selective plastic absorber (variant 7) or a bigger amount also at higher temperatures by a selective metal absorber (variant 8). Herein the direct solar delivered heat is the main cause for the reduction of the electricity consumption. A PVT absorber as heat source leads in this comparison to a smaller amount of direct supplied heat for preheating but also to the highest renewable surplus electricity.

5. Discussion

All system simulation results show the characteristics of the respective systems. However, for each system it is not claimed to be the far optimized system presented here, but a system of proper design and also well operated that could be developed to a robust solution. Hence, there is a remaining uncertainty for each system simulation variant of some percent, but this is considered to have in the end a negligible influence on the presented results and conclusions.

The authors are well aware of the fact, that seasonal energy storage is considered only for heat appliances and not for electricity from photovoltaic. The photovoltaic generators in this study should show the possible use of the defined and restricted roof surface of the building. Further combinations of PV generated electricity and heat pump systems are not in the focus of this study. But, since a PVT-solution is part of the thermal system variants, the potential electricity generation is taken for comparison. Furthermore, for the PVT-system variant it has to be mentioned that there are up to now only few experiences with PVT-modules operated below ambient temperature, thus facing condensing water on the modules, and the behavior over a longer time period. For all variants with solar absorbers as only heat source for the heat pump, the effect of snow or ice on the absorber surface is not considered with these simulation models, hence it is recommended to install the absorbers so that snow could slide from the roof by natural force.

There is an actual risk of making a combined solar and heat pump system worse than the individual components could work. The origins of this risk are mainly not to operate the solar collector, the storage or the heat pump in their well optimized way anymore. For the collector or a PV module this means that it is e.g. usually not suitable for operation below dew point temperatures facing condensation, which could lead on the longer run to a destroyed selective coating or soaked insulation. For the storage in solar heat systems, a well stratified operation is crucial. A higher mass flow from a connected heat pump compared to a boiler could destroy this stratification. For the heat pump it is advisable to operate at as low flow temperatures on the sink side as possible. This rule could be disturbed by too small heat exchanger surfaces in combi-storages due to missing space, or by wrong connections of the heat pump to the storage and the heat pump thus working on higher temperatures than necessary, e.g. working on a DHW temperature level also for low temperature space heating.

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 [8]. The project contributes to the IEA SHC Task 44 / HPP Annex 38 “Solar and heat pumps” [1]. The permission of Meteotest for using Meteonorm climate data for simulations within the IEA-SHC Task 44 / Annex 38 is gratefully acknowledged.

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