EVALUATION OF SOLAR & HEAT PUMP SYSTEM COMBINATIONS

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Abstract: A local solar heat generation with solar thermal collectors or photovoltaic modules combined with the use of ambient heat by heat pumps can provide powerful solutions in building heat supply for a one hundred per cent renewable energy strategy. Four system combinations are compared in the field of energetic, economic and ecologic criterion. Therein a heat pump plus photovoltaic variant shows benefits in all three fields of evaluation while the other systems have their individual specific strength. A predominantly solar thermal heat generation with long-term heat storage causes the lowest electricity consumption at all, but prohibits on-site electricity generation with in the end highest cost. Ice storage systems can also reduce the grid electricity consumption especially by using photovoltaic-thermal absorbers, but include optimization potential in the field of reducing system cost due to their rather new application for space heating.

Key Words: heat pump, solar heat, photovoltaic

1 INTRODUCTION

Future energy supply systems need to support the transition from a fossil to a renewable energy generation. The heat generation for space heating and domestic hot water in buildings therein plays an important role. Solar energy systems as well as heat pumps are key technologies.

This study investigates three combinations of heat pumps with systems using solar energy, striving for high renewable energy shares. These systems are still robust and can be realized with a reasonable technical effort at affordable cost. Furthermore a forth system gives an outlook to a solution for situations requiring high roof area specific energy generation. Aim of the paper is a juxtaposition of 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 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” http://task44.iea-shc.org (A38T44).

2 METHOD

The generated heat 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. Haller et al. 2013. 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 Dott et al. 2013. In this study only the SFH45 of these buildings is used. All simulations use the moderate climate data set for Strasbourg, a French city in central Europe.

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 balance of electricity generation and consumption is evaluated on the bases of daily energy sums. The reason for the evaluation of a daily energy balance is that the heat storage is assumed to be able to store the heat for one day if an advanced control, which has not been modeled in detail, would be applied. 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 and as an estimation of a potentially own consumption of an own photovoltaic generator for SH and DHW heat demand.

2.1 Applied tools and parameter data sets

Four different heat generation systems have been defined to evaluate their respective characteristics. They are described in detail in chapter 3. The used flat plate collector data set is the generic collector data set named “flat plate collector, premium quality” of the simulation environment Polysun 2012. The storage tank model uses generic storage data with typical insulation thicknesses between 20 mm and 200 mm. For the air/water heat pump, performance data of a Viessmann Vitocal 350 A AWHI 351.A10 are used, for the brine/water heat pump the data set Vitocal 300 G BW 301.A08, c.f. Viessmann 2012. The photovoltaic generator is calculated in Polysun 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” (Polysun 2012). The ice storage system is modeled according to the Isocal 2012 solar ice system and consists of Isocal SLK-S pipe absorber modules and an Isocal SES12 ice storage. The absorber is modeled as described in Frank 2007 and parameterized according to the data in Isocal 2012. 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.

2.2 Method to ensure comparability of results

The simulation study is conducted using Polysun 2012 for two systems and Matlab/Simulink 2011 for the other two systems. In all systems the heat distribution and emission systems are equal and the heat is supplied via a buffer storage that is heated whether by the heat pump or by solar thermal collectors. The annual heat load is defined and implemented according to A38T44 with a space heat demand for the SFH45 building of 46 kWh/m^2/a or 6500 kWh/a and a domestic hot water heat demand of 2133 kWh/a. Platform independence checks show for both software environments the compliance with the A38T44 reference space heating and domestic hot water heat load definition, c.f. Peter et al. 2014 and Zimmermann et al. 2012. Thus the heat load for all compared systems is equal with the particular reference. Furthermore for all components used in both software environments, the same parameter data sets have been used.

3 SYSTEMS

The four heat generation concepts evaluated in this paper use the building envelope to generate solar heat or solar electricity combined with heat pumps. The systems are (system 1) a direct use of solar energy for heat generation with heat pump as backup, thus requiring highly efficient components to overcome the seasonal mismatch of solar energy and heat demand in the building, (system 2) a combination of PV and heat pump with an adapted heat pump control that assures high own PV electricity usage, (system 3) non-selective solar thermal absorbers combined with a buried ice-storage as only heat source for the heat pump and (system 4) a hybrid photovoltaic thermal absorber combined with a buried ice-storage that is also used as only heat source for the heat pump.

The following abbreviations are used to describe the systems:

HP: heat pump
PV: photovoltaic
IceST: buried ice storage
SC: glazed solar thermal collector
UC: unglazed thermal absorber
PVT: uncovered photovoltaic thermal absorber

System 1: HP + SC

This system uses the whole roof surface of 50 m^2 for glazed thermal collectors for direct heat generation and seasonal heat storage. The buffer storage is extended to 10 m^3 in this case. The heat generation relies mainly on solar thermal with heat pump back-up. There is no space left for PV (c.f. Figure 1).

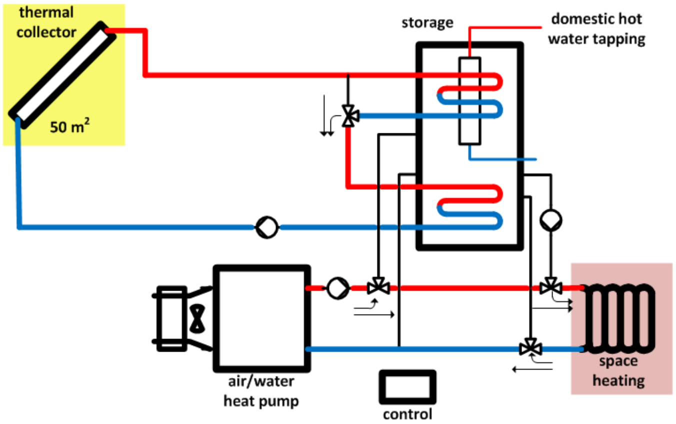

Figure 1: System and hydraulic scheme of system 1 heat pump + solar thermal collector

System 2: HP + PV

In this system all heat is generated by an air/water-heat pump and supplied to a 900 liter buffer. It uses no solar thermal collectors but the whole roof area for a PV-generator of 50 m^2 (c.f. Figure 2).

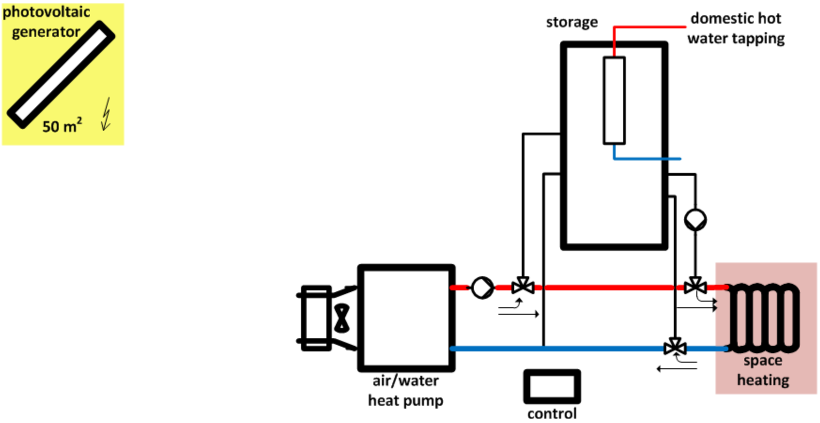

Figure 2: System and hydraulic scheme of system 2 heat pump + photovoltaic

System 3: HP + IceST + UC + PV

The uncovered solar thermal absorber of 10 m^2 and the ice storage of 12 m^3 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 remaining 40 m^2 roof area are covered with PV. (c.f. Figure 3)

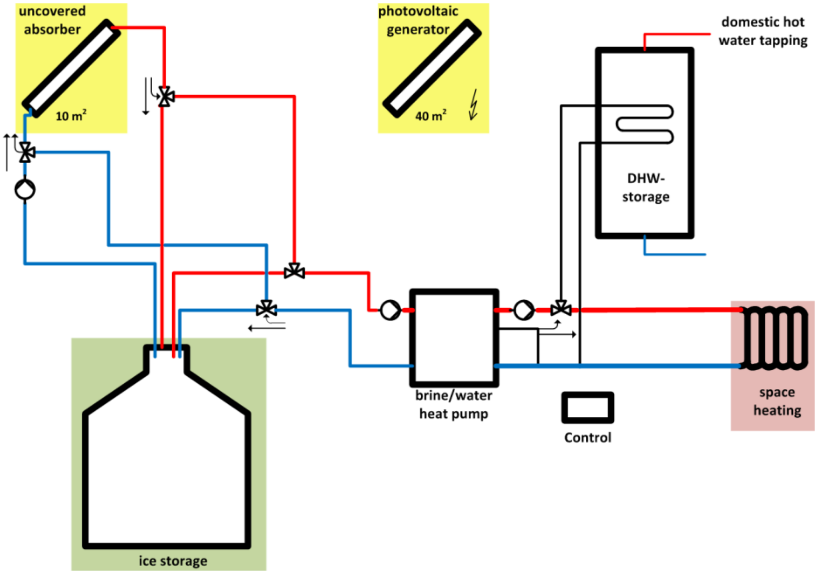

Figure 3: System and hydraulic scheme of system 3
uncovered absorbers & ice storage as heat source for the heat pump plus PV

System 4: HP + IceST + PVT

System 4 is equal to system 3 except for the roof utilization. Here a combined photovoltaic-thermal collector replaces the uncovered solar thermal absorber as heat source for the heat pump. Since the thermal properties cannot be that far optimized, the whole roof area of 50 m^2 is covered with PVT-elements (c.f. Figure 4).

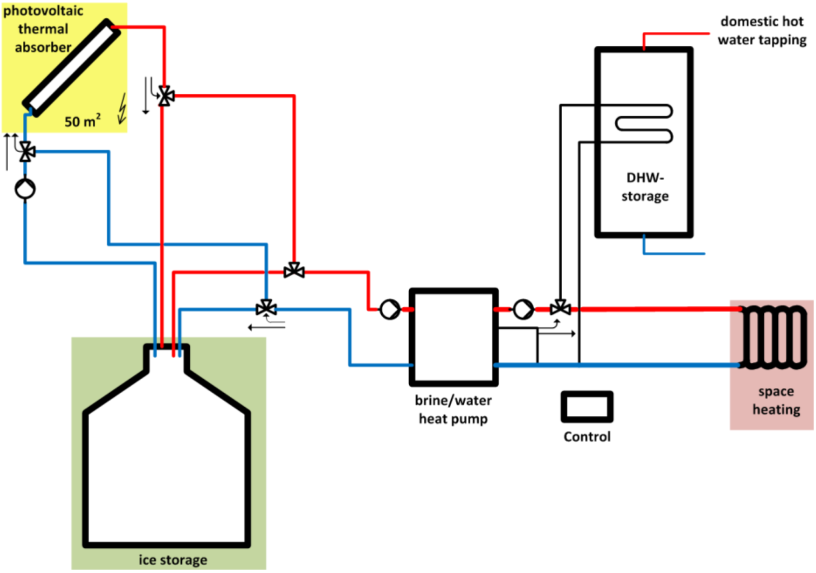

Figure 4: System and hydraulic scheme of system 4
PVT-modules & ice storage as heat source for the heat pump

4 ENERGETIC RESULTS

The simulations directly show the energetic results for the four above described systems. The discussion of results concentrates on the resulting electrical end energy demand and energetic performance figures since generated heat is equal in all four systems. The seasonal performance figures are equal to the A38T44 definitions in Malenkovic et al. 2012 and defined as following:

SPF$_{bSt}$ - This system boundary bST takes into account all useful energy outputs of the solar heat and the heat pump system to its useful energy storages. Thus, the storage losses, as well as the energy needed to supply the heat to the storages are not included. All components and respective energy consumptions needed to generate the heat are considered.

$$SPF_{bST} = \frac{\int\left(\dot{Q}_{SC,H} + \dot{Q}_{HP,H} + \dot{Q}_{BU,H}\right)dt}{\int\left(P_{el,SC,H} + P_{el,SC,C} + P_{el,HP} + P_{el,HP,C} + P_{el,BU} + P_{el,CU}\right)dt}$$

SPF$_{SHP+}$ - This system boundary SHP+ contains all components of the system, including the heating and domestic hot water distribution subsystems. The useful energy for heating and domestic hot water is considered at the interface between the solar heat pump system and the heat distribution system, e.g. before the heating manifold. Also all components and respective energy consumptions needed to generate, distribute and supply the heat are considered.

$$SPF_{SHP+} = \frac{\int\left(\dot{Q}_{SH} + \dot{Q}_{DHW}\right)dt}{\int\left(P_{el,SC,H} + P_{el,SC,C} + P_{el,HP} + P_{el,HP,C} + P_{el,BU} + P_{el,CU} + P_{el,SH} + P_{el,DHW}\right)dt}$$

Variables

SPF	seasonal performance factor		
$\dot{Q}$	thermal power in W	P	electrical power in W

Subscripts

bST	before storage	SHP+	solar and heat pump plus heat distribution system
SC	solar collector	HP	heat pump
BU	back up unit		
SH	space heating	DHW	domestic hot water
H	high temperature	C	low temperature
CU	control unit	el	electrical

Figure 5 shows the balance of grid consumed and on-site generated electricity for space heating and domestic hot water generation as well as the surplus PV electricity. Therein the electrical energy evaluation distinguishes between:
Grid electricity consumption, where the electricity is taken from the electric grid;
PV self-usage, where PV electricity generated at the own building during a day is used as far as possible in the heat generation system;
Surplus PV, which sums up the PV generated electricity that could not be used in the heat generation system and can be sold to the grid or used in other electric appliances in-house.

In the HP + SC system the solar thermal collector delivers 81% of the overall generated heat directly to the buffer storage. Hence the total electric energy demand is with 860 kWh/a the lowest of all. Since the roof is covered with thermal collectors and there is no space for PV, all consumed electricity comes from the grid. Although the heat losses of the big heat buffer are the highest in this comparison, the annual performance figures are still the highest. The heat generation performance of heat pump and solar system SPF$_{bSt}$ reaches 14.5, the overall system performance SPF$_{SHP+}$ 10.0.

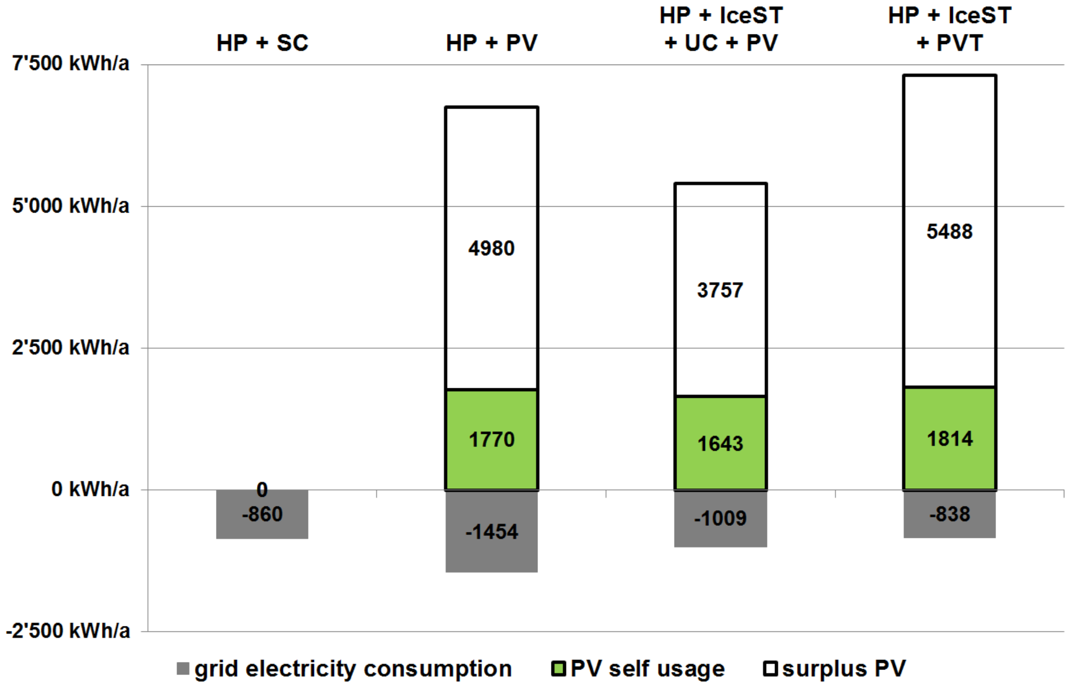

Figure 5: Balance of annual grid consumed and on-site generated electricity for space heating and domestic hot water generation

In the HP + PV system all heat is generated by an air/water heat pump. Hence this systems reaches the lowest performance figures of this comparison with a heat generation performance SPF_{bSt} of 3.0 and an overall system performance of SPF_{SHP+} = 2.7. This corresponds to the highest total electricity consumption of 3224 kWh/a, of which ~55% can be produced on site. Since all roof area is covered with PV a surplus of 4980 kWh/a remains for further uses.

The ice storage systems also uses air as main heat source for the heat pump, but during some periods also latent heat and ground heat. This is the reason for better performance figures with a heat generation performance SPF_{bSt} of 3.4 and an overall system performance SPF_{SHP+} of 3.3.
Splitting up the roof usage into 20% optimized uncovered absorbers and 80% photovoltaic in the system HP + IceST + UC + PV results in 1009 kWh/a grid electricity consumption and 1643 kWh/a own PV generated and self-used electricity. Furthermore 3757 kWh/a remain for further uses outside the heat generation system.
PVT modules as heat source for the heat pump in system HP + IceST + PVT results in an even lower grid electricity consumption of 838 kWh/a and higher own PV generated and self-used electricity of 1814 kWh/a due to the bigger PV generator, that furthermore also generates the highest amount of surplus PV electricity with 5488 kWh/a.

In summary it can be stated that the focus on solar thermal heat generation with seasonal heat storage reduces the electricity consumption to the lowest level. The heat generation only by heat pump comes with the highest electricity consumption but a combination with a PV generator leads to a high surplus electricity generation in summer. A combined solar heat and electricity generation with PVT modules reduces with a well-adapted control the electricity demand from the grid to a comparable level to the seasonal solar heat storage and furthermore also produces surplus electricity.

5 ECONOMIC RESULTS

The economic evaluation of the four systems is based on actual Swiss prices for components, work and average Swiss electricity tariffs. Prices contain all components and work that are necessary to build up the heat generation system and dismantle it at the end of lifetime. In particular, the following elements are included: heat pumps, collectors, absorbers, PV-modules, PV-inverters, storages, domestic hot water preparation components, system control, installation and assembling material, installation and assembling work, additional constructional expenses like e.g. earth moving for the buried ice storage, dismantling as well as planning fees. Not included are in particular the heat distribution and emission system. Furthermore subsidies or grants are also not considered. For the calculation of annual investment cost an economic lifetime of 20 years is used, 1% annual increase in prices and an interest on capital of 3%. The tariff for consumed grid electricity is set to 0.194 CHF/kWh and feed-in tariff for the surplus PV generated electricity to 0.304 CHF/kWh.
Based on these assumptions, Figure 6 shows the comparison of annual cost for the four systems divided into investment cost, operation cost and maintenance cost. Therein the maintenance cost is estimated as 1% of the investment in plant and equipment, the operation cost consists only of the grid electricity consumption. As additional information, all surplus PV electricity as stated in chapter 4 is rated with the feed-in tariff to give estimation about the maximum possible PV-Feed-In refund.

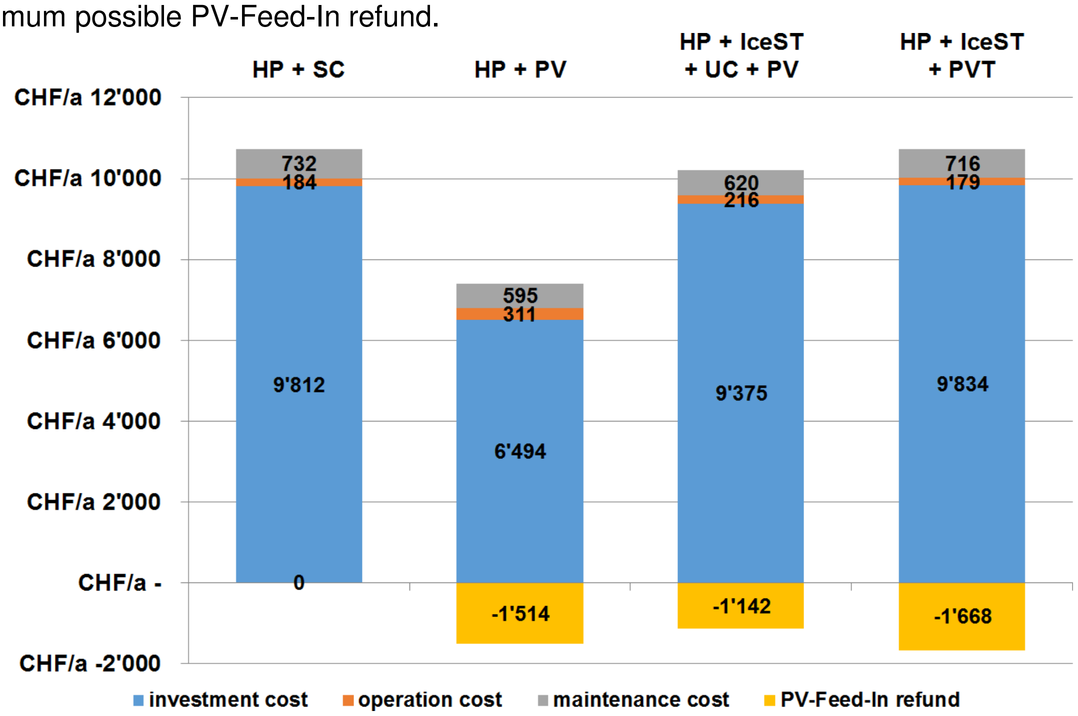

Figure 6: Annual cost comparison

The HP + PV system shows the by far lowest total annual cost with 7’400 CHF/a due to the most simple system composition. An additional PV-Feed-In refund of up to 1’514 CHF/a can be possible. All other systems cost in total more than 10’000 CHF/a. Thereof, the ice storage systems can possibly generate PV-Feed-In refund, which is in its amount based on actual data, but on the other side unclear how this will develop in future. The HP + SC system generates, due to the lowest total electricity consumption, also the lowest operation cost, but the highest total annual cost with 10’728 CHF/a. The HP + IceST + PVT system generates with 10’729 CHF/a the same annual cost as HP + SC system, whereas the HP + IceST + UC + PV system comes with slightly lower total annual cost of 10’211 CHF/a. Both ice storage systems can be expected to be able to reduce the investment cost since the buried ice storage as well as the PVT-modules are young technologies with cost optimization potential.

6 ECOLOGIC RESULTS

The ecological evaluation is conducted based on the concept of ecological scarcity as ecological impact calculation (Frischknecht et al. 2009). Infrastructure related impacts for production and waste disposal are calculated separate to operation related impacts. A simplified method is applied here using accumulated building component data from the KBOB 2009 list of building material. This list is mainly based on the ecoinvent-database 2014 with additional further data sources. Therein the method of ecological scarcity is applied to the situation and the objectives in Switzerland. In KBOB 2009 not all material and processes are available with information in detail, but the information for the most common construction materials and products is provided for easy use. Hence, most used material for the heating systems can be found directly, like solar flat plat collectors, photovoltaic system, heat pump or heat distribution and floor heating. Also the impact of electricity from different primary energy sources is declared explicitly. Components like the ice storage or the uncovered absorber are not included in the database. Therefore their impact has to be estimated by their used material quantities. The PV system is calculated as infrastructure impact in relation to its occupied roof surface and afterwards weighted with the energy share used for space heating and domestic hot water preparation. The impact due to system operation, here the grid electricity consumption, is calculated over 20 years of operation for the cases Swiss consumer mix grid electricity (CH consumer mix) and photovoltaic generated electricity from the grid (photovoltaics).

Figure 7 shows the in the above described way obtained results for the ecological impact of the four systems. Therein the HP + SC system comes with the lowest operational and the highest infrastructure impact. The high infrastructure impact of the HP + SC system originates from the big collector area and storage volume and can be explained by the relatively low area specific heat energy gain of the solar collectors and storage volume due to the seasonal storage effect. The other systems produce a significantly smaller infrastructural impact, whereof the HP + PV system produces the smallest impact of all. Comparing the HP + PV and the HP + IceST systems, it can be seen that the higher system performance SPF_{SHP+} of the HP + IceST systems leads to smaller operational impacts both with CH consumer mix and photovoltaic grid electricity, but the difference gets smaller with in future possibly mainly renewable generated grid electricity.

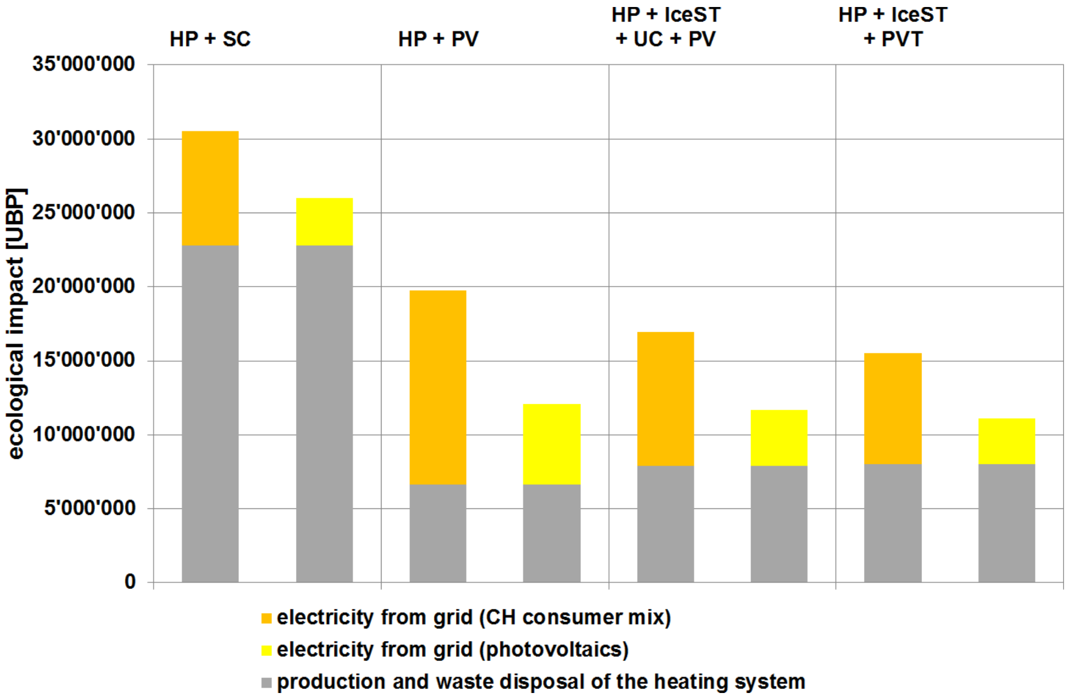

Figure 7: Ecological evaluation of the compared systems by method of ecological scarcity

7 CONCLUSIONS

The four system combinations of using solar energy and ambient heat for heat generation in space heating and domestic hot water preparation are compared in the field of energetic, economic and ecologic criterion. Therein the HP + PV variant shows benefits in all three fields of evaluation while the other systems have their individual specific strength. The HP + SC system includes as only system long-term energy storage and hence comes with the lowest electricity consumption at all, but prohibits on-site electricity generation by PV at highest cost. The ice storage systems can reduce the grid electricity consumption to a comparable level like HP + SC by using PVT, but are at the moment still younger technologies with optimization potential in the field of ensuring the robustness of efficient operation and reducing system cost.

8 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. 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. 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. This originates from solar collectors, storages or heat pumps not operated 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.

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