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L-Sol – heating system with PVT-collectors as single heat source for a brine-water heat pump

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L-Sol – heating system with PVT-collectors as single heat source for a brine-water heat pump

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Abstract. The building sector has a huge potential for reducing greenhouse gas emission without the need of a higher sufficiency. The key is to build and retrofit buildings with good envelopes as well as choosing efficient heating systems. A heating system with a brine-water heat pump and PVT collectors as single heat source is suggested here as an alternative to an air-water heat pump system for single family houses. In the system simulations performed, the PVT-heat pump System ("L-Sol") is more efficient than an air-water heat pump system and still affordable. As the System L-Sol produces heat and electricity on the same area it saves space, disadvantages like noise emission of air-water heat pumps or costly drilling of bore holes are omitted. The system has been optimized in terms of efficiency by testing different dimensioning of the components and regarding the grid purchase by optimizing the system control.

1. Introduction

In the retrofitting of existing single-family houses, fossil heating systems are replaced by new fossil heating systems rather often [1]. If the heating system is changed to a renewable one, a very common heat generator that is used are air-water heat pumps. Air-water heat pumps have the advantage that they are cheap compared to other renewable heating systems. But on the other hand they have the disadvantage that they are noisy and they are therefore, especially in urban areas, not always eligible for approval. Different further options are necessary to have possibilities to change to a renewable energy system. We have examined a system where a brine-water heat pump is used instead of an air-water heat pump by performing system simulations. The source for the heat pump are unglazed PVT collectors that collect heat from radiation as well as heat from the ambient air.

The scheme of the system is shown in Figure 1. The heat is buffered within a cold storage. This cold storage is the source for the heat pump that is heating water to the temperatures needed for sanitary hot water and space heating. Electrical heating elements are installed as a backup system for the case that the temperature within the cold storage is getting too low. Additionally, we allowed pre-heating of the sanitary hot water in case the cold storage reaches temperatures above 24 °C.

2. Methods

2.1. Model Setup

The collector model for the thermal gain of PVT collectors used in Polysun is the same as for conventional unglazed-collectors (EN 12975) and describes the efficiency η as follows [2]:
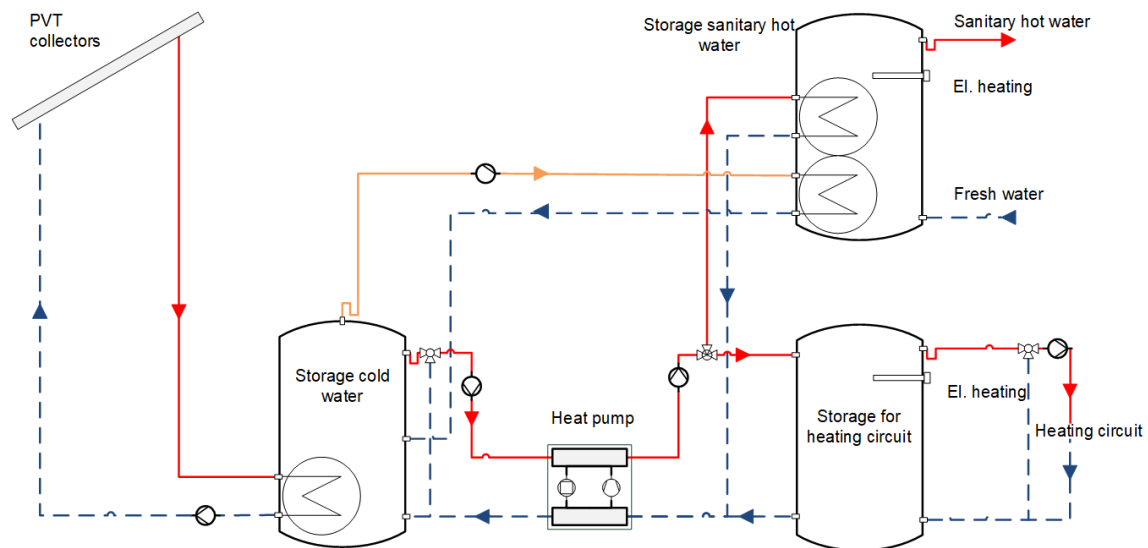
Figure 1. Scheme of the system L-Sol. The heat collected by PVT modules is buffered within the cold water storage which is used as heat source for the heat pump. If the temperature within the cold storage is getting higher than 24 °C it is possible to transfer heat directly from the cold storage to the sanitary hot water storage to pre-heat the fresh water.

$$\eta = \eta_0(1 - b_u u) - \frac{(b_1 + b_2 u)(T_M - T_a)}{G''}$$

T_M is the mean temperature of the collector, T_a the ambient temperature. η_0, b_u, b_1 and b_2 are empiric parameters of the collector type (indicated in data sheet). G'' is the total incident irradiance determined by the following equation:

$$G'' = G_K + \left(\frac{\eta}{\alpha}\right)(E_L - \sigma T_a^4)$$

G_K is the irradiance at collector level, E_L the long wavelength irradiance. For $\frac{\eta}{\alpha}$ a value of 0.85 should be assumed if not specified differently by the manufacturer [2].

For the building model a very simple quasi-dynamic model is used. The user defines static consumption values for energy demand for space heating and sanitary hot water but dynamic building properties are taken into account as well (such as solar yield through windows/walls). This model is permissible for parameter studies [2]. For analyzing a specific building, a more accurate building model should be imported to use exact values for heating and cooling requirements. Thermal storages are calculated as stratifying storages with 12 layers.

The thermal circuit of the PVT plant is running as soon as the mean collector temperature exceeds the storage temperature in the lower part by more than 4 K. To be able to cool the cold storage below 0 °C we assume a 33.3 % glycol-water mixture within the PVT collectors as well as within the cold storage.

2.2. Properties of the comparative systems

To classify the system L-Sol among well-known systems, we set up Polysun models for different comparative systems as well (Table 1). The goal was to make those systems as similar as possible. Therefore, we chose 2-Sol with PVT and ground source loops, an ice storage system fed by heat from PVT collectors and an air-water heat pump system with PV instead of PVT on the roof. The demand for space heating and the sanitary hot water profile were equal for all systems (10'000 kWh/a for space heating and 3'400 kWh/a for sanitary hot water). The heat pumps were chosen equally for all brine-water heat pumps and as similar as possible (comparing COP curves) for the air-water heat pump system.

Table 1. Overview over the compared systems characterized by the number of PVT or PV and the heat source for heat pump. AW_WP stands for air-water heat pump system.

System Name	number of PVT	Heat source for heat pump
Ice-Storage	30	Ice-Storage (Viessmann standard dimensioning)
2-Sol	30	ground source loops (dimensioned following SIA)
AW_HP	30 PV	ambient air
L-Sol	30	PVT/cold storage
L-Sol cost-optimized	20	PVT/cold storage
L-Sol combination	20 retrofitted PVT	PVT/cold storage

For calculating the costs of the system, different sources were taken into account for investment and maintenance costs [3–5]. In addition, information about typical costs were obtained from two engineering offices.

*2.3. Optimization of self-consumption*

For increasing the self-consumption of the heat pump system, we considered overheating of the storage for sanitary hot water as well as overheating of the buffer-storage for space heating. Overheating of storages with excess electricity from the PV plant is compatible with SG-ready control for heat pumps [6]. Different limit values for PV production in relation to the nominal power of the heat pump for both switching the overheating on and off were tested in order to get an optimal balance between reducing efficiency (due to higher temperatures at the warm side of the heat pump) and increasing self-consumption. Different control strategies were set up as MATLAB plugin to the Polysun model. Unlike in previous work about determining optimal limit values for switching overheating on and off [7], the "on" limit values were not necessarily identical to the "off" limit values. Rather than that, we examined different combinations of the two limit values. Further on, a combined storage for sanitary hot water and space heating was tested versus two separated ones in order to increase the system efficiency.

3. Results

We compared the system L-Sol to three different heat pump systems. Every system has a PVT plant or, in case of the air-water heat pump system, a PV plant of the same size to obtain comparable costs.

3.1. Comparison of different systems

Comparing the life-cycle costs of these three systems to L-Sol (Figure 2), L-Sol, which costs about 70'000 CHF, is 56 % more expensive than the air-water heat pump (AS_HP) at 44'000 CHF. Compared to 2-Sol and ice–storage heating system, L-Sol is cheaper. As the biggest part of the costs of L-Sol is the PVT plant, we tried to reduce the costs by testing the system with 20 instead of 30 PVT modules ("L-Sol cost-optimized") and with 20 retrofitted ones ("L-Sol combined"). With the combination of reducing the number of PVT modules as well as using retrofitted ones, we reached life-cycle costs that are only 25 % higher than the life-cycle costs of the air-water heat pump system.
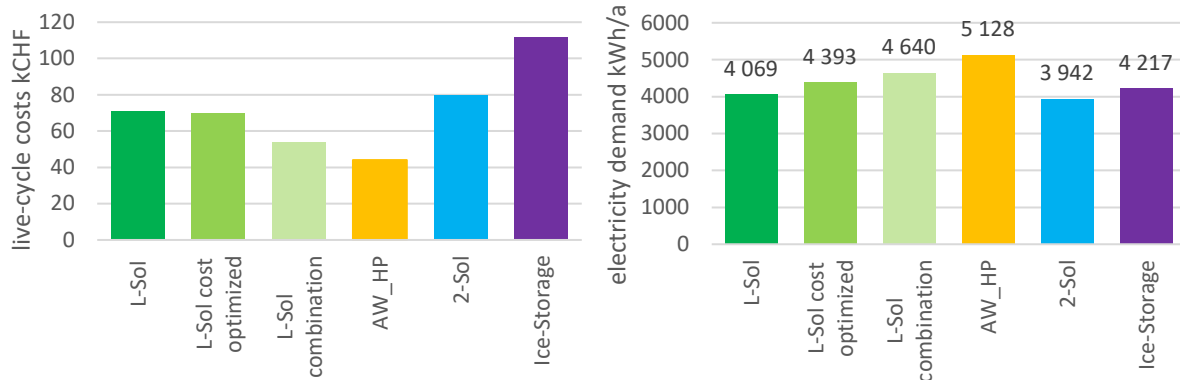
Figure 2. Comparison of the life-cycle costs (left hand side) and for the electricity demand (right hand side) for the different systems. Included are investment costs and yearly operation costs for the heating systems. The main difference between air-water heat pump and L-Sol is caused by the high price of the PVT collectors. Therefore, cheaper alternatives (20 instead of 30 PVT collectors – "L-Sol cost-optimized", 20 retrofitted PVT collectors – "L-Sol combination") are tested and shown here.

The cost reduction measures are not for free but influencing the efficiency of the heat pump system because a lower number of PVT collectors or retrofitted PVT collectors, which lead to a smaller thermal yield of the system. A comparison from the energetic point of view is shown in Figure 2 (right hand side). It is obvious that cost reduction and system efficiency are directly connected. As the air-water heat pump system needs about 20 % more energy than the standard L-Sol system with 30 PVT collectors, the difference to the most cost-reduced L-Sol system (L-Sol combination with 20 retrofitted PVT-collectors) is only about 9.5 %.
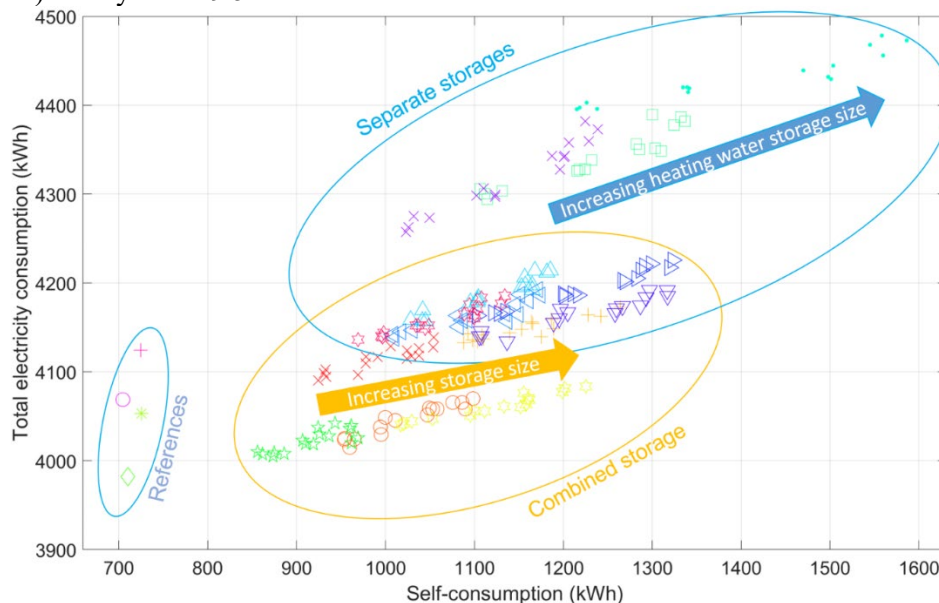

Figure 3. Overview over different runs for system optimization. Main differences are combined storage for heating and warm water vs. two separate storages for heating and warm water, the size of the storages and overheating one or two storages. The references are calculated without overheating. They show a bit higher efficiency but a lot less self-consumption. Within one type of marker the differences are the on and off criteria for overheating the storage.

3.2. Improvement of the system
The System L-Sol has been improved in terms of dimensioning of different system components as well as in terms of finding the best control strategies for operating the system over the year by performing an extensive parameter study. The main focus points were the system efficiency and increasing the self-consumption rate. Figure 3 shows an overview over several runs for system optimization. The efficiency

of the system can be increased using smaller storages or a combined storage instead of two separated ones for heating and sanitary hot water. The self-consumption can be increased by increasing the storage volume. Within one type of marker the on and off criteria for overheating the storages are varied. A detailed plot for one example is shown in Figure 4. In Figure 3 it is obvious that increasing the self-consumption always reduces the efficiency of the heat pump system. This effect is caused by the higher temperature within the heating and warm-water storage due to the overheating in case of testing different control strategies and by heating up larger amounts of water than needed in case of larger storages. As efficiency and self-consumption are opponent, optimizing one always means impairing the other. For this reason we are using the grid supply as an indicator to find the optimal system instead of efficiency and self-consumption.
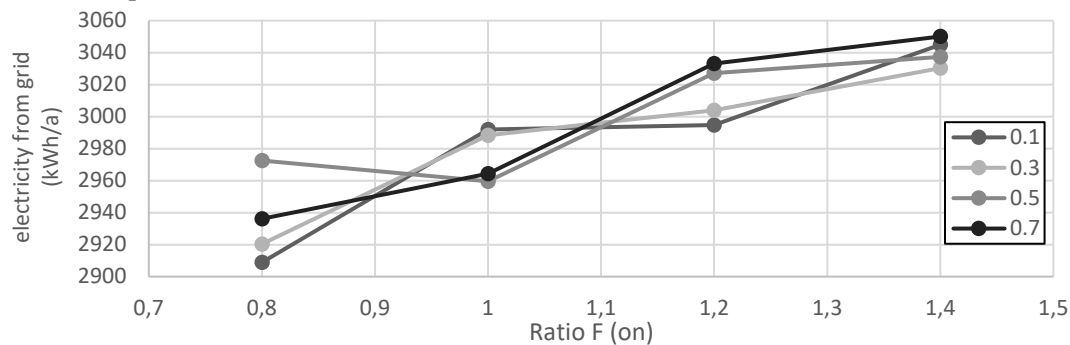
Figure 4. Electricity, supplied from the grid of a selected system with varying parameters for the overheating control strategy. The values on the x-axis indicate the ratio of grid feed to nominal heat pump power at which the overheating was turned on. The different lines show different off-criteria ratio (of grid feed to nominal heat pump power) as indicated in the legend. System properties of this example: Demand for space heating 10'000 kWh/a, demand for warm water 3'400 kWh/a, volume of the cold storage 2000 l, volume of the combined storage on the warm side 600 l.

Figure 4 shows an example for varying the criteria for overheating. The factors F and G stand for the ratio of grid feed power to nominal power of the heat pump. F is used as the criterion for starting overheating, G is used for stopping overheating. F-Values below one, which means the grid feed power is lower than the nominal power of the heat pump, lead to lower electricity demand from the grid. For the G-values the result is less clear but the lowest grid purchase can be found for a value of 0.5. The heat pump is, especially during the day if the sun is shining, running often with a lower electrical power than the nominal power.

Table 2. Overview over the seven best runs regarding grid supply (left hand side) and system efficiency (right hand side). The systems are characterized by storage sizes (cold storage; warm water; heating or cold storage; combined storage, respectively) and by the on-off criteria for overheating. To simplify the reading, the runs with combined storage for heating and warm water are marked in grey. For rating the systems, the annual grid purchase and the seasonal performance factors (SPF) are used.

best grid supply					best efficiency				
F on	G off	Grid purchase (kWh/a)	SPF	storage sizes (l)	F on	G off	Grid purchase (kWh/a)	SPF	storage sizes (l)
0.8	0.5	2887	3.0	1000; 500; 800	-	-	3364	3.3	2000; 300; 300
0.8	0.7	2896	3.0	1000; 500; 800	-	-	3021	3.3	2000; 400
0.8	0.5	2898	3.2	2000; 300; 500	1.4	0.5	3116	3.2	2000; 300; 300
0.8	0.3	2902	3.2	2000; 300; 500	1.4	0.7	3166	3.2	2000; 400
0.8	0.3	2909	3.1	2000; 600	1.4	0.7	3038	3.2	2000; 300; 500
0.8	0.5	2920	3.1	2000; 600	1.4	0.9	3234	3.2	2000; 500; 300
1	0.7	3027	3.2	2000; 300; 300	1.4	0.7	3037	3.2	2000; 600

The best system for system efficiency is one without any overheating and storage volumes of 2000 l for the cold storage and 300 l for both, the warm-water and space heating storage. Best grid purchase is

reached with overheating systems with on-criteria for overheating at 0.8. Those systems show a lower seasonal performance factor from 3.0 to 3.2. With optimization of the efficiency seasonal performance, factors of 3.3 can be reached if the storages are not overheated. In all cases the warm water storage is overheated over the whole year while the storage for space heating is overheated within the heating period only.

4. Discussion and outlook

We could show that PVT as single source for the heat pump is a good alternative to air-water heat pumps in the sector of renovated single-family houses where drilling ground source loops is often not an option. As optimizing self-sufficiency always increases the total electricity demand, one has to balance the optimization. We decided that the amount of electricity purchased from the grid should be minimized in an optimized system. The minimum grid purchase is reached in a system with separated storages where the cold storage has a volume of 1'000 l, the warm water storage has a volume of 500 l and the heating storage has a volume of 800 l. Accepting a deterioration of the grid purchase of about 1%, different combinations of storage dimensioning can be found with seasonal performance factors of 3.0 to 3.2 (all options with an on-criteria of 0.8 in Table 2). The best efficiency is reached in systems without overheating.

In a next step, a recommendation for system dimensioning should be derived from these results and two to three retrofitted pilot houses should be realised to validate the findings of our research.

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