PV driven Air Heat Pump using Overheating Effects as Thermal Battery in Single Family Houses

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Abstract

Theoretical investigations based on TRNSYS simulations are carried out for an electric driven air heat pump in combination with different concepts of thermal activation of the building mass and a water storage in small single-family buildings. Building mass and water storage are acting as thermal battery for local produced photovoltaic electricity. Several different heat pump characteristics and control strategies in combination with a low energy house (new built or after renovation) and different heat capacities (concrete or screed and different water storage volumes) are investigated. Using PV with 7,362 kWh electricity gain per year the household grid electricity consumption of 3,058 kWh/a can be reduced by 35% resulting in 1,987 kWh/a. Additionally the air heat pump grid electricity consumption of 3,169 kWh/a as reference case can be reduced by only 15% (without any thermal activation) resulting in 2,676 kWh/a grid consumption. When using building mass and water storage as thermal battery for the photovoltaic - heat pump system, up to 60% less grid electricity consumption resulting in 1,251 kWh/a grid electricity consumption can be achieved. Photovoltaic self consumption for household and heat pump electricity on the other side can be increased from 22% in the reference case up to 46% in the best case, thus more than doubling. In fact the heat storage effect in the screed of the floor heating system or the concrete ceiling is in the range of about 30 kWh per day which is in the same magnitude of the potential of a 800 liter water storage. Operating cost can be reduced by ca. 30% using existing thermal mass just by simple advanced control strategies.

Keywords: heat pump, photovoltaic, thermal battery, single-family house, building mass activation

1. Introduction

Electrical driven air heat pumps in combination with thermally activated building systems (TABS) and conventional hot water tanks as thermal energy storage (TES) can be used as thermal batteries for electricity produced by a photovoltaic (PV) system with the goal to realize a maximum of PV self-consumption and minimized electricity grid consumption respectively.

Within the national research project “Energieschwamm”, it was investigated how an air heat pump system in combination with different building types with different designed TABS (thermal activation of the building mass) can act as a thermal battery when supplying space heating and domestic hot water to the building with different control strategies (Heinz et al., 2022). The project was based on a set of theoretical simulations in combination with some field measurements in real buildings and the experience of the recent research project TheBat (Thür et al., 2018).

An air heat pump can be operated in different ways like: a) power controlled depending on availability of photovoltaic electricity, b) with or without using a desuperheater for domestic hot water (DHW) preparation, c) charging a TES up to different temperature levels or up to different volumes or d) heating the building to room temperatures with more or less hysteresis of the set room temperature. Within this study it is investigated, which operation modes, parameter settings and design parameter are best to achieve high PV self consumption and low electricity operating cost in combination with no additional investment cost beside some adaption of the controller setup. Household electricity as a realistic load profile created with the Load Profile Generator (Pflugradt, 2016, 2018) is taken into account, but no strategies like load shifting or use of an electric battery for improvement of PV self consumption is used (see Fig. 1, left). In general, always the PV electricity first is used to serve the household electricity, only the remaining excess PV electricity is further used for heat pump operation. Also the

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DHW tap-profile (see Fig. 1, right) created with DHWcalc (Jordan, 2005) in all simulations is the same, e.g. no optimization of tappings in point of time is done.

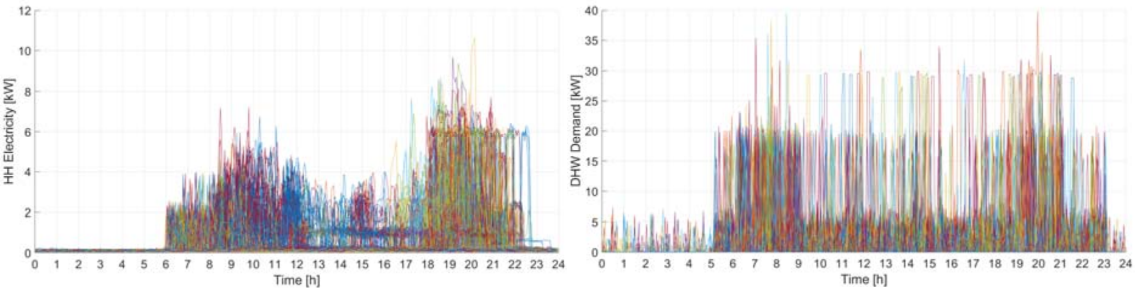


Fig. 1 Load profile as 24h-lines for 365 days for household electricity (left) and DHW tapping (right) in 3 minute time steps.

2. System description

Simulations are done for a single family house (based on the IEA SHC Task44 reference building) with low energy standard (RES45: 45 kWh/m^{2}a nominal space heating demand) at central European climate in Innsbruck, Austria. Different thermal active mass variations of floor heating (FH) or concrete ceiling activation (CCA) with different heat capacities and different configurations of the TES were investigated.

In Fig. 2 the potential heat capacities of the different components used in this study as "thermal battery" are shown. Air itself to store heat is useless as well known. The screed of the floor heating system with 0.08 m thickness in a 140 m^2 single-family house has about the same potential (31.12 kWh) as the 0.8 m^3 water tank (37.22 kWh), where the concrete ceiling with 0.2 m thickness as a potential has a threefold capacity (93.38 kWh) compared to 0.08 m screed and 0.8 m^3 water tank. The "dynamic" heat capacity during operation, which finally really can be activated, is strongly depending on several boundary conditions, as the most important are: a) stratification and temperature level in the water tank, b) u-value and temperature difference between heating water and screed/concrete, c) available power of PV and heat pump, d) length of period how long excess PV electricity is available, e) actual DHW demand and heating load of the building, etc.

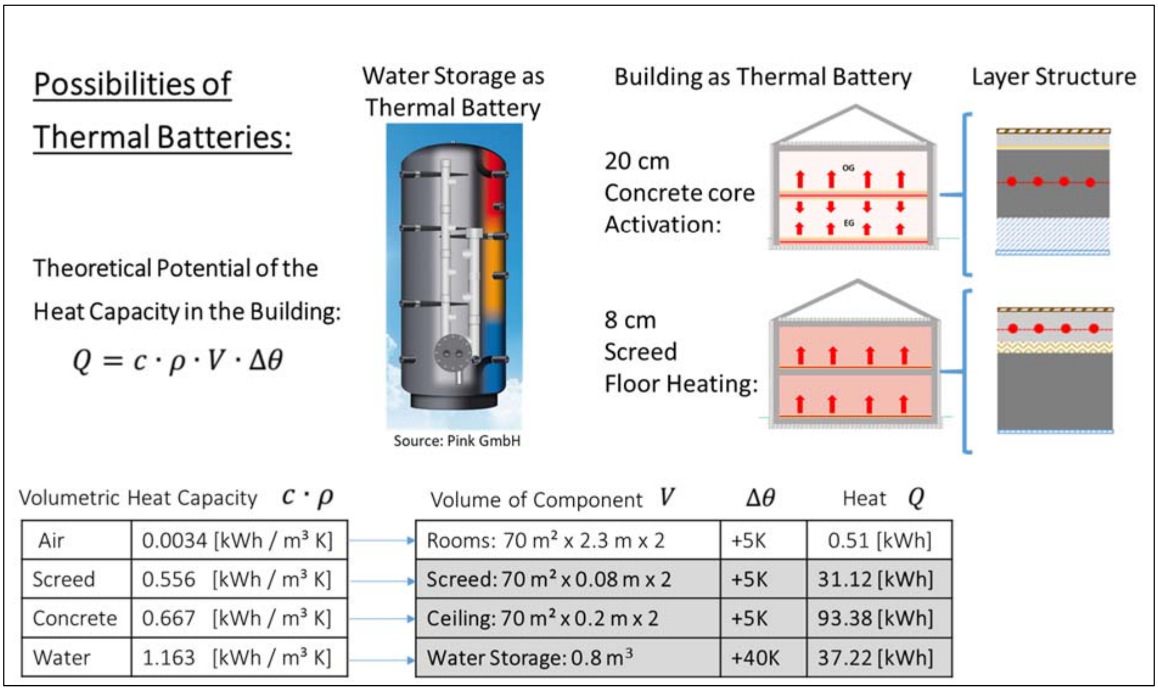


Fig. 2 Characteristic figures of the different materials used as thermal mass in the RES45 building.

In Tab. 1 the main characteristic figures of the reference building and the PV - heat pump system are shown.

In Fig. 3 the hydraulic scheme of the PV - heat pump system and the main control settings are shown. The heat pump is operated in a) standard mode or b) PV-overheating mode. PV-overheating mode is possible when excess PV electricity is available with sufficient power to run the heat pump in space heating mode or in DHW mode. Based on technical data of the heat pump at any time a theoretical "dummy heat pump" is calculated in parallel based on the actual boundary conditions (air temperature, set space heating flow temperature, bottom tank temperature) for minimal possible compressor speed. If the resulting electricity consumption is less than the available PV excess electricity, the heat pump starts operation in PV-overheating mode, first priority in DHW mode or second priority in space heating mode.

Tab. 1 Characteristic key figures of the reference building RES45 and the heat pump system.

Name	Value	Unit
Space heating consumption	6,726	kWh/a
Treated floor area	140	m^2
Room set temperature @standard control	21	°C
Room max. temperature @PV-overheating control	24	°C
Domestic hot water consumption @Tap-Temp.: 45°C	2,980	kWh/a
Household electricity consumption	3,058	kWh/a
PV system	40	m^2
PV gain	7,231	kWh/a
PV tilt angle	45	deg
PV azimuth	South	-
Heating season	Oct 1st – March 31st	-
Air - water heat pump A2/W35	5.92	kW_{th}
Water storage tank	0.8	m^3

The air heat pump has a condenser and a desuperheater. During space heating mode the water mass flow is split by a controlled 3-way valve after the condenser in order to have a controlled mass flow passing the desuperheater to reach a set outlet temperature of 53°C in standard mode or 62°C in PV-overheating mode, which is fed into the TES at the top for DHW preparation. Condenser outlet temperature is controlled by the compressor speed to reach the set temperature according to the heating curve depending on the ambient temperature. The total water mass flow passing the condenser is directly coupled to the compressor speed. The heat pump starts, when the TES outlet temperature (out 4) falls below the actual set space heating flow temperature for more than 15 minutes. The heat pump stops when the bottom sensor of the water tank exceeds the set space heating flow temperature by the hysteresis of 4K in standard mode or when the bottom sensor of the water tank exceeds 54°C in PV-overheating mode.

For heating the TES for DHW the total water mass flow passes condenser and desuperheater in series and is controlled to reach the set outlet temperature of 53°C in standard mode while the compressor runs at a fixed speed.

In PV-overheating mode the compressor speed is controlled to consume the excess PV-power (within minimum and maximum limits) and the water mass flow is controlled to reach the set outlet temperature of 62°C. The heat pump starts, when the upper temperature sensor (below "in 1") falls below 46°C at any time. During defined time windows (in this study: 5-7 and 17-19 or 11-16) the heat pump starts when the lower temperature sensor (above "in 3") falls below 46°C. The heat pump stops in all cases when the lower temperature sensor (above "in 3") of the water tank exceeds the set temperature of 52°C in standard mode or 61°C in PV-overheating mode.

DHW is prepared via an external heat exchanger unit (fresh water unit) by a speed controlled pump to reach the set tap temperature of 45°C in all cases of DHW flow rates.

Space heating loop is fed from the water tank via a mixing valve with controlled flow temperature according to an ambient temperature depending heating curve (see Fig. 4). The flow temperature is controlled in three different modes: a) standard mode, b) PV-overheating with flow temperature reinforced by +3K or c) PV "Boost" overheating with flow temperature reinforced by +10K. Space heating mass flow is individual controlled for each of the 10 thermal zones. The flow rate is constant according to the design value for each zone and just switched on or off based on a special control concept of the space heating controller to reach the set room temperature of 21°C in standard mode. In PV-overheating mode the control valve of each zone is open as long as the PV-overheating set room temperature of 24°C is reached. Additionally as a basic setting for each zone it can be defined if PV-overheating in general shall take place or not, e.g. no PV-overheating of the parents sleeping room.

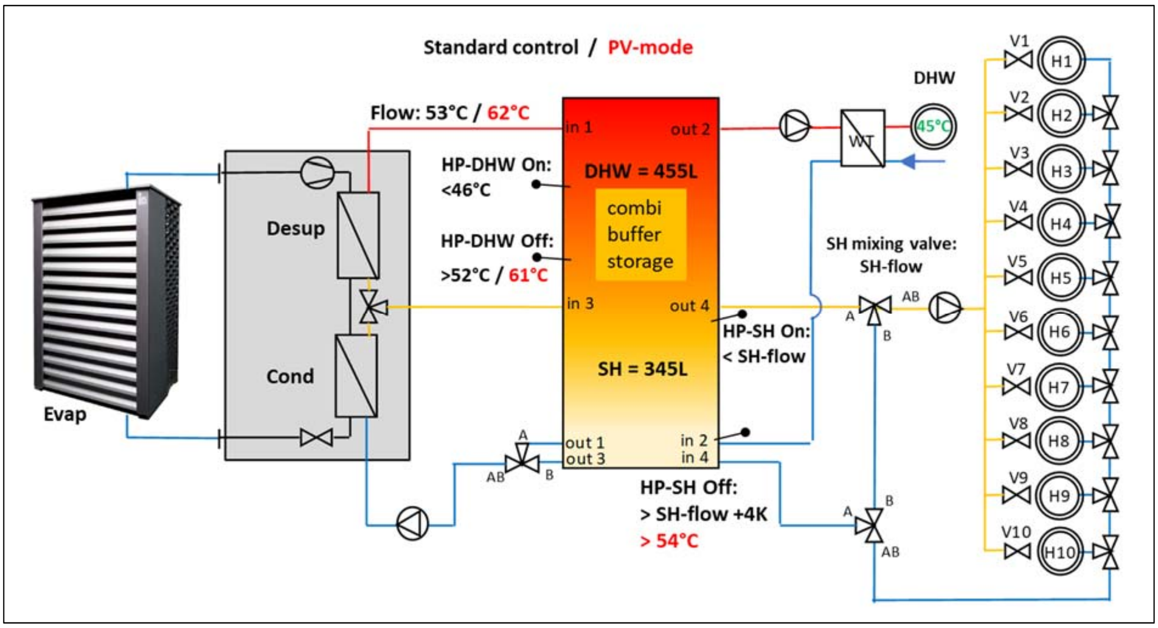


Fig. 3 Hydraulic scheme of the PV – heat pump system with a combi buffer storage as TES and a fresh water unit for DHW preparation @45°C and 10 space heating loops for 10 individual thermal zones in the RES45 single-family house.

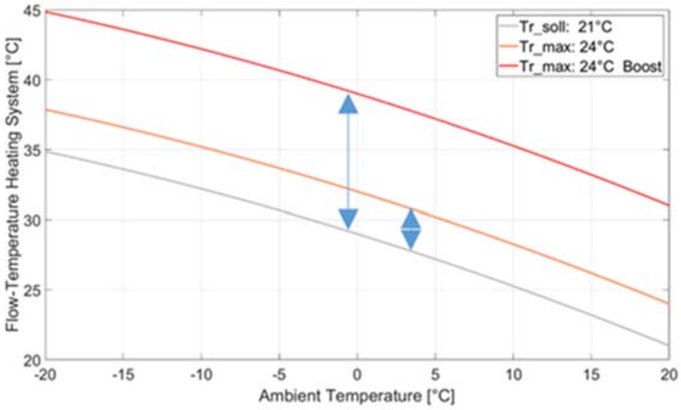


Fig. 4 Heating curve for space heating depending on ambient temperature for a) standard mode, b) PV-overheating with +3K flow temperature, c) PV "Boost" overheating with +10K flow temperature.

3. Results - Virtual 24h-day for one year

Simulation results first are presented in a qualitative way to show principle effects of different system behavior. In Fig. 5, Fig. 6 and Fig. 7 electric energies of the whole year are summed up for each hour resulting in one virtual "day" of the air heat pump system with a 40 m^2 PV system. Grid electricity consumption for household (HH) and heat pump (HP) is negative on the y-axis and the use of PV electricity for household (HH) and heat pump (HP) and remaining PV feed in (PV feed in) is positive on the y-axis.

In Fig. 5 the left graph shows the reference system without PV and with standard control system. For DHW preparation two time-slots are defined from 5 h to 7 h and 17 h to 19 h, which is a typical standard setting with the goal to be sure to have sufficient DHW during the typical peak tapping periods in the morning and in the evening. Therefor at 5 h and at 17 h a clear peak of electricity consumption from grid of the heat pump can be observed.

In Fig. 5 the right graph shows the result when the 40 m^2 PV system is added, but without any changes of the control strategy of the system. First, the PV is used to serve for household electricity (HH from PV) as much as possible, but still around two third of household electricity consumption is covered by the grid and a huge amount of PV electricity (about 85%) is available. From 7 h to 13 h a small additional fraction of PV production (7%) can be used for the heat pump, mainly for space heating, therefor still 78% of PV production must be fed into the grid. The two time slots for DHW preparation hardly can use PV electricity because of luck of sunshine at that time.

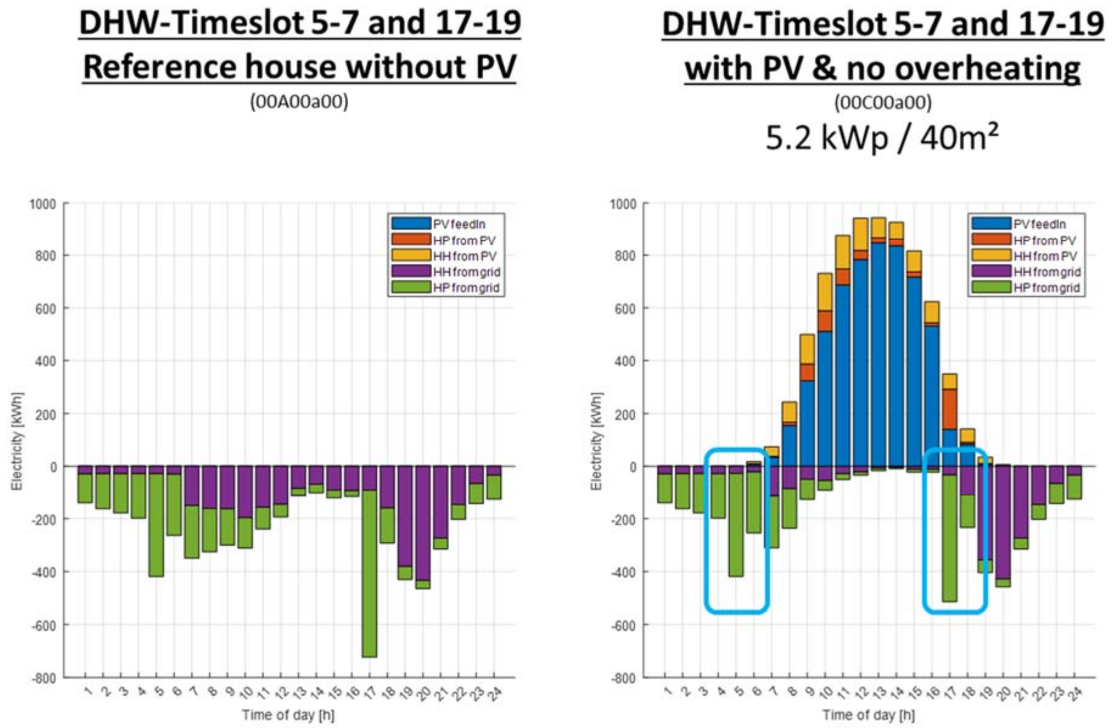


Fig. 5 Virtual 24-hour day of the whole year for the reference case without PV system (left) and with PV system (right) but without any changes of the control strategy.

In Fig. 6 the left graph shows already a significant change when just the time slots for DHW preparation is shifted to only one time slot from 11 h to 16 h. At 17 h the grid consumption of the heat pump for DHW preparation has completely disappeared and only very little space heating operation remains. At 5 h the grid consumption for DHW preparation also disappears almost completely. At 11 h the major part of DHW preparation takes place and at that time around two third can be covered by PV. Since 455 liter of the 800 liter tank are reserved for DHW, the daily consumption easily can be covered by only one defined time slot for DHW preparation. There is no need to define two time slots at very disadvantageous points in the early morning and late afternoon.

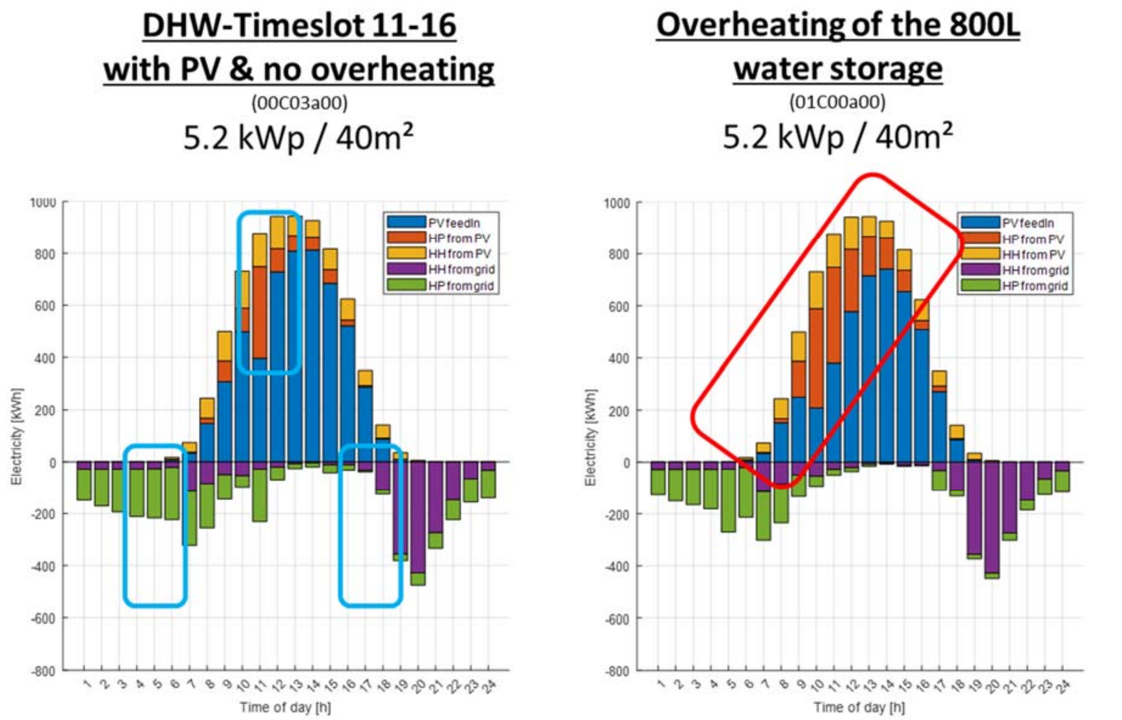


Fig. 6 Virtual 24-hour day of the whole year for the system with PV system but DHW time slot changed to only one from 11 h to 16 h (left) and the system with overheating the 800 liter water storage (but no overheating of the building) in DHW mode or space heating mode at any time whenever excess PV is available at high enough power.

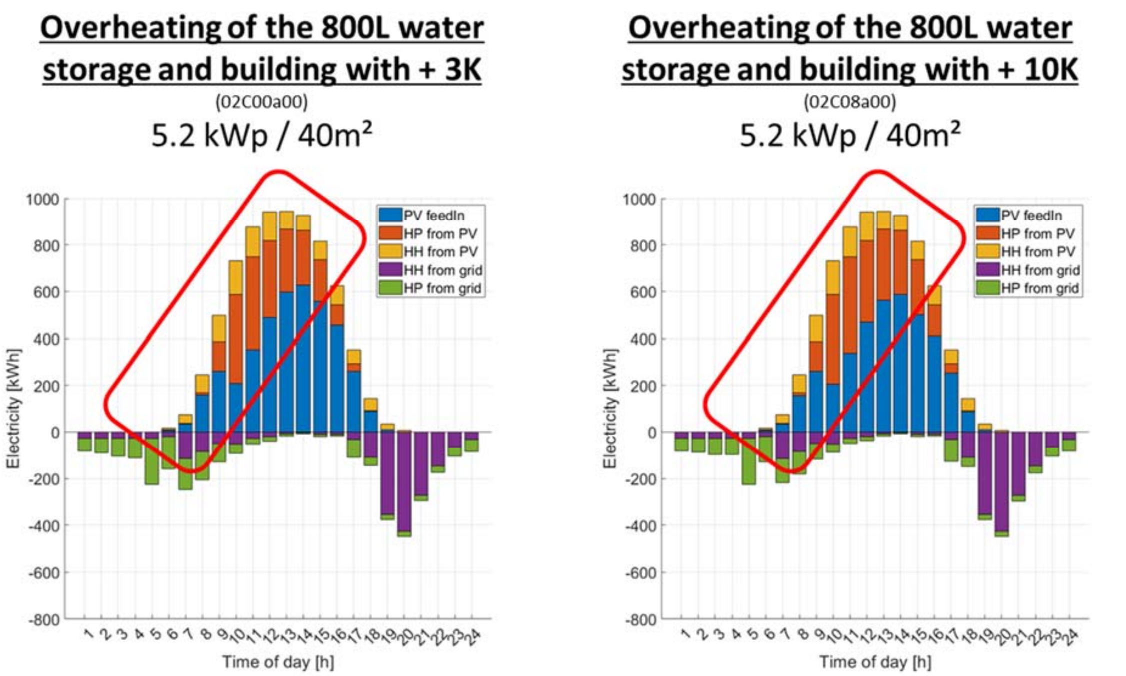


Fig. 7 Virtual 24-hour day of the whole year for the system with PV system with overheating the 800 liter water storage and overheating of the building with an extra lift of +3K of the flow space heating temperature (left) and an extra lift of +10K of the flow space heating temperature at any time whenever excess PV is available at high enough power.

In Fig. 6 the right graph shows a further significant improvement, when the control concept allows the heat pump to overheat the 800 liter water storage in DHW mode or space heating mode at any time (but no overheating of the building), whenever excess PV is available at high enough power. Even though the DHW time slots are defined again from 5 h to 7 h and 17 h to 19 h, what can be observed at 5 h with slightly higher HP grid consumption compared to the left graph.In Fig. 7 the left graph shows the next step of significant improvement, when the control concept allows the heat pump to overheat beside the 800 liter water storage also the building at any time, whenever excess PV is available at high enough power. Overheating the building takes place with an extra lift of +3K of the flow space heating temperature and is allowed until the room temperature reaches 24°C as a maximum, but only if excess PV electricity is available.

In Fig. 7 the right graph shows almost no further improvement anymore, when overheating of the building takes place with an extra lift of +10K of the flow space heating temperature and again until the room temperature reaches 24°C as a maximum.

In general, when comparing the four graphs above (Fig. 6 and Fig. 7), it can be observed, besides less operation of the heat pump with grid electricity, a significant shift of the air heat pump operation more and more to day time instead of operation during night time. This leads not only to much more air heat pump operation powered by the PV electricity, but also to operation during daytime periods with significant higher ambient air temperature with higher COP, even though the flow temperatures during PV-overheating modes are higher compared to standard DHW or space heating modes (see also Fig. 9).

4. Overall Efficiency

In Fig. 8 as the results of the effects discussed before the electricity balance for several variants of floor heating systems and screed thickness (above the line) and concrete ceiling (below the line) with different space heating flow temperatures for overheating is shown.

In each bar from the left to the right the following electricity energies are shown: grid consumption for household electricity (HH grid), PV self consumption for household electricity (HH PV), grid consumption for heat pump operation (HP grid), grid electricity savings for the heat pump in comparison to the reference system shown in the first bar (Grid savings), PV self consumption for heat pump operation (HP PV) and finally the remaining excess PV electricity which is fed into the grid (PV FeedIn).

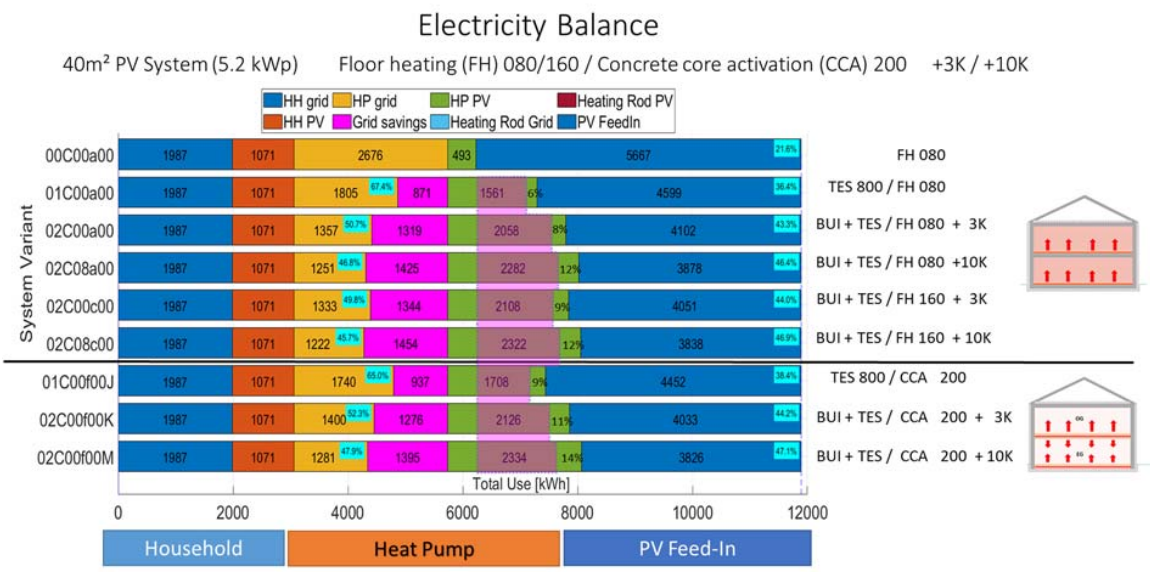


Fig. 8 Electricity Balance for several variants of floor heating systems and screed thickness (above the line) and concrete ceiling (below the line) with different space heating flow temperatures for overheating.

Within the green bar (HP PV) the Grid savings are mirrored to show at the right the remaining part of (HP PV), which in fact is the amount of additional electricity consumption of the heat pump, which is needed to cover the additional heat losses due to the overheating of the water storage and the building respectively. Therefore, just overheating the 800 liter water storage causes 6% [=(1805+1561)/(2676+493)] additional electricity consumption for the heat pump to cover the additional heat losses just of the water storage (see second bar: TES 800 / FH 080). When additionally the building is overheated with "+3 K" in the case of floor heating, the additional annual electricity consumption is 246 kWh (= 2058+1357-2676-493) or 8%, just 2%-points higher (see third bar:

BUI+TES / FH 080 +3K). However, the grid savings can be increased from 871 kWh to 1319 kWh by 51%. In other words, the grid consumption (HP grid) of the heat pump can be reduced to 50.7% in comparison to the reference case: from 2676 kWh to 1357 kWh.

If the overheating takes place with "+10K" instead of "+3K" the grid saving can further be increased from 1319 kWh to 1425 kWh or by 8%. But the additional electricity consumption significantly increases from 8% to 12%, which is +50% relatively. In terms of operating cost Fig. 14 further down will show that the economic advantage is only very little.

Also doubling the screed thickness from 0.08 m (FH080) to 0.16 m (FH160) does not improve the result significantly. Surprising is the fact, that concrete core activation with 0.2 m thickness (CCA 200) with threefold theoretical thermal capacity as potential compared to 0.08 m screed (see Fig. 2) has even worse results of grid savings: 1276 kWh for (BUI+TES / CCA 200 + 3K) compared to 1319 kWh for (BUI+TES / FH 080 + 3K). With Fig. 12 an explanation will be given for this effect.

As mentioned already in the chapter before, due to the PV-overheating the operating conditions for the heat pump can change significantly in both directions: beneficially or disadvantageous. As shown in Fig. 9, based on different definitions of seasonal performance factors (SPF) the system behavior and the heat pump itself can be analyzed. For electricity consumption in general the overall consumption of the heat pump including fan of evaporator but excluding the water pump is used. There is just to differentiate between $P_{el.sys}$ and $P_{el.grid}$. Where $P_{el.sys}$ counts all electricity consumption of the heat pump but $P_{el.grid}$ counts only the electricity delivered from grid.

SPF_{use} is a clear indicator of the overall system performance because as useful heat beside the constant DHW demand always the reference space heating demand is used. Therefore, due to the additional overheating losses of all other variants the reference system (FH 080) shows the highest SPF_{use}.

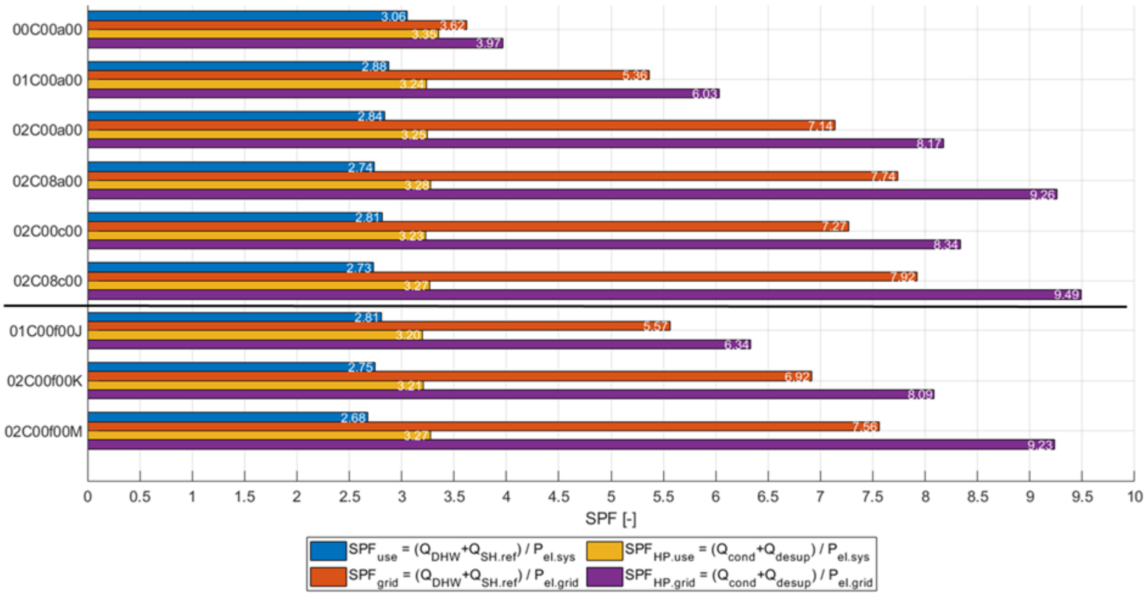


Fig. 9 Differently defined seasonal perfomance factors for several variants of floor heating systems and screed thickness (above the line) and concrete ceiling (below the line) with different space heating flow temperatures for overheating (according to Fig. 8).

For the heat pump itself the $SPF_{HP.use}$ shows already interesting effects in overheating cases ($SPF_{HP.use}$ anyway is highest in the reference case "FH080": 3.35). As more as the floor heating is used for overheating $SPF_{HP.use}$ is increasing slightly. Just using the TES leads to $SPF_{HP.use}$ of 3.24 (TES 800 / FH080) where overheating with "+3K" leads to $SPF_{HP.use}$ of 3.25 and "+10K" leads to $SPF_{HP.use}$ of 3.28. PV-overheating of the water storage stops at 54 °C, where the space heating flow temperature including overheating of "+3K" or even more "10K" leads to about 32°C and 38°C respectively at ambient temperature of 0°C. Therefore overheating the floor heating in average leads to lower condenser outlet temperatures than overheating the water storage. In the case "+10K" more heat can be stored in the screed what additionally leads to the effect that the heat pump has less operating hours during cold night with significant lower evaporator temperature. Nevertheless due to the overheating losses SPF_{use} is lowest in case "+10K".

SPF definitions using only the grid electricity consumption ($P_{el.grid}$) gives an indication how big is the PV contribution in comparison including all heat losses (SPF_{grid}) or just for the heat production of the heat pump itself ($SPF_{HP.grid}$). For example the system PV-overheating the water storage plus the floor heating screed with "+3K" (BUI+TES / FH 080 + 3K) in comparison to the reference system with PV but without any adaption of the control strategy (FH 080) shows SPF_{grid} of 3.62 and 7.14 respectively, which is a difference of factor 2. This fits to the result in Fig. 8 showing a heat pump grid electricity consumption (HPgrid) of 50.7% of the PV-overheating system compared to the reference system.

Due to PV-overheating additional heat losses of the building and the water storage take place which causes a negative effect. In Fig. 10 is shown how big this effect in comparison to other possibilities of energy storage technologies is. The blue circles "Strategies" show how big is the effect of "Effective Use" (which is equal to the reduction of grid electricity consumption) in comparison to the "PV electricity use" which is directly used to operate the air heat pump. In average around 80% of "PV electricity use" in the end leads to "Effective Use" in terms of grid electricity savings.

As an alternative, the excess PV electricity could be fed into the grid and "stored" in a pumped storage hydro power station und consumed by the air heat pump later for standard operation. Assuming 75% efficiency of the pumped storage hydro power station and 5% electricity grid losses in total an efficiency of around 70% can be expected, which is shown by the red circles "GridStorage".

Another option is the installation of a chemical battery in the house. A battery with 1 kWh capacity typically can store around 250 kWh per year in terms of full-cycles. Therefore, a battery with 5 kWh capacity would lead to annual "Effective Use" of 1250 kWh per year, which is in the same range as the two other options called "Strategies"and "GridStorage". BUT: for the battery a severe investment is needed and the lifetime is quite limited and for storing in the pumped storage hydro power station quite a significant fee has to be paid per kWh. The building mass and the water storage as a "thermal battery" are available anyway and therefore do not cause any additional investment cost nor operation cost and also maintenance cost are negligible.

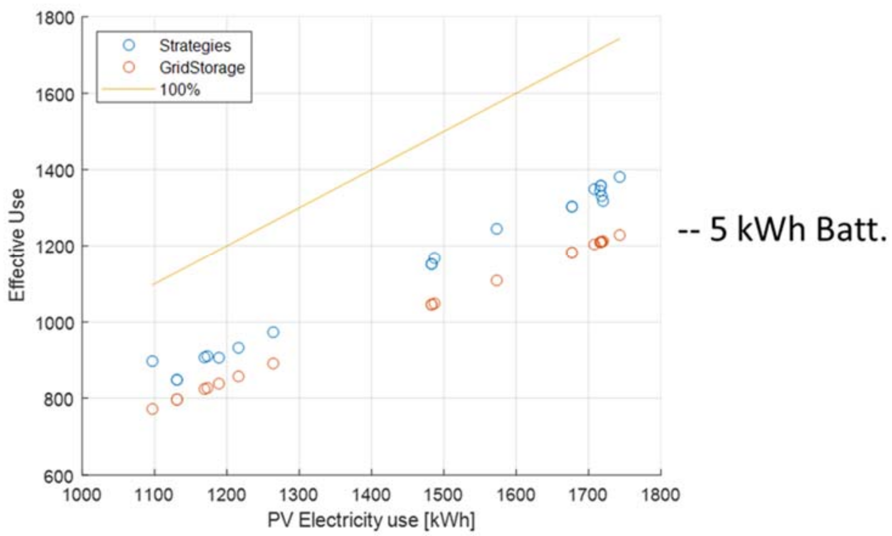
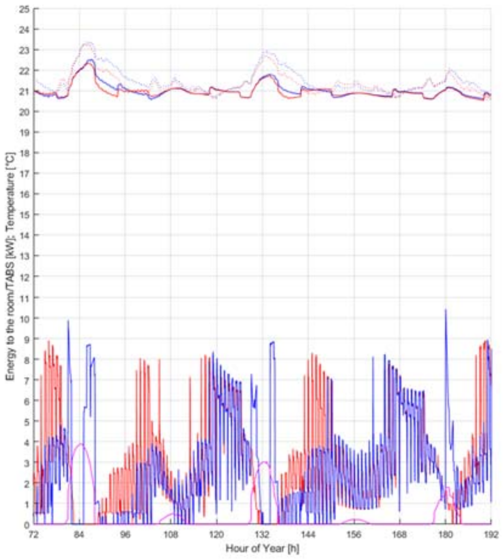


Fig. 10 Comparison of PV self consumption efficiency "Strategies" with pumped storage hydro power station "GridStorage" and chemical battery "5 kWh Batt."

5. System behaviour in detail

Overall evaluations have shown significant effects and grid electricity savings on an annual basis. Details how the effect of PV-overheating works can be observed in Fig. 11 and Fig. 12 where the simulation results of five days (Jan 4^{th} – 9^{th}) are shown in detail.

First clear to see is the replacement of space heating power of the water flow into the floor heating screed from night and early morning hours (90h to 102h, red lines) mainly to the sunny afternoon the day before (86h to 90h, blue lines) in Fig. 11. This is the result of storing heat in the screed with an amount of approx. 23 kWh as indicated in Fig. 12. Similar behavior can be observed two days later but with slightly less PV power resulting in just 12 kWh storing heat in the floor heating screed. In comparison the day between with almost no PV production (96h to 120h) causes almost the same behavior of the heating system from late afternoon until late morning (112h to 128h).



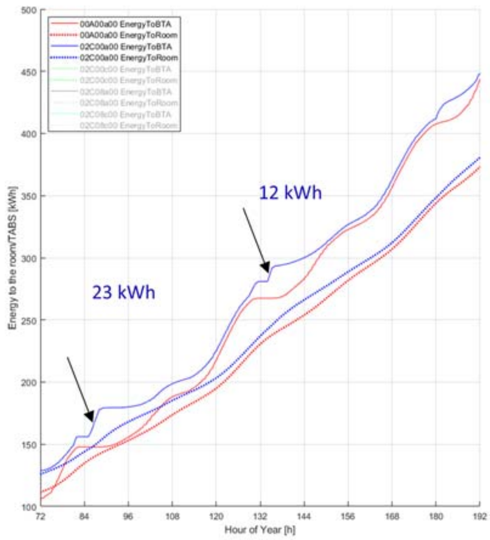


Fig. 11 left: Evolution over time of PV production power (rosa solid line) in combination with space heating power of the water flow (lower curves) and room air temperatures (upper curves: living room dotted line, parents sleeping room solid line) for the reference system (red) and the system with PV-overheating (blue);

Fig. 12 right: The cumulative curve of space heating energy from floor to room air (EnergyToRoom, dotted line) and of space heating energy of the water flow (EnergyToBTA, solid line) showing the storage effect of overheating for the reference system (red) and the system with PV-overheating (blue).

Second also clear to see is, that the room temperature evolution shows minimal higher peak room temperatures during sunny days due to overheating but significant higher room temperatures lasting until after midnight. However, “significant higher room temperatures” has to be interpreted carefully, since the difference is just around 0.5 K!

Therefore, solar radiation into the room and internal loads due to electricity household consumption and persons being in the rooms have much more significant influence than the PV-overheating control concept.

Based on Fig. 11 and Fig. 12 it can also be explained, why the increase of screed thickness or concrete ceiling activation does not result in significant additional savings of grid electricity consumption and increase of PV self consumption. Even during a very sunny day the potential to store heat in the building mass is limited due to the following facts: a) around noon a significant part of excess PV electricity is used to overheat the water storage for DHW, b) the time window with sufficient excess PV power to run the heat pump beside overheating the water storage is limited, especially in the winter period and c) the heating power of the heat pump is limited according to the standard design rules and it is not economic to install a more powerful heat pump just to be able to use some kWh PV excess electricity more.

An overview of the resulting room air temperatures only during the winter season (Oct 1st – March 31st) is shown in Fig. 13 with box-plots showing the median (red line) and 50% of the data in the blue box. The “+3K” PV-overheating strategy also here shows just marginal increase of the room air temperature: just 0.3K increase of the median and the maximum does not reach 24°C (beside some whiskers). The “+10K” PV-overheating strategy shows significant increase of the room air temperature in all cases of creed thickness or concrete ceiling, but still within potentially acceptable limits. However, the energetic benefit of the “+10K” PV-overheating strategy is as limited as the economic, what will be shown in the next chapter.

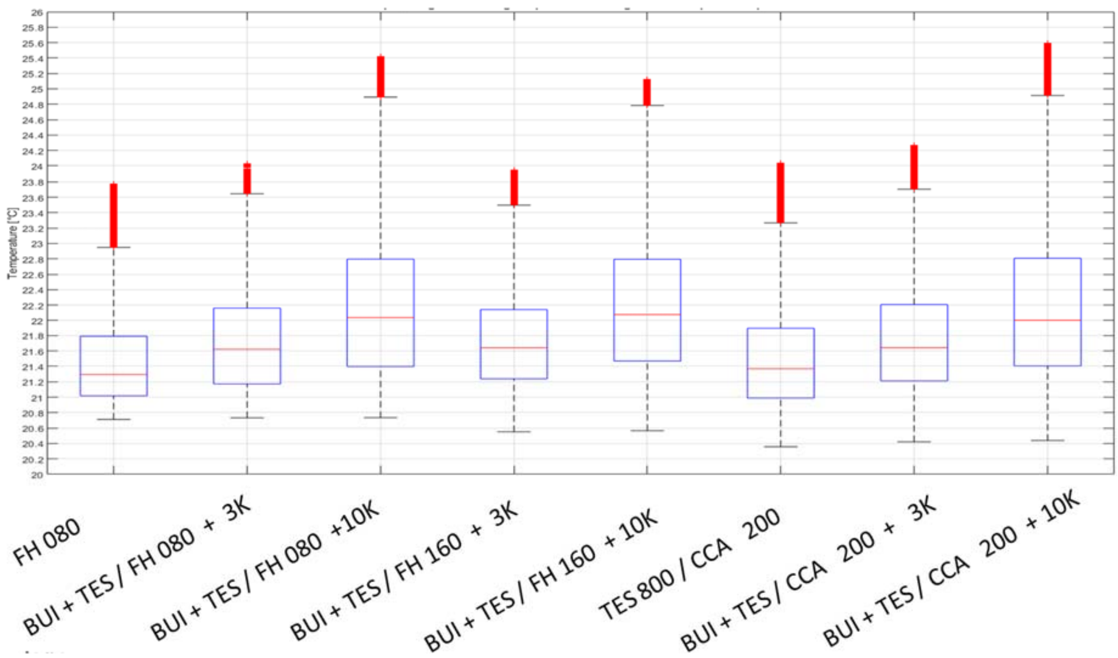


Fig. 13 Room air temperature for several variants of floor heating systems (FH) and different screed thickness and concrete ceiling (CCA) with different space heating flow temperatures for overheating.

6. Operating Cost

Final discussion is done based on Fig. 14, for the economic point of "operating cost" only, since there are no (or just marginal) differences in investment cost of the different simulation variants related to the goal of increasing the system performance based on simple control strategies.

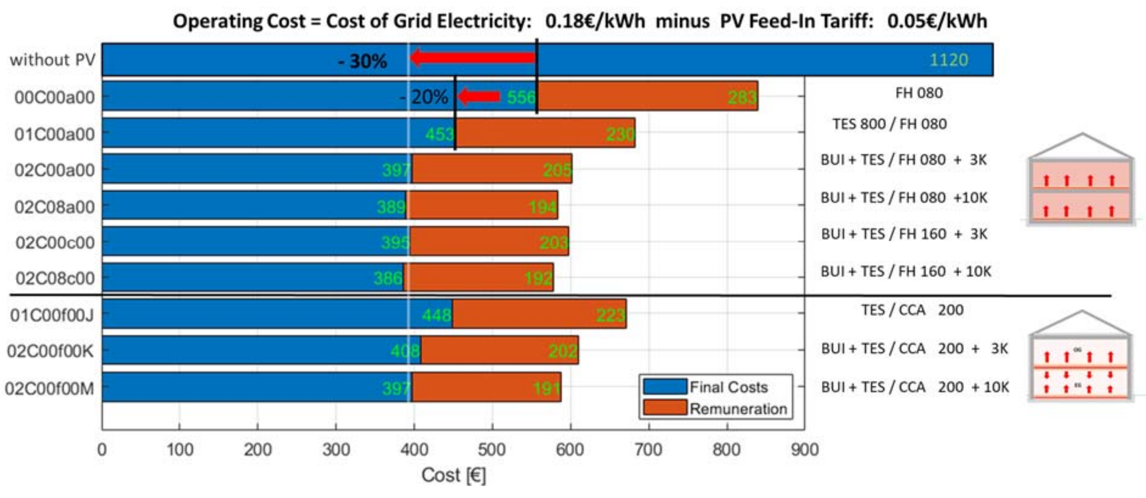


Fig. 14 Final operating cost of electricity (cost of grid minus PV feed in remuneration) including household electricity for several variants of floor heating systems and screed thickness (above the line) and concrete ceiling (below the line) with different space heating flow temperatures for overheating.

Operating cost are defined as cost of grid electricity (0.18 EUR/kWh) for the heat pump and the household electricity consumption minus the remuneration (0.05 EUR/kWh) for the excess PV fed into the grid and sold to the utility. This financial assumption was taken in 2018 based on the actual situation at that time.

The reference system without PV has overall cost of 1,120 EUR per year, as Fig. 14 shows. After installation of the 40 m^2 PV system, cost savings due to PV self-consumption result in 839 EUR per year (75%) minus 283 EUR remuneration leading to 564 EUR per year for refinancing the PV system. Using the "+3K" PV-overheating strategy (BUI+TES / FH 080 + 3K) the remaining operating cost are 397 EUR per year and the saved amount for refinancing increases to 723 EUR per year, which is significantly 28% more. As it can be observed, all variants of screed thickness or concrete ceiling from an economic point of view are in the same range. Just using the 0.8 m3 water storage (TES800/FH080 and TES/CCA200) already has a significant effect, of course mainly due to the fact that only with the water storage the DHW demand can be covered and especially in the summer period almost 100% of the DHW demand can be covered by the PV heat pump system.

7. Conclusions

For a PV air heat pump system in a single-family house designed as a low energy building the grid electricity consumption can be halved compared to a PV – air heat pump system without overheating control concept. Several boundary conditions and parameters were studied concluding that the standard screed thickness (0.08 m) of a floor heating system with about +3K increased space heating flow temperature during PV-overheating already results in around 30% additional operating cost savings compared to a standard control concept.

PV self consumption just for heat pump operation can be quadruplicated. Including household electricity consumption for the entire system still the PV self consumption can be doubled. This is roughly the same effect as a chemical battery typically can achieve (with typical design of: 5 kWh capacity for a 5 kW_p PV system), but much more cheaper since no investment cost occur for the “thermal battery”, which is anyway in the house.

Even though the room air set temperature during PV-overheating is increased from 21°C to 24°C, the finally resulting room air temperature as mean value in the winter period just increases by 0.3K. The peak temperatures during day shows almost no increase but the period from late afternoon to after midnight stays at about 0.5K to max 1K higher after a sunny day.

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