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Smart Grid and PV driven Heat Pump as Thermal Battery in Small Buildings for optimized Electricity Consumption

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Abstract

The purpose of this paper is to show the possible increase of self-consumption of PV electricity production for a building by intelligent use of thermal masses in the building. TRNSYS simulations are carried out for an electric driven heat pump in combination with PV, thermal activated building systems and water storage (TES) in small single family buildings. Several different control strategies adapting set-temperatures in combination with different building types and heat capacities are investigated. For the RES45 single family house with 8,900 kWh space heating and domestic hot water demand per year and a 20m^2 PV system the solar fraction (SF) increased from 11% for a standard configuration up to 61% with maximized use of overheating of TES (2,000 liter tank) and the building. The running cost for the heat pump due to grid electricity consumption (18 EUR-cent per kWh) decreased from 420 EUR per year in the reference case (without PV) to 373 EUR (SF=11%) and to 69 EUR per year (SF=61%), when remaining PV electricity is completely sold with 5 EUR-cent per kWh.

Keywords: *heat pump, thermal battery, photovoltaic, smart grid, desuperheater*

1. Introduction

Electrical driven heat pumps in combination with thermally activated building systems (TABS) and conventional hot water storages (TES) can be used as thermal battery for electricity produced based on renewable energy sources. This electricity might be produced locally with photovoltaic systems on the building with the goal to realize a maximum of self-consumption. Based on a set of theoretical simulations it was investigated how a heat pump system in combination with a building with different designed TABS can act as a thermal battery when supplying space heating and domestic hot water to the building with different control strategies. Based on dynamic hardware in the loop (HiL) laboratory measurements the heat pump model developed by TU-Graz / IWT and SPF-Rapperswil (Dott et.al., 2012) was parameterized.

2. Set Up of Simulations

For the simulations a TRNSYS model is set up with several building types, a general hydraulic concept and several control strategies.

2.1. Buildings

Simulations are done for single family houses (based on the IEA SHC Task44 reference building; Dott et.al., 2013) designed as passive house standard (RES15: 15 kWh/m^{2}a space heating consumption, SH) or low energy standard (RES45: 45 kWh/m^{2}a) and for a small office building (OFF45: 45 kWh/m^{2}a) at Innsbruck climate with different thermal active mass variations of floor or ceiling heating with different heat capacities.

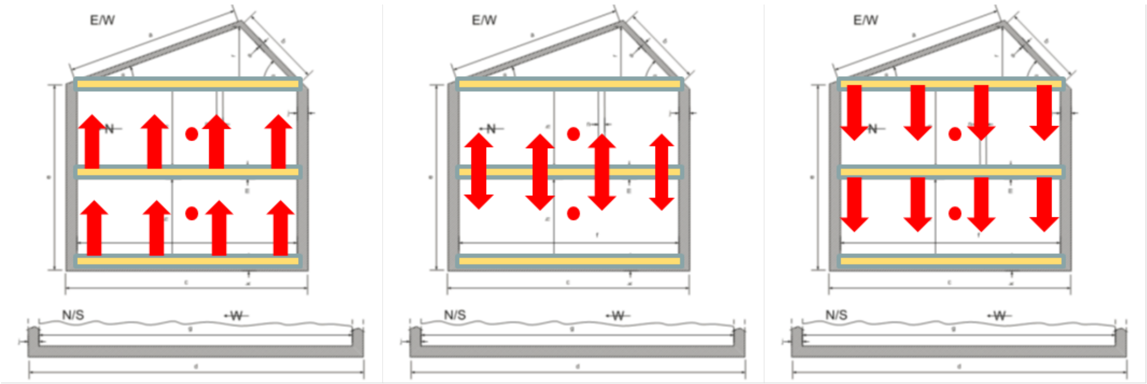

Fig. 1: TABS placed in the buildings, left: RES45, middle: RES15 and right: OFF45

The reference floor area is 140 m^2 for all buildings. The domestic hot water (DHW) consumption is 2,175 kWh per year for the residential buildings and no domestic hot water consumption for the office building. As shown in Fig. 1 the RES45 is equipped with floor heating as TABS in both floors, the RES15 has only TABS in the floor between first and second floor and OFF45 is equipped with ceiling heating/cooling as TABS in both floors.

2.2. Hydraulic and Control Concept

The heat pump is equipped with a desuperheater with variable volume flow. As shown in Fig. 2 the ground source brine heat pump (HP) is connected to a water storage (TES) directly via the desuperheater. The condenser of the HP can charge the TES or bypass the TES for direct heating of the building. Domestic hot water preparation is done with an external plate heat exchanger with controlled primary mass flow.

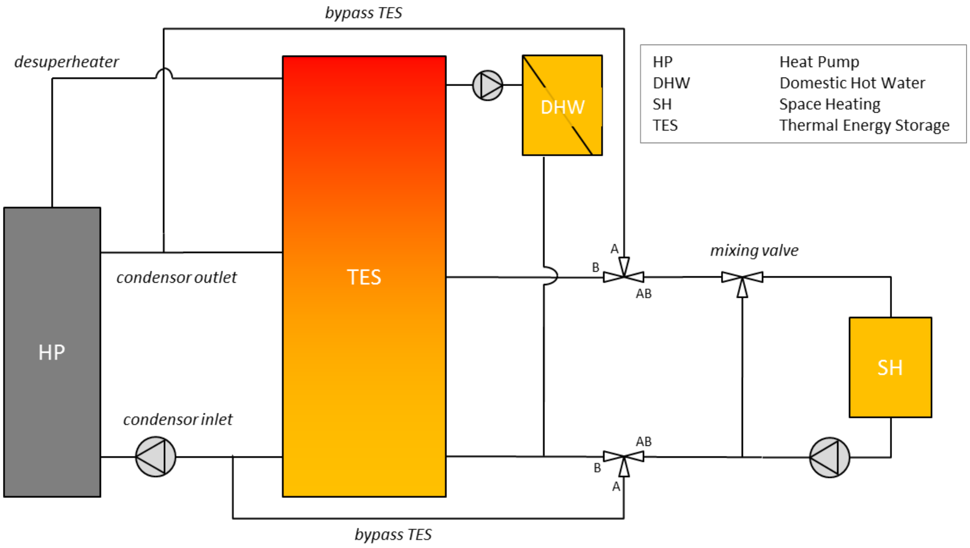

Fig. 2: Hydraulic concept of the heat pump system and connection to TES and building.

The heat pump is designed for thermal power output of about 10 kW$_{th}$ at B0W35. The brine source temperature is modelled with average temperature of 5°C ± 6K varying over the year. The heat pump can be operated in different ways like: a) power controlled depending on the ambient temperature, b) power controlled depending on availability of photovoltaic electricity, c) with or without using a desuperheater for domestic hot water preparation, d) charging a water storage tank at different temperature levels or e) heating the building to room temperatures with more or less hysteresis.

The five control concepts are named “REF”, “SELF, “TES”, “BUI” and “BUI+TES”. The “REF” system is using only electricity from the grid. The “SELF” system is operating exactly like the “REF” system and using PV electricity only if just by coincidence the heat pump is also in operation according to standard control algorithm.

If the PV power is higher than 1 kW and greater than the actual electricity demand of the compressor according to the standard control strategy, the heat pump is in operation with compressor speed matching the PV electricity and therefor the system can store heat in the TES or the TABS. In the "TES" control strategy the TES is heated up to 60°C. In the "BUI" control strategy (in winter season) the building with the TABS is heated until a maximum room temperature of 26°C is reached. In "BUI+TES" first the "BUI" algorithm is used and second, if still PV power is available, the "TES" algorithm is used. As standard algorithm the PV electricity is used first directly by the heat pump, second for household in the building and third fed into the grid. In Fig. 3 the possible energy flows and control algorithms are shown.

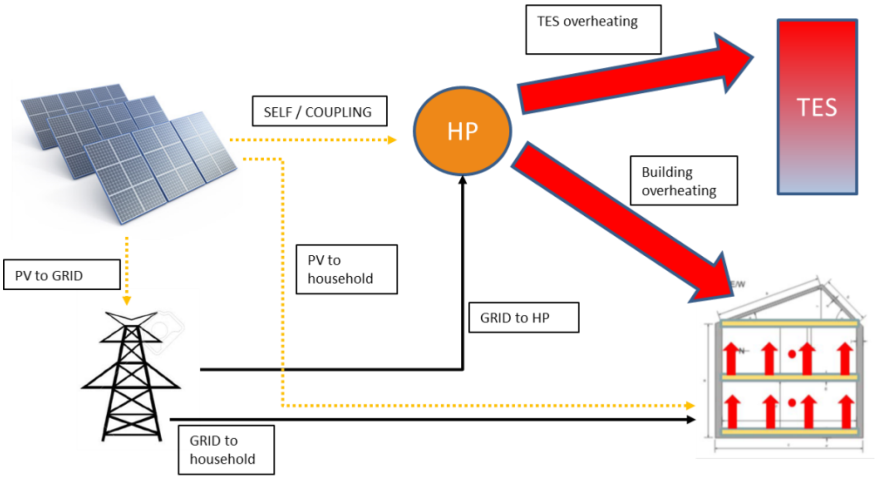

Fig. 3: Energy flow concept for coupling PV and grid electricity via heat pump to the TES and the building via TABS.

In this paper the results in terms of operating cost are presented without taking into account the household electricity to avoid the influence of assumptions for the household consumption profile. Therefore the PV electricity is first used by the heat pump and the remaining electricity is completely sold to the grid.

3. Simulation Results

The presentation of the simulation results is split according to the buildings: RES45, RES15 and OFF45. In this paper only the results for RES45 are presented.

3.1. Solar Fraction and Useful Heat

The main key figures are presented in Fig. 4 for the building RES45 with PV area of 20 m^2 (PV20) or 40 m^2 (PV40) and TES volume of 500 (TES500), 1,000 (TES1000) and 2,000 (TES2000) liter. The key figures are defined as following:

- SF_HP: Solar Fraction is defined as "heat provided by the heat pump with PV-electricity" divided by "total heat provided by the heat pump".
- Q_PV-Heat_spec: Specific solar heat is defined as heat produced by heat pump with PV electricity per square meter PV area.
- Q_PV-Heat_useful_spec: Useful specific solar heat is defined as heat produced by the heat pump with PV electricity minus additional tank losses (compared to REF) minus overheating of the building (compared to REF) per square meter PV area (TES500 has 50mm, TES1000 and TES2000 have 100mm insulation thickness).

For the RES45 system with 20 m^2 PV area (about 2.5 kW$_{peak}$) and the standard TES volume of 500 liter a solar fraction of SF_HP=11% can be achieved with the SELF control concept (see chapter 2.2) resulting in a useful heat production (Q_PV-Heat_useful_spec) based on PV-electricity of 54 kWh per year per square meter PV area. By increasing the TES volume up to 2,000 liter, a SF_HP=19% and 99 kWh/m^{2}a useful heat can be achieved.

Changing to the TES control concept already with 500 liter TES volume a solar fraction of SF_HP=31% and useful heat of 147 kWh/m^{2}a can be achieved, which is 50% more than before with 2,000 liter TES volume and SELF control concept. By increasing the TES volume up to 2,000 liter, a solar fraction of SF_HP=53% and 262 kWh/m^{2}a useful heat can be achieved.

Changing to the BUI control concept already with 500 liter TES volume a solar fraction of SF_HP=46% and useful heat of 210 kWh/m^{2}a can be achieved, which is again 50% more than just the TES control concept. But in this case it is important to notice the comfort disadvantage, because the room temperature in average is significant higher due to the building overheating up to 26°C. As it also can be observed, the useful heat in the BUI control concept is significant lower than the produced heat because of significant overheating losses of the building (see also Fig. 5).

Using both the BUI+TES concept already with 500 liter TES volume a further increase of solar fraction to SF_HP=56% and useful heat of 262 kWh/m^{2}a can be achieved, which is 80% more than just the TES control concept and still 22% more than the BUI concept. But again the disadvantage of the overheating temperature in the building has to be taken into account. In comparison, with the TES concept and 2,000 liter TES volume an equivalent solar fraction and useful heat can be achieved but without any comfort disadvantages. With the BUI+TES concept with 2,000 liter TES volume the highest solar fraction of SF_HP=61% and useful heat of 290 kWh/m^{2}a can be achieved.

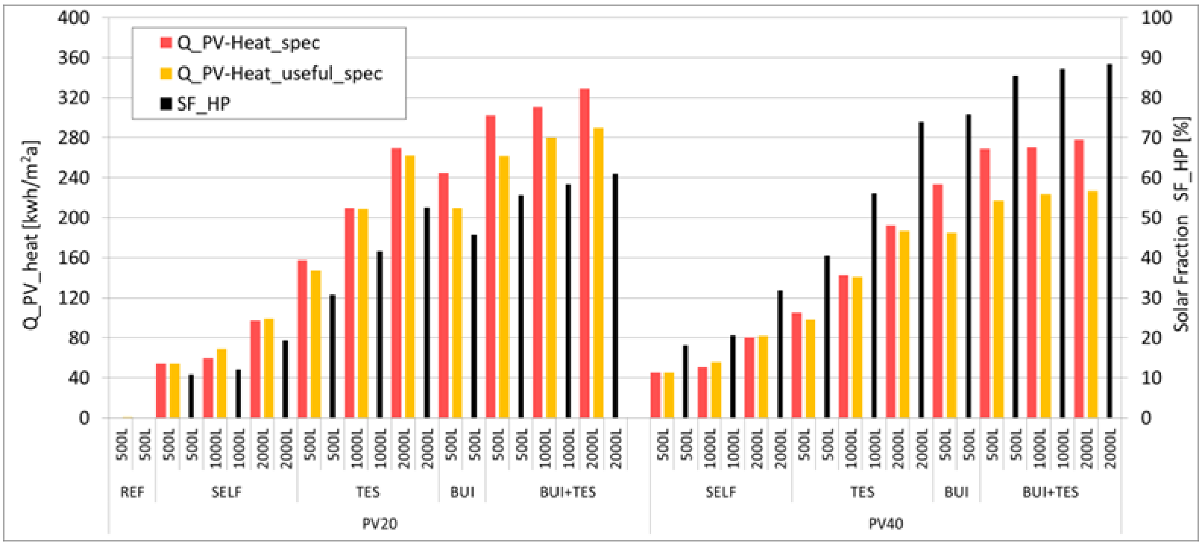

Fig. 4: Solar fraction (SF_HP), heat (Q_PV-Heat_spec) and useful heat (Q_PV-Heat_useful_spec) produced by heat pump using PV electricity depending on control algorithm and PV area.

Increasing the PV area from 20 m^2 to 40 m^2 (around: 2.5 kW$_{peak}$ to 5 kW$_{peak}$) the results are presented on the right side of the graphs. Solar fractions and useful heat produced with PV electricity are significant higher. But with the standard SELF concept still a solar fraction of only SF_HP=18% can be achieved, not much more compared to PV20 with SF_HP=11%. With TES concept and 2,000 liter TES volume an already remarkable solar fraction of SF_HP=74% can be achieved with PV40, but useful heat is only 187 kWh/m^{2}a compared to 262 kWh/m^{2}a with PV20. However, the remarkable potential with PV40 is a solar fraction of SF_HP=85% using the BUI+TES concept with the standard TES volume of 500 liter, which is almost what can be reached with 2,000 liter TES volume (SF_HP=88%).

3.2. Seasonal Performance Factors

In Fig. 5 and Fig. 6 different versions of “Seasonal Performance Factor – SPF” are presented for the RES45 building and the cases presented before in Fig. 4. It can be observed how the heat pump efficiency (SPF_el_HP) is changing according to the operating conditions (condensor temperature level, start/stop frequency).

In Fig. 5 the overall system efficiency of PV + heat pump (SPF_el_use) is changing more significant due to the hydraulic and the control concept including additional system heat losses (TES losses and building overheating) compared to the reference system (therefore SPF_el_use is based on the reference consumption for domestic hot water and space heating: DHW+SHref). “SPF_el_grid” is defined to show how efficient the reference consumption (domestic hot water plus space heating) is covered just by grid electricity consumption, therefor assuming that PV electricity is for free.

With the SELF control concept, a clear optimum with the TES volume of 1,000 liter can be observed for “SPF_el_HP” and “SPF_el_use”. This shows that even in standard control concepts a significant water storage (1,000 liter instead of 500 liter) has a positive effect on the operation behaviour of the heat pump in terms of start/stop frequency which cause start/stop losses (see SPF_el_HP).

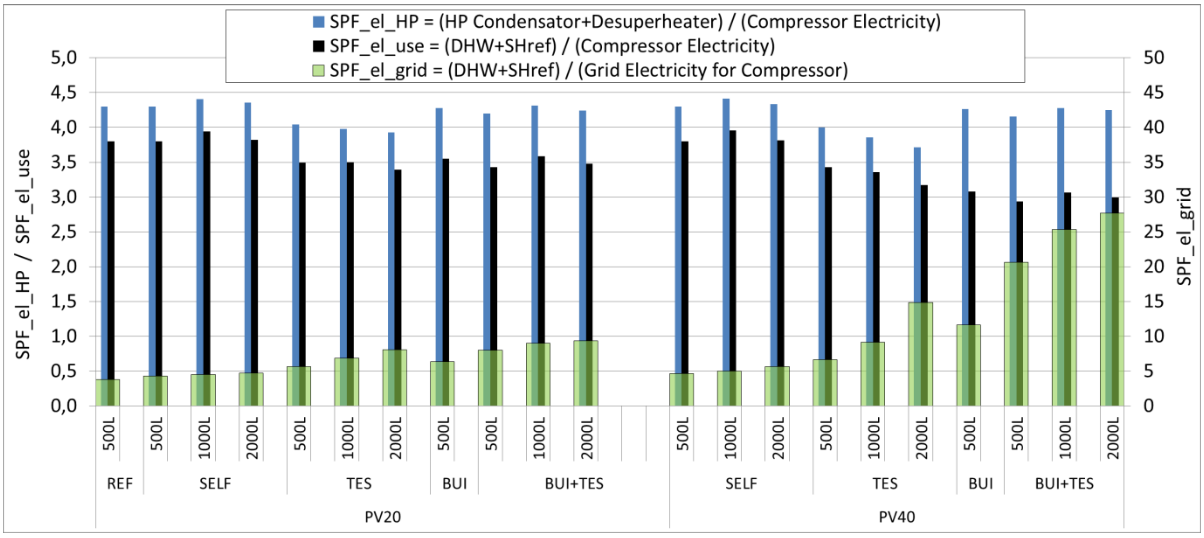

Fig. 5: Seasonal performance factor for the heat pump itself based on compressor electricity consumption (SPF_el_HP), for the reference used energy (domestic hot water and space heating consumption of REF) based on compressor electricity consumption (SPF_el_use) and for the reference used energy based on grid electricity consumption (SPF_el_grid).

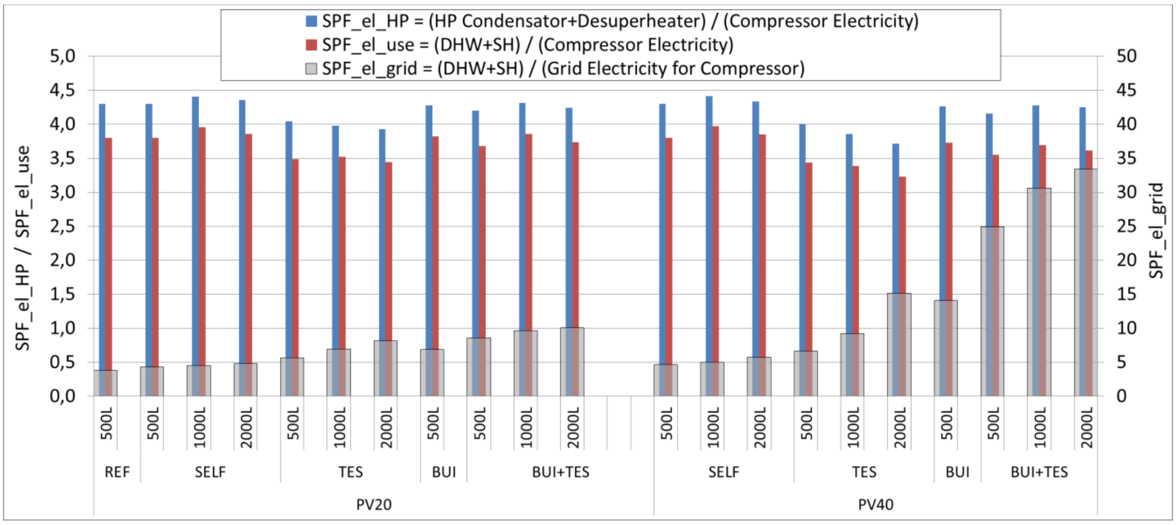

Fig. 6: Seasonal performance factor for the heat pump itself based on compressor electricity consumption (SPF_el_HP), for the used energy (domestic hot water and space heating consumption) based on compressor electricity consumption (SPF_el_use) and for used energy based on grid electricity consumption (SPF_el_grid).

However, the grid electricity consumption still is very high as it is indicated with almost no increased value for “SPF_el_grid” (3.8 for REF increasing to 4.49 for SELF with 1,000 liter for PV20) in this case. A significant increase of SPF_el_grid up to 8.1 can be observed with the TES control concept with 2,000 liter or even more a SPF_el_grid up to 9.4 with the BUI+TES control concept. In other words, based on grid electricity consumption, the heat pump in combination with PV20 can provide 2.5 times more useful heat (9.4/3.8) to the building compared to the reference system.

If a PV area of 40m^2 (PV40) is coupled to the heat pump, even higher “SPF_el_grid” up to 28 can be reached as maximum. Especially in the PV40 cases with BUI or BUI+TES control concept it can be observed a significant increasing difference between “SPF_el_HP” and “SPF_el_use”. This can be explained due to the increasing additional heat losses which are created by overheating the building because solar fraction already reaches very high values in the range of 70% to 90% (see Fig. 4). The heat losses occur to a small extend in the TES, but much more due to the overheating of the building up to 26°C.

In Fig. 6 for comparison, the overall system efficiency of PV + heat pump (SPF_el_use) is presented based on the “actual” consumption for domestic hot water and space heating (DHW+SH).

“SPF_el_grid” is defined to show how efficient the “actual” consumption (domestic hot water plus space heating) is covered just by grid electricity consumption, therefor assuming that PV electricity is for free. Comparing with Fig. 5 it can be observed the influence of the overheating control strategies for the TES and/or the building on the key figures “SPF_el_use “ and “SPF_el_grid”.

3.3. Overheating of the Building

In Fig. 7 the effect of overheating the building is shown for the RES45 system with a TES volume of 500 liter and 20 m^2 PV area. In the reference case the set temperatures for the room temperature is 20.5°C to switch on and 21.5°C to switch off the space heating. In order to be able to store PV electricity in terms of heat in the building mass, during periods with sufficient PV-power the controller allows to overheat the building up to 22, 23, 24, 25 or 26°C in the maximum case.

With overheating up to 26°C the additional space heating consumption is 678 kWh/a or 10% compared to the reference case. Nevertheless, grid electricity consumption due to the building overheating is significantly decreasing (-40%) and only about 15% of the consumed PV electricity is used for generating this overheating losses of 678 kWh/a.

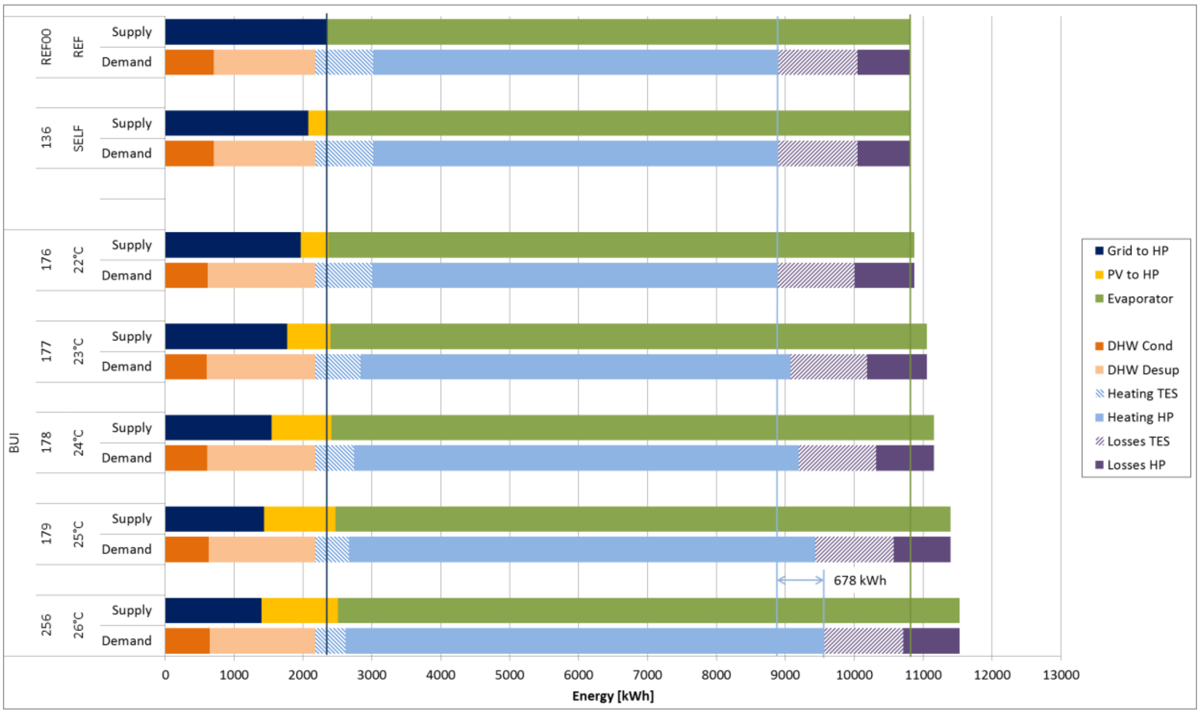

Fig. 7: Energy balance of RSE45 building with control concept BUI and different building overheating set temperatures of 22°C up to 26°C.

In Fig. 8 the effect on the room temperature for different overheating set temperatures is shown. It is clear to see that the advantage of increased use of PV electricity by overheating the building leads to significant higher room temperatures which in case of higher set temperatures (e.g. BUI 26°C) reach about 1.5 K more than the reference and the SELF case and might not be comfortable anymore.

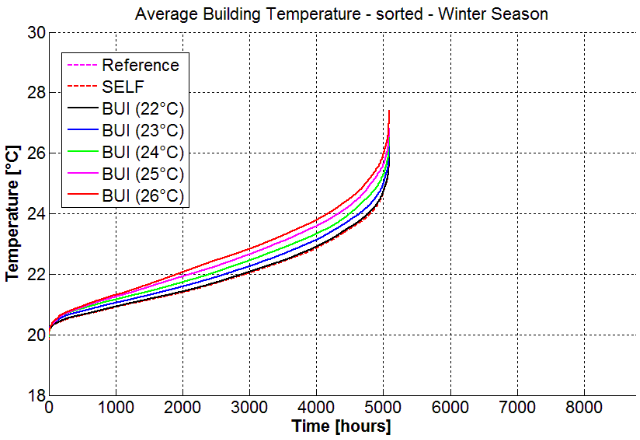

Fig. 8: Sorted average room temperature during winter season due to building overheating (Ref and SELF are identical).

3.4. Domestic Hot Water Preparation

A special investigation was done for hot water preparation. In Fig. 9 the control concept “SELF” shows the standard situation with heating the tank after typical large water tapping in the morning and in the evening. The heat pump immediately starts to heat the TES and during day when PV produces electricity the heat pump cannot use it. Since the DHW-volume in the TES is big enough the operation of the heat pump can be blocked during night from 8 p.m. until 11 a.m. resulting in the system behavior “SELF + DHW NIGHT OFF”. The heat pump operates only once per day anymore and always starting at 11 a.m. with a big chance to use PV electricity. If the control concept “TES COUPLING” is used, the heat pump always is heating the tank if PV electricity is available and the compressor power is controlled matching the PV power. Thanks to the heat capacity automatically the heat pump operation period is shifted from morning and evening to day periods with potential PV electricity production.

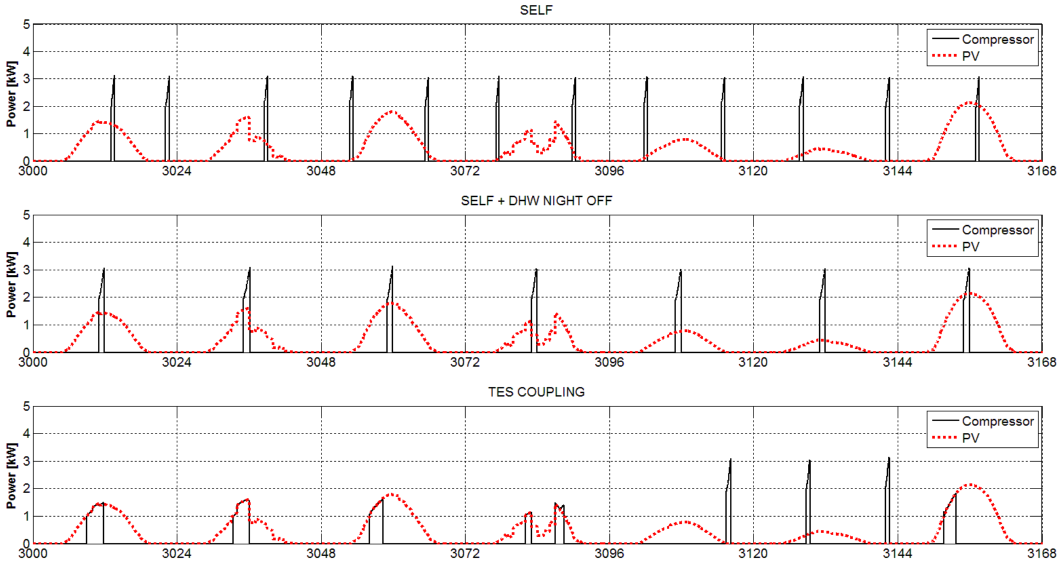

Fig. 9: Different control concepts for hot water preparation during summer time.

In Fig. 10 the energetic effect of the different operation strategies for the system with a TES volume of 500 liter is shown. With the “SELF+NIGHT OFF” concept the PV-self consumption already can be increased from 261 kWh (SELF concept) to 470 kWh by 80%. Additionally the overall heat pump demand slightly reduced in this case thanks to reduced TES losses and significant less heat pump losses (longer running periods and less start frequency). With the “TES” concept (including some small use for space heating also during heating season in winter time) the PV-self consumption can be further increased to 975 kWh. If this value is corrected by the additional losses, still a useful PV-self consumption of 767 kWh can be achieved, which is 3 times more than with the SELF concept.

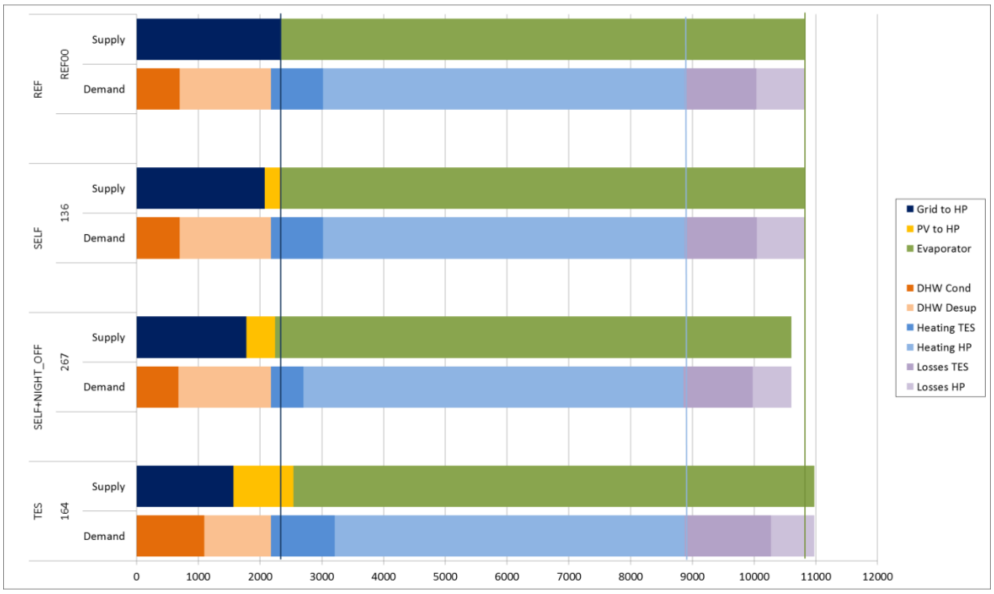

Fig. 10: Saving potential of grid electricity for domestic hot water production.

3.5. Energy Balance of all Control Strategies

In Fig. 11 finally for the RES45 building with 20 m^2 PV area the energy balances for the different control strategies in combination with TES-volumes of 500, 1,000 and 2,000 liter are shown. Main goal of the investigations is to maximize the direct PV electricity (PV to HP) consumption by the heat pump and therefor to minimize the grid electricity consumption (Grid to HP). Basic concept to reach the goal is to store the PV electricity as heat produced by the heat pump in the water storage (TES) or in the building mass (TABS) by overheating the building. But several effects occur which are disadvantageous and reduce the saving effect more or less significant. Additional heat losses (Losses_TES, Losses_HP) due to higher temperatures in the TES and in the space heating system during building overheating, higher start/stop frequency of the heat pump and also higher building heat losses (transmission and ventilation) due to the overheating up to 26°C.

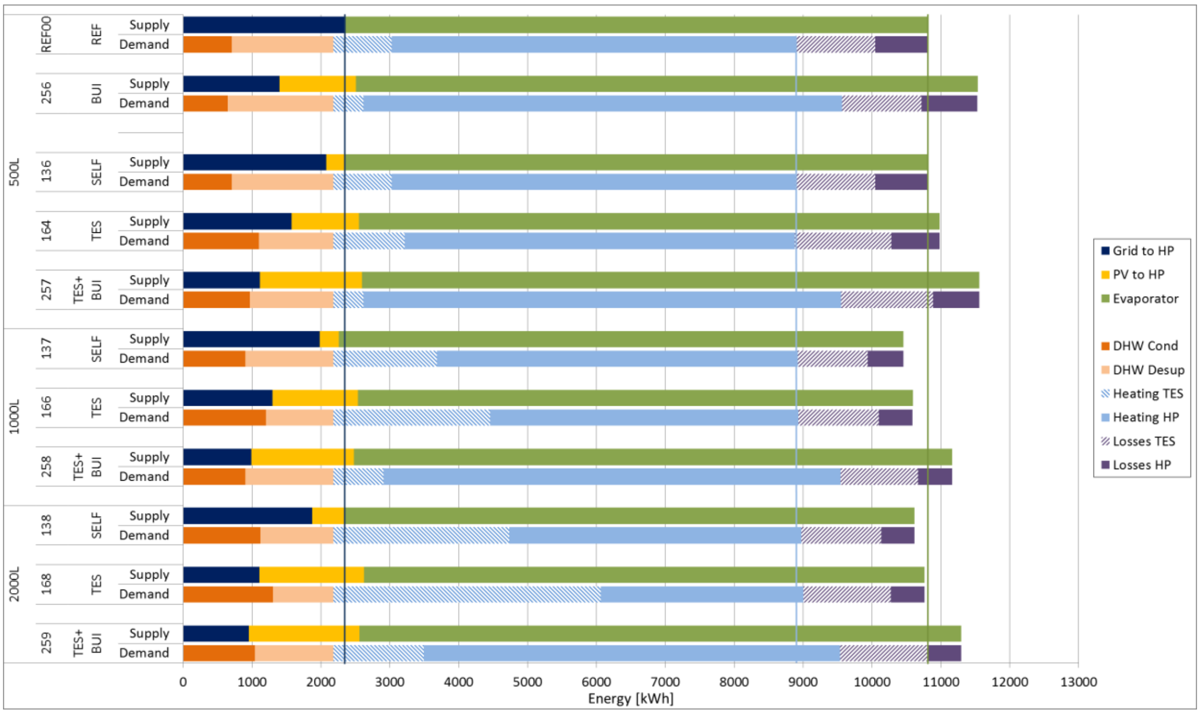

Fig. 11: Energy balances of RES45 building with 20 m^2 PV area, control concepts SELF, BUI, TES, BUI+TES and TES volumes of 500, 1,000 and 2,000 liter.

Fig. 11 shows each case in two bars. The upper bar shows the energy input to the heat pump by PV and grid electricity to the compressor and environmental heat to the evaporator. The lower bar shows how the produced heat is used: heat from condenser and from desuperheater to domestic hot water, heat from TES to space heating, heat from heat pump direct to space heating, heat losses of TES and finally heat losses of the heat pump (start/stop losses and thermal losses).

In all cases with building overheating (BUI and TES+BUI) it can be observed that due to the building overheating the total heat demand is higher compared to the reference case. Nevertheless the grid electricity consumption is significant lower thanks to the PV electricity consumption.

In all cases with TES volume more than 500 liter the losses of the heat pump are significant lower, which can be explained with a much lower start/stop frequency.

In Fig. 12 the effect on the grid electricity supply and PV electricity production and PV self-consumption is shown for the RES45 building with 20 m^2 (PV20) and 40 m^2 (PV40) PV area.

For the PV20 case, the share of PV to the heat pump (PV to HP) can be significantly increased from 7% up to about 44%. The grid electricity consumption can be reduced by up to 54% compared to the SELF concept.

For the PV40 case, the share of PV to the heat pump (PV to HP) can be significantly increased from 6% up to about 36%. The grid electricity consumption can be reduced by up to 83% compared to the SELF concept.

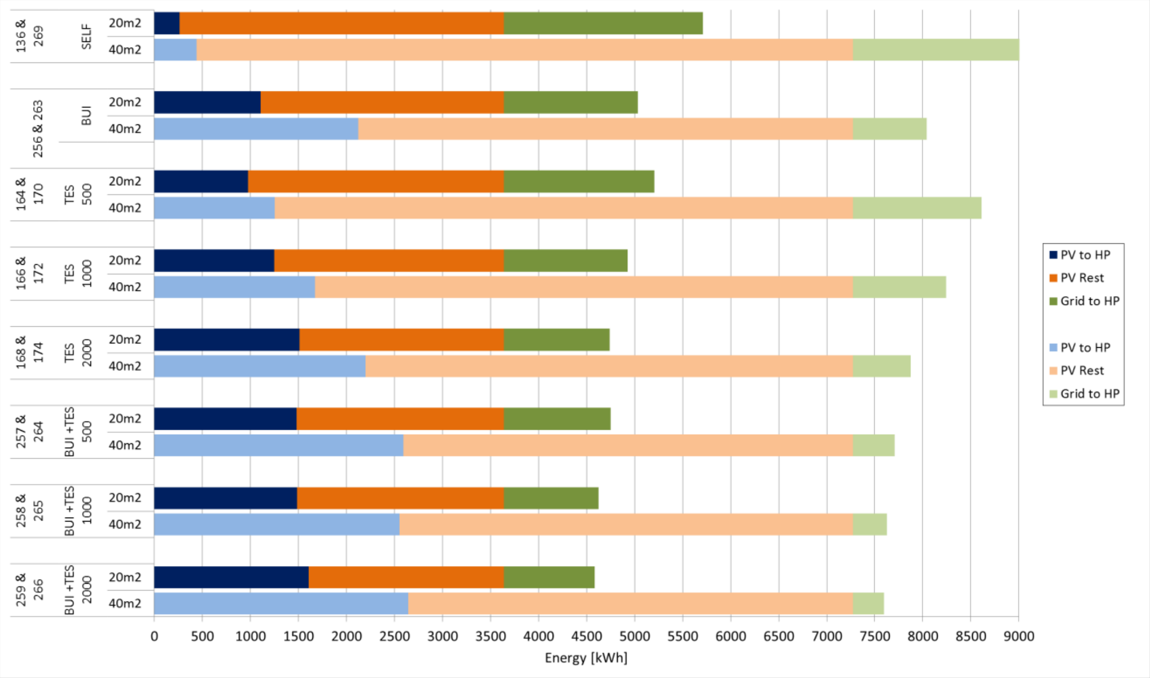

Fig. 12: Distribution of PV- and Grid Electricity

3.6. Qualitative Effects of the Control Strategies

The different operation strategies and the effects which can be observed are described with the following graphs based on the RES45 building with the concepts SELF, TES1000, BUI+TES1000. Each graph is split into 7 sub-graphs showing the following:

1. Temperatures in the TES at the top (TES T1) and at the bottom (TES T5).
2. For the heat pump the inlet temperature (T condens in) and the outlet temperatures from condensor (T condens out) and from desuperheater (T desup out).
3. The control functions (CF) showing if it is possible to run the heat pump direct coupled with the PV (Coupling PV-HP: 1 or 0) and the relative input signal for the compressor speed (Speed HP: in %).
4. The control functions (CF) showing if space heating is needed (room T.) according to the room set

temperatures 20.5°C (on) and 21.5°C (off), if the heat pump is only heating the TES to ensure the domestic hot water consumption (DHW) and the actual COP of the heat pump (COP/10).

5. The room temperature is shown for both floors, (Ground Floor) and (First Floor).
6. The electricity power consumed by the heat pump compressor (Compressor) and the produced PV electricity (PV).
7. The ambient (T. amb) and the brine source inlet temperature to the heat pump (T. evap in).

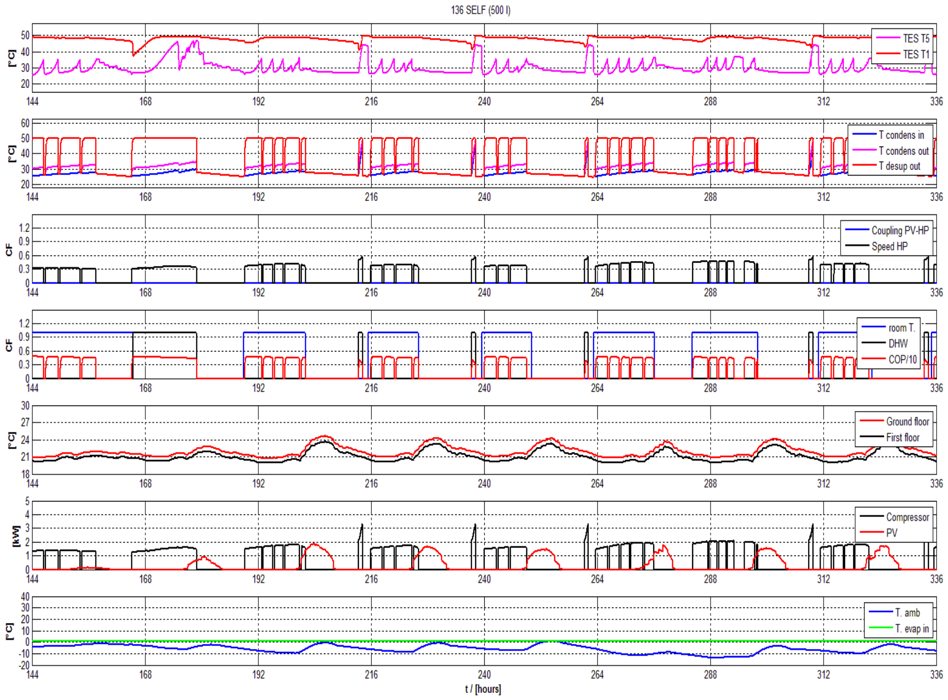

Fig. 13: System behaviour for the SELF system (also the REF system) in winter week in January.

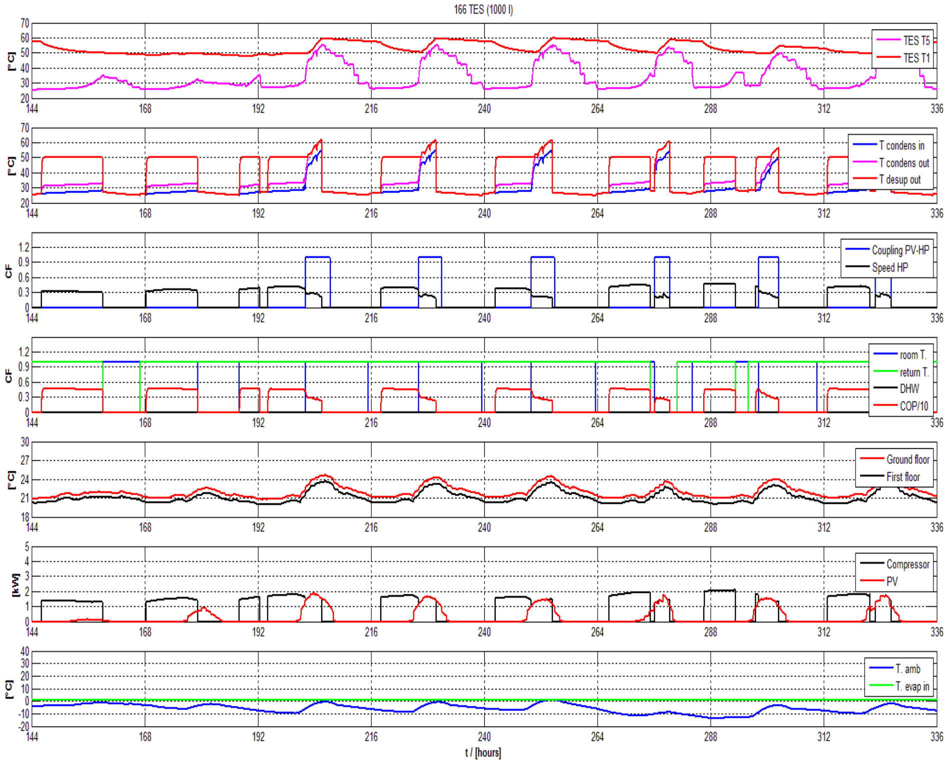

Fig. 14: System behaviour for the TES system (TES overheating if PV is available) in winter week in January.

In Fig. 13 the standard control concept in combination with a 500 liter TES volume is shown for one week in January as it is valid for the reference system (REF) and for the SELF system as well. Main message is the fact that the heat pump typically is in operation in the night and early morning, clear before the PV electricity production starts. The heat pump stops for very short time when the TES is heated by the desuperheater allowing for about 20 minutes to heat from the TES.

In Fig. 14 the positive effect of a 1000 liter TES volume combined with PV-coupling when possible is shown (no overheating of the building). The heat pump is running much longer and the stop period with direct heating out of the TES lasts for about 2 hours. In the night space heating can be supplied for about 3 hours out of the TES (based on stored PV-heat) before the heat pump has to start again. During day when the TES is heated with PV-coupling to high temperatures, it can be observed that the COP significantly decreases due to the high operating temperatures.

In Fig. 15 the system behavior with overheating of the building up to 26°C and afterwards if possible overheating of the TES with 1000 liter is shown. The heat pump is operating at lower temperatures resulting in a higher COP during overheating the building compared to overheating the TES (see Fig. 14). The need for space heating (room T.) after a sunshine day is shifted for about 3.5 hours compared to SELF or TES system. The room temperatures reach higher values during overheating the building mass (TABS).

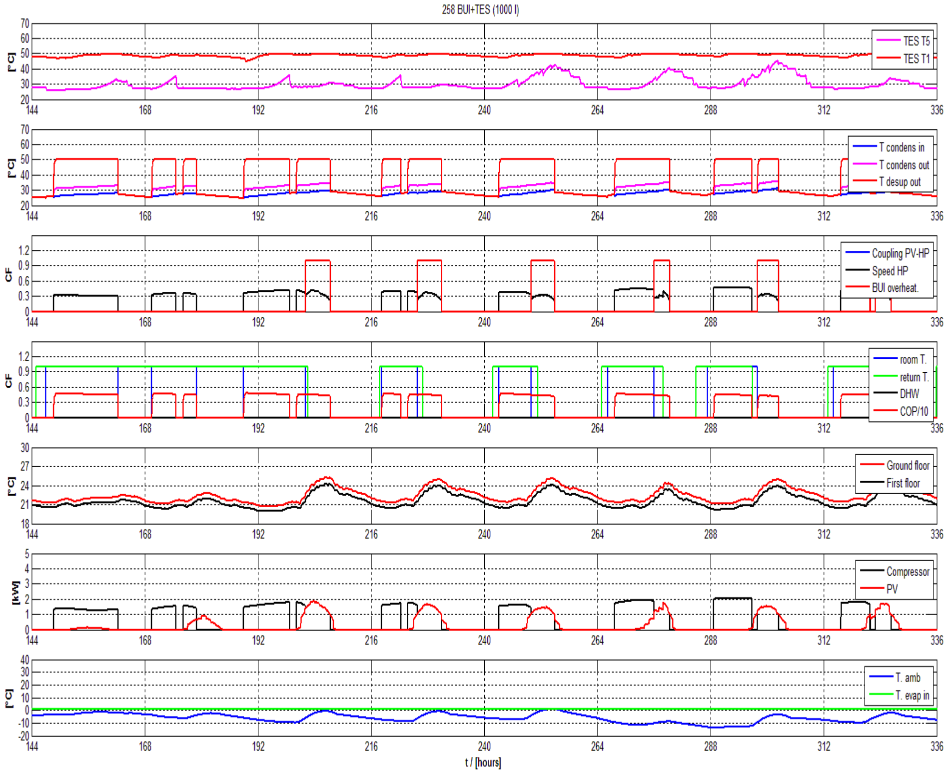

Fig. 15: System behaviour for the BUI+TES system (first BUI overheating and then TES overheating if PV is available) in winter week in January.

3.7. Operating Cost of the System

Finally a simple economic investigation based only on operation cost is shown in Fig. 16 for the RES45 building. The following assumptions are used:

- The PV area is 20 m^2 (2.5 kW_{peak}) or 40 m^2 (5.0 kW_{peak}) oriented south and with a slope of 40°. The simulated annual electricity production is 1,455 kWh_{el}/kW_{peak}.
- Electricity produced by PV is only used by the heat pump, surplus is fed into the grid.
- Cost for electricity purchased from the grid: 0.18 EUR per kWh_{el}
- Feed-in tariff for PV: 0.05 EUR per kWh_{el}
- “Net cost” is the difference of “Annual Cost HP” minus “Annual Profit PV”.
- “Net gain” is the difference of “Annual Profit PV” minus “Annual Cost HP”.

As Fig. 16 shows, the annual cost to run the heat pump are 420 EUR for the reference case, just slightly reduced to 373 EUR (PV20) and 342 EUR (PV40) if PV electricity is used when by coincidence also the heat pump is in operation. An increase of the TES volume shows also only little improvement. A significant reduction to 200 EUR (52% less) annual cost can be achieved with the TES control concept with 2,000 liter TES volume or with the BUI+TES control concept in combination with the standard TES volume of 500 liter but accepting overheating the room temperature. In combination with PV20 always "Net cost" appears but with PV40 already in all cases "Net gain" is possible.

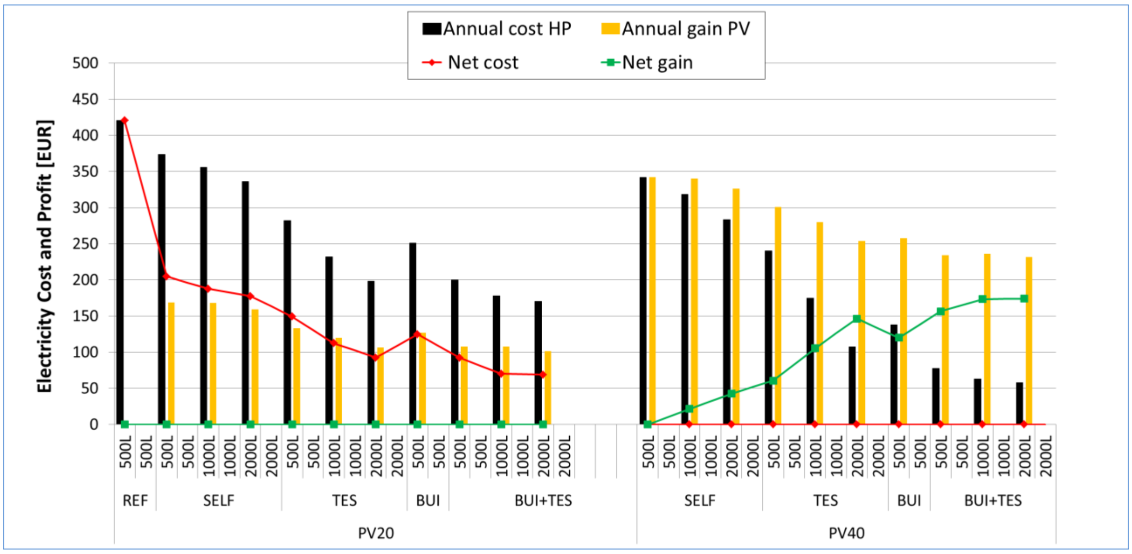

Fig. 16: Operating cost for the RES45 building with a heat pump in combination with 20 m^2 (left) and 40 m^2 (right) PV area.

4. Conclusion

Depending on control strategy, the solar fraction SF_HP can be increased from 11 / 18% (with PV20 / PV40) as standard configuration (SELF) up to 61 / 88% with maximized use of overheating (BUI+TES). The running "net cost" for the heat pump decreased from 420 EUR per year in the reference case (without PV) to 205 EUR per year (SELF500, SF_HP=11%) and to 69 EUR per year (BUI+TES2000, SF_HP=61%), when remaining PV electricity with PV20 is completely sold. With PV40 already up to 174 EUR "net gain" based on operation cost can be achieved.

With the TES control concept (only heat storage acts as thermal battery for the PV20) and a TES volume of 2,000 liter and without overheating of the room the same result can be achieved as with the BUI+TES control concept, using the standard TES volume of 500 liter but accepting overheating with room temperatures up to 26°C. Increased investment cost for larger water storage (TES) must be balanced with personal room comfort requirements.

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5. Reference

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