TheBat – The Thermal Battery in the Smart Grid in Combination with Heat Pump and PV

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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.

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 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) 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. 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.

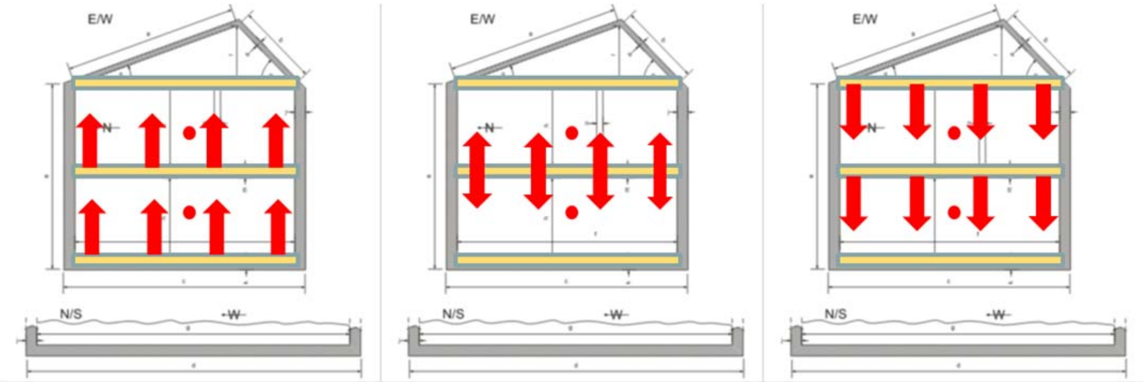

Fig. 1: TABS placed in the buildings, left: RES45, middle: RES15 and right: OFF45

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.

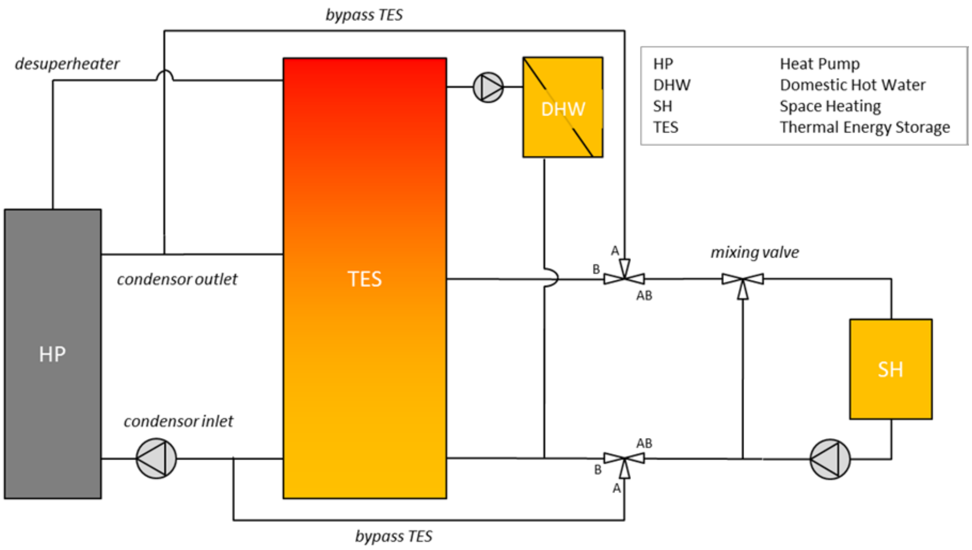

Fig. 2: Hydraulic concept of the heat pump system and connection to TES and building.

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 “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.

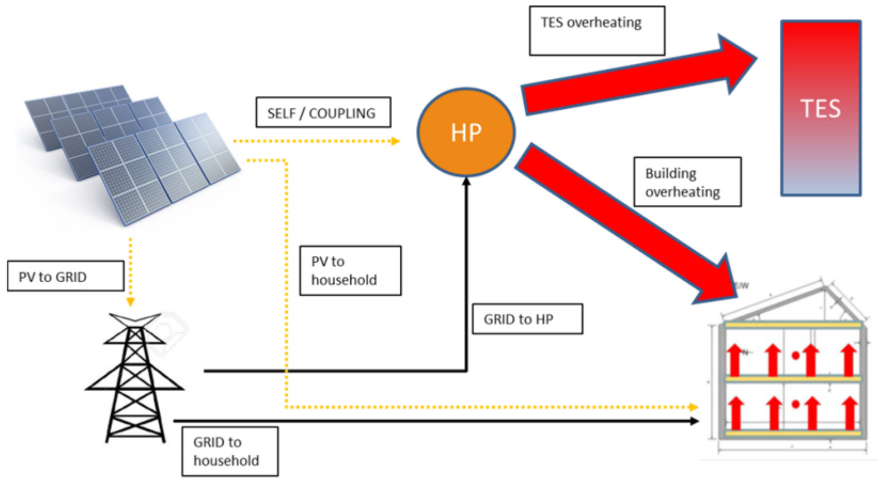

Fig. 3: Energy flow concept for coupling PV and grid electricity via heat pump to the TES and the building via TABS.

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^2a 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^2a 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^2a 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^2a 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. 6).

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^2a 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^2a can be achieved.

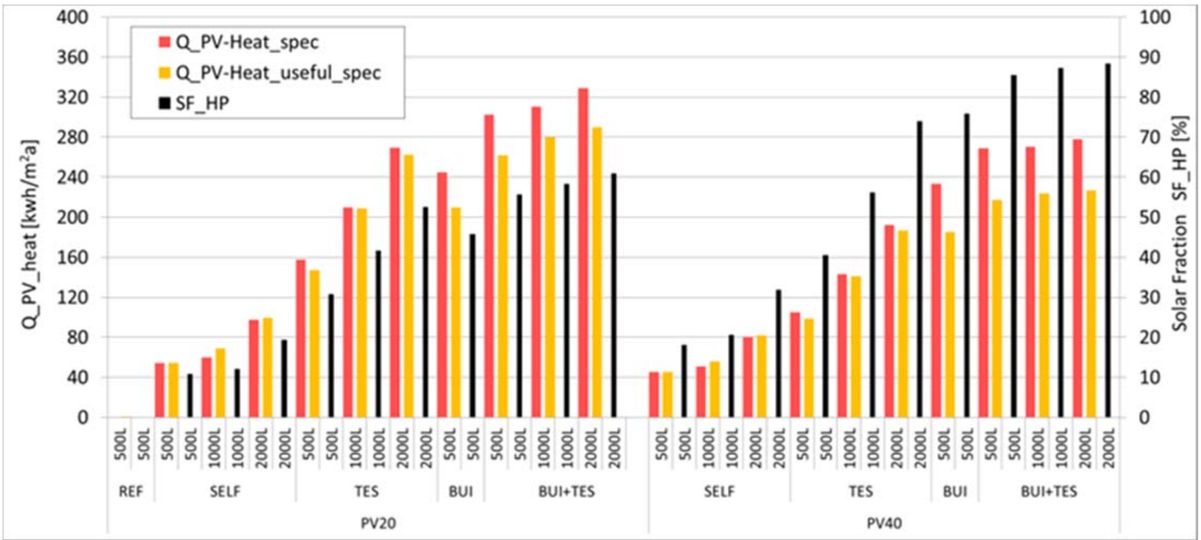

Fig. 4: Solar fraction (SF_HP), heat (Q_PV-Heat_spec) and useful heat (Q_PV-Heat_useful_spec) produced by heat pump using PV electricity depending on control algorithm and PV area.

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^2a compared to 262 kWh/m^2a 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 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). 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. "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).

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.

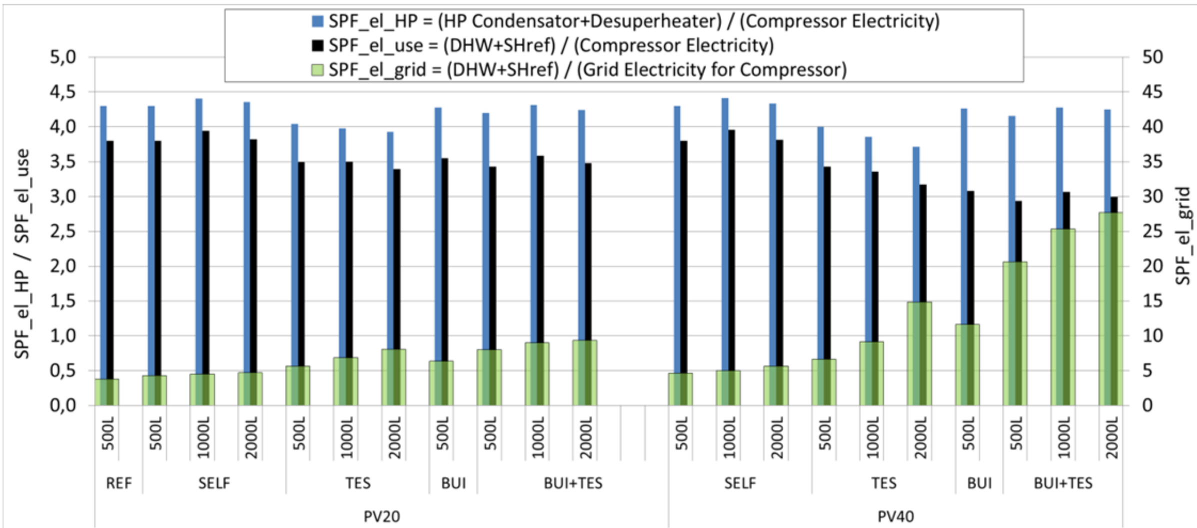

Fig. 5: Seasonal performance factor for the heat pump itself based on compressor electricity consumption (SPF_el_HP), for the reference used energy (domestic hot water and space heating consumption of REF) based on compressor electricity consumption (SPF_el_use) and for the reference used energy based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

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.

3.3 OVERHEATING OF THE BUILDING

In Fig. 6 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.

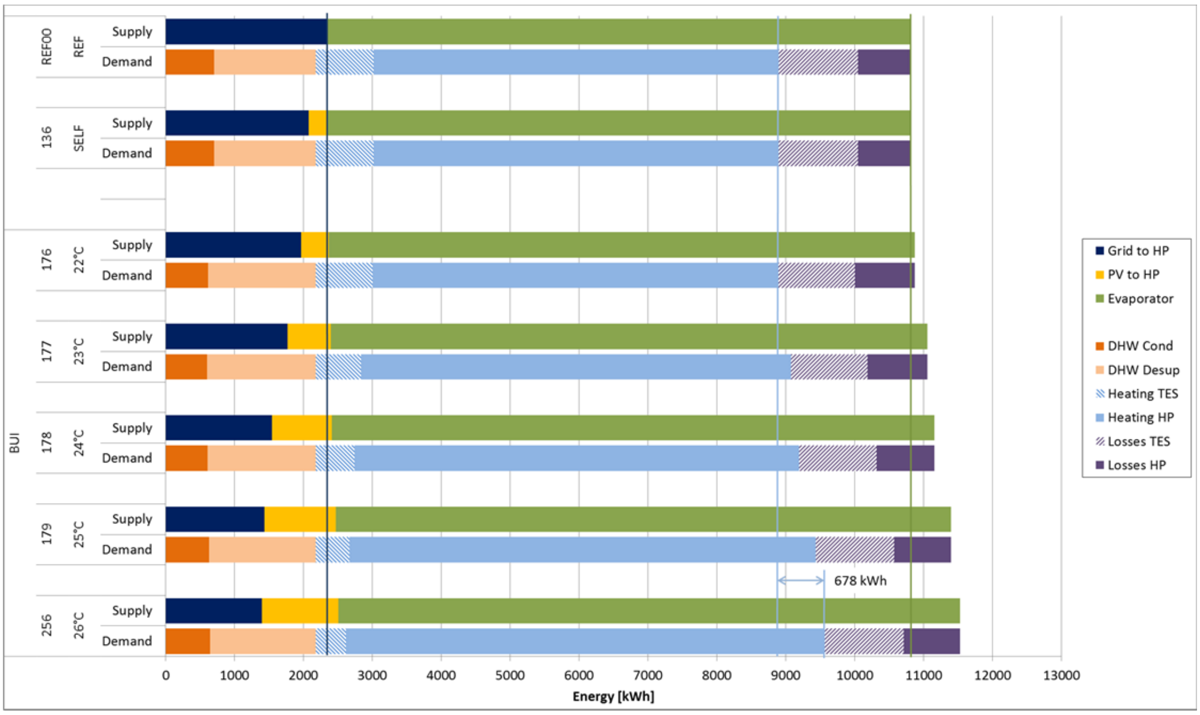

Fig. 6: Overheating losses due to additional space heating consumption

3.4 ENERGY BALANCE OF ALL CONTROL STRATEGIES

In Fig. 7 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. 7 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.

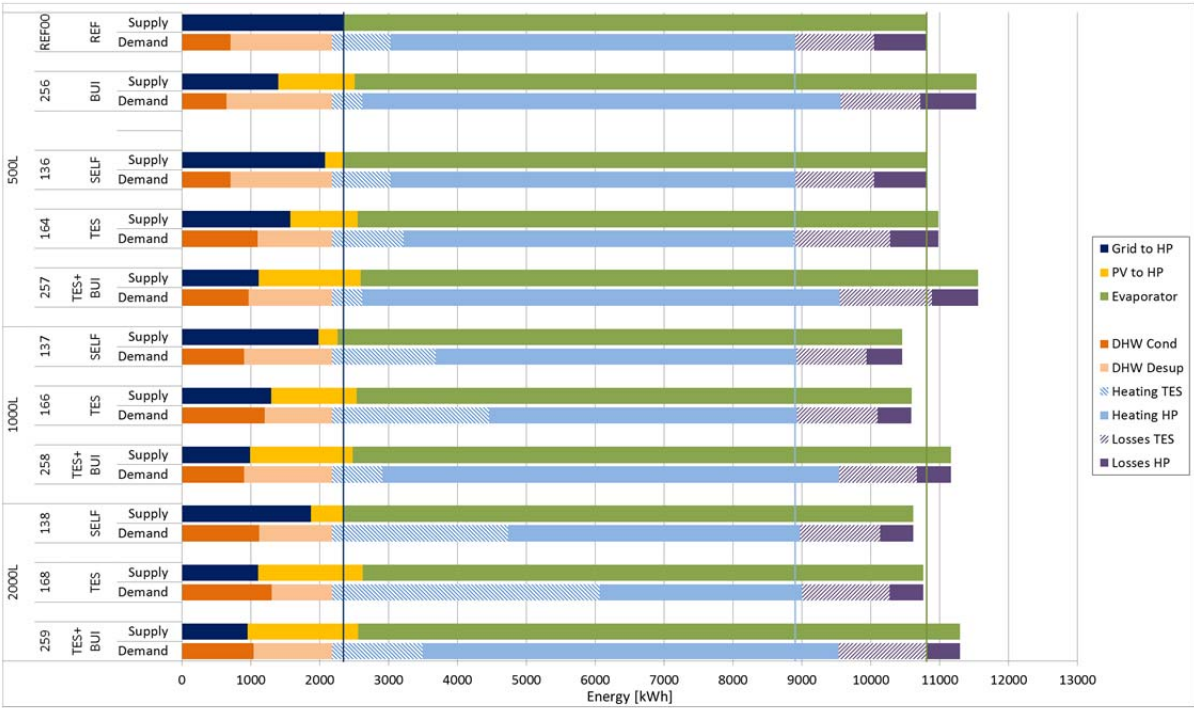

Fig. 7: Energy balances of RES45 building with 20 m^2 PV area, control concepts SELF, BUI, TES, BUI+TES and TES volumes of 500, 1,000 and 2,000 liter.

3.5 OPERATING COST OF THE SYSTEM

Finally a simple economic investigation based only on operation cost is shown in Fig. 8 for the RES45 building. The following assumptions are used:

- The PV area is 20 m^2 (2.5 kW_{peak}) oriented south and with a slope of 40°. The simulated annual electricity production is 3,637 kWh_{el}/a (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”

As Fig. 8 shows, the annual cost to run the heat pump are 420 EUR for the reference case, just slightly reduced to 373 EUR 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.

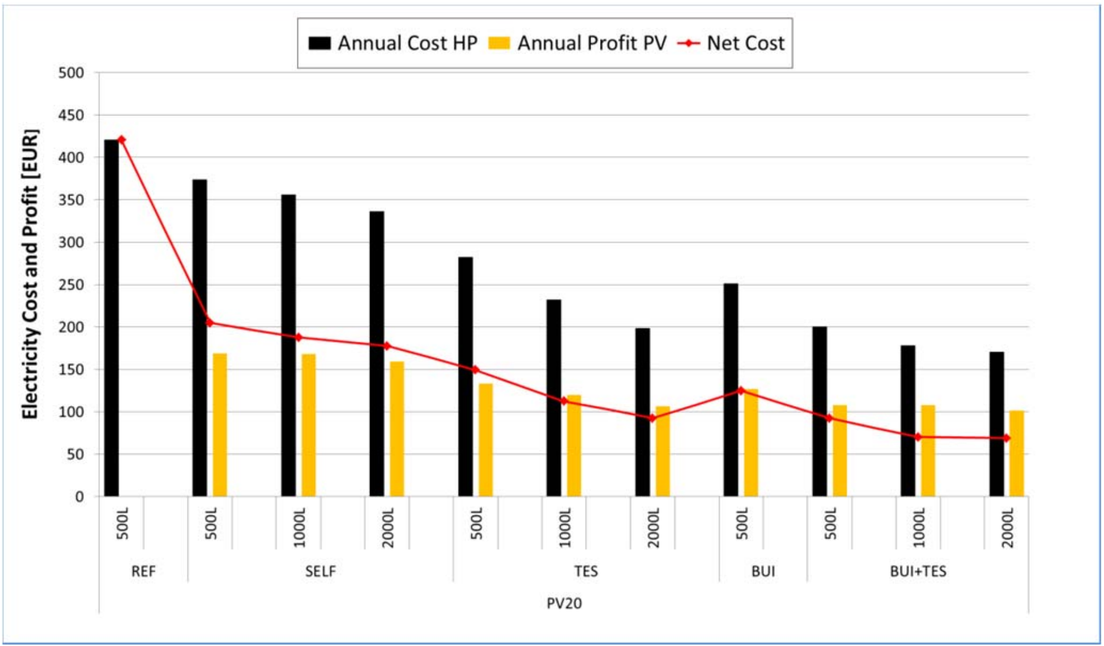

Fig. 8: Operating cost for the RES45 building with a heat pump in combination with 20 m^2 PV area.

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 cost for the heat pump due to grid electricity consumption decreased from 420 EUR per year in the reference case (without PV) to 373 EUR per year (SF_HP=11%) and to 69 EUR per year (SF_HP=61%), when remaining PV electricity is completely sold.

With the TES control concept (only heat storage acts as thermal battery for the PV) 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.

This project is financed by the Austrian „Klima- und Energiefonds“ and performed in the frame of the program „ENERGY MISSION AUSTRIA“.

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