Increasing PV self-consumption with heat pumps – sense or non-sense of additional electric heaters

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Abstract

Hot water and space heating are increasingly being provided by photovoltaics in combination with heat pumps. In most cases, end user purchase tariffs for electric energy are significantly higher than feed-in tariffs for photovoltaic electricity. Therefore, increasing self-consumption of locally produced photovoltaic electricity makes economically sense, if a corresponding reduction of electric energy consumed from the grid can be achieved. At the same time, the self-consumption measures must not lead to a too high increase in system energy consumption, which also causes a strong reduction of PV feed-in. In this contribution it is shown that the optimization of thermal storage management by the heat pump is advantageous, while the use of electric heaters in order to heat the storage further when the heat pump has reached its maximum supply temperature generally leads not only to energetic inefficiency, but also to a financial loss for the end user or owner of the system.

Keywords: Heat pump, domestic hot water, space heating, PV self-consumption, control, thermal storage

1. Introduction

With a change from cost-covering feed-in tariffs for photovoltaics (PV) to one-time subsidies and feed-in tariffs that are lower than the tariffs for electricity that is consumed from the grid, the optimization of self-consumption of PV electricity has become economically interesting. Domestic hot water (DHW) and space heating are increasingly being provided by photovoltaics in combination with heat pumps (HP). In combination with thermal storage for DHW only or for storage of DHW and space heat in so called stratified combi-tanks, optimal control for charging of these storages in order to achieve higher PV self-consumption and thereby less cost for electric energy that is purchased from the grid is an attractive and low-cost solution for the optimization of self-consumption.

PV-coupled residential HP systems and measures for increasing PV self-consumption have been analyzed by several authors during recent years. Battaglia et al. (2017) analyzed the potential for increasing the self-sufficiency by overheating a thermal energy storage (TES) with a PV-coupled air-source HP system in a simulation study for a single family house, reporting savings in grid electricity consumption of 11 % using a water TES. PV-coupled air-source HP systems in renovated single family buildings coupled with a radiator heating system were analyzed by Heinz and Rieberer (2021), using different rule-based control strategies for increasing the self-sufficiency. Thür et al. (2018) studied a PV-coupled ground-source HP and used thermally activated building systems and water TES together with a rule-based control. Toradmal et al. (2018) also used the thermal mass of the building and a water TES both for PV-coupled air- and ground-source HPs. The results of these two studies showed that the building itself can offer significant thermal storage capacity, avoiding an additional large TES. An additional possibility for significantly increasing self-consumption in PV-HP systems is to use a battery. This was also demonstrated in the above mentioned publications by Toradmal et al. (2018) and Battaglia et al. (2017). However, both studies state that a water TES is economically beneficial compared to batteries, which are significantly more expensive.

It is important to note that energy storage comes along with energetic losses, and for the case of thermal storage with HPs, increasing the temperature of the thermal storage decreases the efficiency of the HP that is charging the storage. Thus, because of losses and inefficiencies of storage, the reduction of electric energy consumption from the grid is often quite lower than the increase of PV self-consumption and corresponding reduction of feed-in

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suggests.

Assuming self-consumption optimization that can be achieved by control only, for which no additional investment cost has to be accounted for, increasing self-consumption is only financially of interest if the net-cost of energy exchanged with the grid (NC, €/a) can be reduced:

$$NC = GC \cdot GT - PVF \cdot FT \qquad \text{(Eq. 1)}$$

where GC (kWh/a) is the annual consumption of electricity from the grid, GT (€/kWh) is the tariff for electricity consumed from the grid, PVF (kWh/a) is the locally produced electricity fed into the grid, and FT (€/kWh) is the corresponding feed-in tariff. (Eq. 2) shows the condition that must be met in order to reduce NC and to benefit financially from an increase of PV self-consumption. From this equation, it can be deduced that if the ratio of grid-tariff to feed-in-tariff is 2:1 (e.g. GT = 0.2 €/kWh, FT = 0.1 €/kWh), an increase of self-consumption is only economically interesting if the ratio of decrease of grid feed-in (ΔPVF, equals increase of self-consumption) to the decrease of consumption from the grid is lower than 2:1:

$$\frac{\Delta PVF}{\Delta GC} < \frac{GT}{FT} \qquad \text{(Eq. 2)}$$

2. Procedure

This study was carried out for two types of systems, both based on an air-to-water HP. On the one hand, a DHW-only system was considered and, on the other hand, a combi-system for DHW preparation and space heating. The most important assumptions concerning the two systems and the used boundary conditions are described in the following sections.

2.1 Domestic hot water system

System layout and simulation tool

Domestic hot water systems with PV, HP and electric heater were simulated with an own developed code written in python. Figure 1 shows the relevant components and the hydraulic layout of the considered system, that contains a DHW storage tank that is charged via a heat exchanger and discharged directly, an air source HP, a PV field, household electricity consumption and a connection to the electricity grid. The developed python code calculates energy transfers and temperatures of the relevant system components based on quarter hourly timesteps for one year based on simplified efficiency assumptions that allow for fast calculation of a whole year within a few seconds. Different sizes have been assumed for the PV system that is always oriented south with an inclination of 45°. PV yield (AC) was calculated based on the total irradiance on the collector plane and an average efficiency of 17% for the PV modules, losses for cables, soiling etc. of 7% and inverter efficiency of 94%.

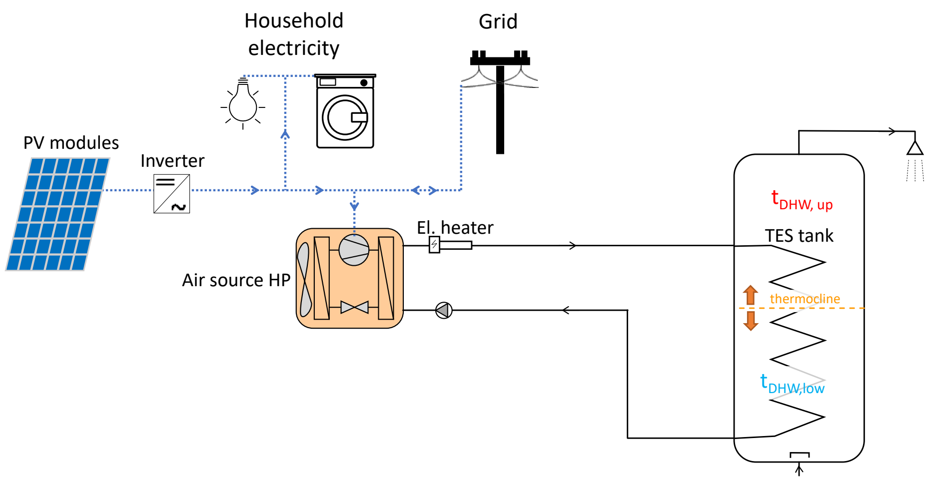

Figure 1: Hydraulic layout of the considered DHW system setup.

Heat pump model

The COP of the HP is calculated as a fraction ($\eta_{hp} = 0.45$) of the carnot efficiency (maximum possible efficiency) of a cycle, using the assumed evaporation (t_{evap}) and condensation (t_{cond}) temperatures of the working fluid:

$$COP_{hp} = \eta_{hp} \cdot \frac{t_{cond} + 273\ K}{\max(t_{cond} - t_{evap},\ \Delta t_{min})} \qquad \text{(Eq. 3)}$$

In order to avoid unrealistically low differences between the evaporation and the condensation temperature ($t_{cond} - t_{evap}$) a minimum temperature difference of $\Delta t_{min} = 5K$ was introduced. Evaporation and condensation temperatures differ from the temperatures of the heat source and the heat sink by the temperature difference needed for heat transfer through the heat exchanger, which was represented by ($\Delta t_{hp,hx} = 5K$). Due to reasons of simplicity, the same value was used here for the evaporator and for the condenser:

$$t_{cond} = t_{c,wat,in} + \Delta t_{hp,hx} \qquad \text{(Eq. 4)}$$

$$t_{evap} = t_{e,air,in} - \Delta t_{hp,hx} \qquad \text{(Eq. 5)}$$

In the case of the condenser, the inlet temperature $t_{c,wat,in}$ is again higher than the temperature in the DHW storage while charging because of the heat exchanger that transfers heat from the condenser water loop to the DHW of the storage tank ($\Delta t_{TES,hx}$ = 5 K):

$$t_{c,wat,in} = t_{TES,charge} + \Delta t_{TES,hx} \qquad \text{(Eq. 6)}$$

The temperature $t_{TES,charge}$ is taken as the average of the corresponding TES zone(s) over the timestep of charging. Nominal capacity of the HP ($Q_{hp,nom}$) was assumed to be 10 kW and not varied (no power modulation and no dependency on temperatures).

TES model

The thermal storage tank is simulated as a two-zone model with sharp thermocline. Hence there is only two volume elements and corresponding temperatures in the tank. During HP charging, it is assumed that first the lower volume ($t_{DHW,low}$) is heated until it reaches the upper volume's temperature ($t_{DHW,up}$), and then both volumes are heated uniformly to the required set temperature. Discharging is carried out by volume displacement, i.e. the upper volume of the TES decreases and the lower increases by an amount that leads to the discharged energy that corresponds to the DHW tapping profile. This kind of discharge simulation corresponds to a perfectly stratifying discharge process. Consequently, inefficiencies due to fluid mixing in the tank are not simulated directly, but included in the term $\Delta t_{TES,hx}$ that is used to express the increase in HP delivery temperatures caused by heat exchange AND ineffiencies due to unperfect temperature stratification as a lumped factor.

Electric heater

The electric heater is assumed to have a maximum power of $P_{elrod,max} = 5\ kW$ and is power modulating, i.e. it will never consume more electricity than would be fed to the grid if the heater was not switched on:

$$P_{elrod} = \min(\max(P_{el,PV,ac} - P_{el,hh}, 0), P_{elrod,max}) \qquad \text{(Eq. 7)}$$

Additionally, the electric heater operation was limited to times after 2 p.m., i.e. after the time-window for TES charging by the HP.

Boundary conditions

The climate used for the simulation was based on weather data from Zurich, a test reference year developed by SPF (CCT climatic data described in Haller et al. 2013), with an annual average of the outdoor temperature of 9.1 °C and solar radiation of 1111 kWh/(m²a) on the horizontal.

The tap profile for DHW as well as the household electricity demand was based on the reference multifamily building profiles described by Mojic et al. (2019), that are based on the software LoadProfileGenerator V.8 (Pflugrath 2016, https://www.loadprofilegenerator.de). For a single household, the total DHW consumption and household electricity of the multifamily building with six apartments was divided by six, leading to an annual consumption of 2'935 kWh/a for DHW (heat) and of 3'288 kWh/a for household electricity.

Control

The HP was set to charge the storage after midday from noon to 2 p.m. to 55 °C. Additionally, if the TES volume above the thermocline was lower than a threshold needed for supplying a quarter hour peak demand (maximum quarter hourly demand of the year), then the HP was allowed to recharge the TES also outside the given time window up to a level that allows for serving the quarter hourly demand at all times. The electric heater was run exclusively with PV electricity and only after 14:00 (i.e. after the time window of HP charging) and up to a temperature of 60 °C. Other maximum temperatures for electric heater charging were tested but did not lead to significantly different results (i.e. only to results that are worse than the one shown from an economic point of view). For this reason, results with other end-temperatures for the electric heater are not shown for the DHW system.

2.2 Combi-system for space heating and DHW

System layout and simulation tool

For the analysis of the combi-system, a detailed TRNSYS system model was used. The model was established in previous work and described in more detail in (Heinz et al., 2020) and (Heinz and Rieberer, 2021).

The considered system consists of an air-to-water HP with speed-controlled compressor, a thermal energy storage (TES), a so-called combi-tank, a PV-system and an electric heater in the flow line of the HP, as shown Figure 2. The HP is connected to the TES, which was considered with two different volumes of 0.5 and 1 m³. The heat losses of the TES were assumed with efficiency class B according to (EC, 2013). Using three-way-valves, the HP can charge either the DHW zone of the TES via the two connections on the top or the space heating zone via the lower connections. The TES is connected to the HP in parallel to the space heating system. This means, when the store is being charged for space heating by the HP, some of the flow will go via the space heating distribution loop and the rest will go through the store. The proportions depend on the current operating conditions (current flow) of the space heating loop. DHW preparation is done via a freshwater station (external plate heat exchanger) to a temperature of 45 °C. The PV system is considered in three different sizes (4, 7 and 10 kWp), oriented to the south and with an inclination of 45°.

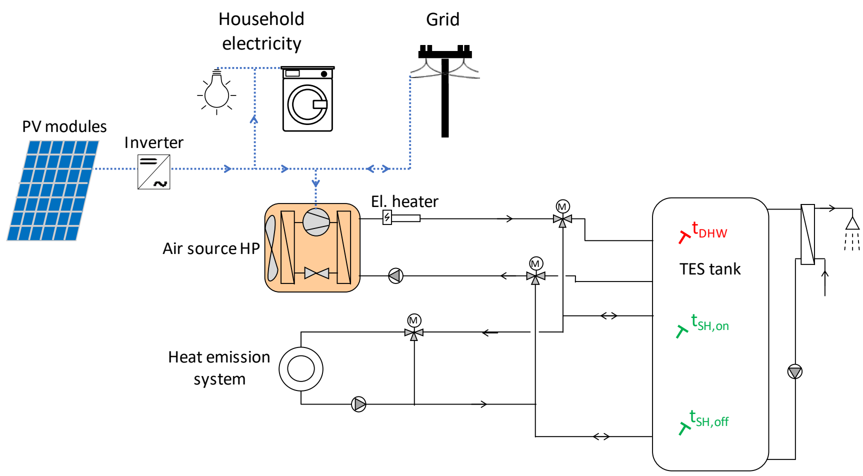

Figure 2: Hydraulic layout of the considered combi-system for space heating and DHW.

Boundary conditions

The system was implemented in a single family residential building with a gross floor area of 185 m², based on the statistical average living space per person in Austria of 45.3 m² per person (Statista, 2020) and a four-person-household. The wall structures were chosen on the basis of Austrian building typologies that were defined in the European project TABULA (2014). The basis was a “usual renovation“ scenario of a building with the according wall structures, as defined in TABULA for the age class 1961-1980. Using this data, a detailed building model with one thermal zone was developed in TRNSYS Type 56. The resulting space heating demand is 10’700 kWh/a in the climate of Zurich, with an annual average of the outdoor temperature of 9.1 °C, heating degree days of

3’553 Kd/a and solar radiation of 1’111 kWh/(m²a) on the horizontal. The heat emission system was considered in two variants, on the one hand radiators with design flow/return temperatures of 56/48 °C, and on the other hand a floor heating system (design flow/return 35/30 °C).

The tap profile for DHW was taken from the FP7 project MacSheep, with details described in (Bales et al., 2015). A realistic DHW profile was chosen with a two-minute time step with many variations in flow rates. The profile was derived for a family of four people with the software DHWcalc (Jordan and Vajen, 2012), which is based on the theory described in (Weiss, 2003). It uses statistical probabilities of different types of discharge and their flow rates and duration. The total heat demand for DHW of the used profile is 3’038 kWh/a.

For the household electricity a detailed annual profile with a time resolution of one minute was created for a four-person-household (both parents employed, two school-aged children) with the software LoadProfileGenerator (Pflugrath 2016, https://www.loadprofilegenerator.de). This profile has a total electricity consumption of 3’058 kWh/a.

Control

Normal charging with the HP: If there is no (or not enough) PV excess yield (as described in the next paragraph), the HP begins to charge the DHW zone of the TES if t_{DHW} < 45 °C (sensor position in Figure 2) and stops, when t_{DHW} > 55 °C. The DHW zone is charged only in a time window from 12:00 to 14:00, in order to shift HP charging into times of available PV electricity. In order to ensure comfort, an “emergency charging” is started if t_{DHW} drops below 40 °C outside of the foreseen time window. The space heating zone is charged, if $t_{SH,on} < t_{fl}$ and stopped when $t_{SH,off} > t_{fl}$ + 2 K, where t_{fl} is the set space heating flow temperature depending on the ambient temperature. During DHW charging, the compressor is operated constantly with 75 % of the maximum speed. In space heating operation, the compressor speed is adapted via a PI-controller in order to reach the set flow temperature t_{fl} at the outlet of the condenser.

Overcharging with the HP: Whenever the available PV excess yield is higher than 0.7 kW, the system is switched to “overcharging mode”. This means that the DHW zone and the space heating zone (only within the heating season) of the TES are both heated to higher set temperatures. Due to the operational limits of the used compressor, overheating is done dependent on the ambient temperature to max. 60 °C when t_{amb} > 5 °C and to 56 °C at $t_{amb} \leq$ 5 °C. Overcharging is stopped when either the TES temperature reaches this temperature limit or PV excess drops below a threshold of 0.6 kW. During overcharging, the speed of the compressor is adapted in order to match the electricity consumption of the HP to the available PV excess electricity (considering the speed limitations of the used compressor). The aim is to make maximum use of the PV yield and to draw as little energy as possible from the grid.

Overcharging with the electric heater: In case of enough available PV excess yield (as described in the last paragraph) the maximum temperature that can be achieved by overcharging with the HP is limited. In this case, the electric heater can be used for additional overheating to higher temperatures. It is assumed to be operated only if the TES has already been heated to the max. possible temperature by the HP. The lower part of the storage (space heating zone) is only overcharged with the electric heater during the heating season. In order to study the effect on the results, additional overcharging was done to different max. temperature levels of 65, 75 and 85 °C. In addition, to limit the overheating by the electric heater to a reasonable temperature level based on the demand, a simple predictive control was implemented in the simulation. The aim here was to overheat only in order to be able to bridge the next night without having to activate the HP. For this purpose, an (ideal) forecast of the outdoor temperature for the period from 18:00 to 6:00 of the next night was used. This variant is referred to as demand oriented overheating "t_{opt}" in section 3.2.

2.3 Key performance indicators

Self-consumption ratio ($E_{PV,self}/E_{PV}$, -) and degree of self-sufficiency ($SS = E_{PV,self}/E_{total}$, -) are often used as key performance indicators for PV self-consumption strategies. However, SC and SS are not suitable for system optimization since they tend to optimize towards inefficient systems. For this reason, neither SC nor SS will be used in this contribution, but the share of grid consumption (SGC) will be used instead:

$$SGC = (E_{total} - E_{PV,self})/E_{total,ref} \quad \text{(Eq. 8)}$$

In this equation, $E_{total,ref}$ refers to the total electric consumption of the system without additional self-consumption measures, and E_{total} refers to the total electric consumption for the system under investigation, i.e. with the corresponding self-consumption measures.

In order to generalize the result and make them applicable to a wide range of systems, for the DHW system the size of the PV system is given as PV production ratio (PV_{ratio}):

$$PV_{ratio} = E_{PV}/E_{total} \quad \text{(Eq. 9)}$$

where E_{PV} (kWh) is the electric energy (AC) produced by the PV system.

3. Results

3.1 Domestic hot water systems

Figure 3 shows the reduction of the share of grid consumption (SGC) for a typical household with a standard DHW demand, depending on the size of the installed PV system. The red curve is valid for “systems without DHW HP” as well as for systems with a DHW HP that is allowed to charge randomly at any time of the day. It is to be noted that “systems without DHW HP” refers to systems where E_{total} as well as $E_{total,ref}$ includes only household electricity consumption, i.e. it excludes energy used for DHW or for space heating, whereas systems with DHW HP refers to systems where E_{total} as well as $E_{total,ref}$ includes electricity used for DHW preparation by a HP. Consequently, a particular point of the red curve, e.g. where $PV_{ratio} = 1.0$, corresponds to quite different values for E_{total} and as $E_{total,ref}$, depending on the question whether DHW preparation is included or not, and hence also the size of the PV system that corresponds to this PV_{ratio} is different for the two systems. Furthermore, the same set of curves can be used for a single home or for a multifamily building, since the size of the required PV system to reach a certain PV production ratio just scales with the size of the electricity demand of the object.

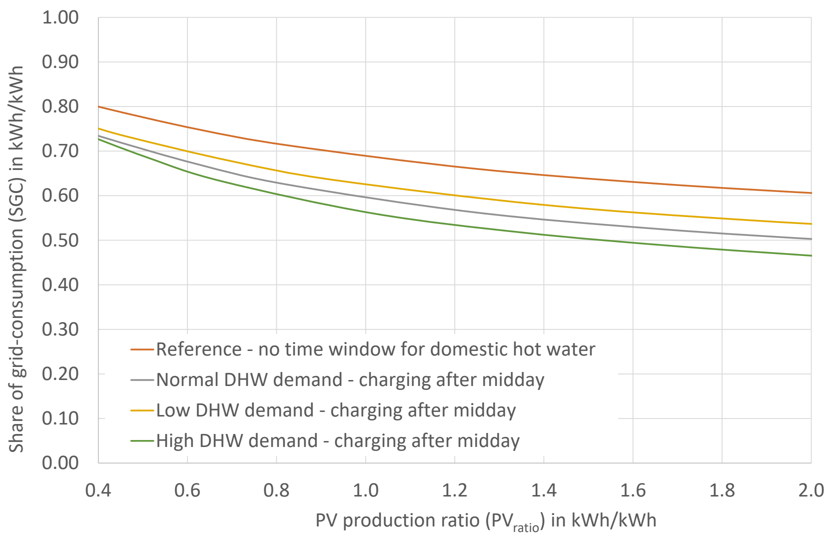

Figure 3: Share of total electric energy consumption covered by the grid as a function of the PV size (PV production ratio) for systems with different DHW demand and charging strategies.

The other curves are valid for normal (grey), low (yellow) or high (green) DHW demand in combination with a HP that is only allowed to charge the storage after midday, i.e. from 12:00 to 14:00. Low DHW demand was assumed to be 50% of the normal, high demand 200% of the normal DHW demand of 2’935 kWh/a for a single apartment or living unit. Also here, the same curves can be applied for single as well as for multi-family buildings, following the same rules as described above. If results are generalized in this way, then normal, low and high DHW demand correspond to a ratio of DHW demand ($Q_{DHW,dem}$) to household electricity consumption ($P_{el,hh}$) as shown in Table 1.

Table 1: General ratio of DHW demand and household electricity represented by the curves in Figure 3.

curve color	label	DHW demand general ratio $Q_{DHW,dem}/P_{el,hh}$	$Q_{DHW,dem}$ for given example
grey	normal	0.89	2'935 kWh/a
yellow	low	0.45	1'468 kWh/a
green	high	1.78	5'870 kWh/a

Results so far have not included the use of an electric heater in order to charge more energy into the DHW storage, and thereby increase PV self-consumption, after the HP has charged the storage (i.e. after 14:00 when the time window for HP charging ends) for cases where there is still a surplus of locally produced PV electricity available. Figure 4 shows the increase of PV self-consumption that is achieved for the investigated system by using an electric heater after 14:00 (i.e. after the time-window where the HP charges) in order to increase the storage tank temperature from 55 °C to 60 °C, for cases where the storage volume at 55 °C is able to cover 100% of the average daily heat demand. Obviously, this kind of control leads to a significant increase of PV self-consumption, i.e. also to an equal amount of reduction of PV electricity that is fed to the grid and reimbursed according to the feed-in tariff. With other words, there is a loss of income for the owner from the reduction of PV feed-in. The thinking behind this kind of control is that while the self-consumption increases, the amount of energy purchased from the grid decreases and thus there is a reduction of cost for energy purchased from the grid that compensates for the loss of income from feeding in.

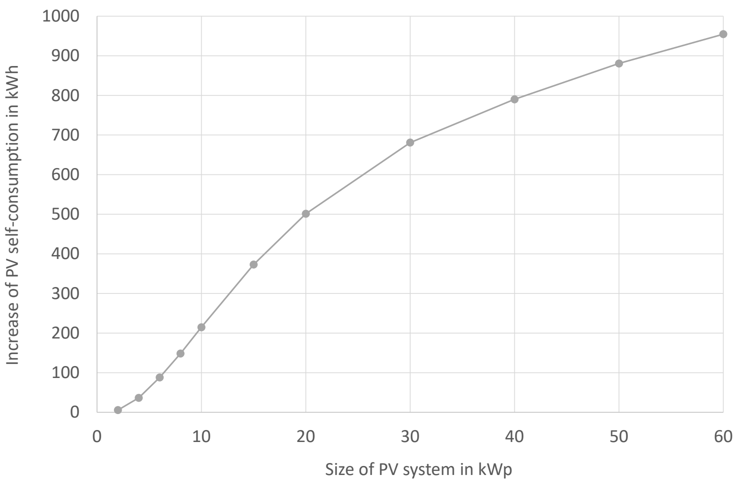

Figure 4: Increase of PV self-consumption achieved by heating the storage from 55 °C to 60 °C with an electric heater after HP charging (i.e. after 14:00), whenever sufficient PV electricity is available, for storage sizes that covers 100% of the average daily DHW demand when heated at 55 °C.

Figure 5 shows for different sizes of storage volumes (different colors) and different sizes of PV systems (size of PV system increases from left to right for each set of values) the reduction of electricity that is purchased from the grid (y-axis) together with the reduction PV energy fed into the grid (equals increase of self-consumption). Strikingly, for all data points the achieved reduction of grid purchase differs substantially from the increase in self consumption or decrease of feed-in, with reduction of feed-in generally being 3.5 to 5 times higher than the corresponding reduction of grid purchase. This means that only if the ratio between the purchase tariff and the feed-in tariff is 3.5 to 5 or higher, an economic benefit can be achieved for this consumer or owner of the system.

A typical current situation in Switzerland is a ratio of tariffs of approximately 2:1 (e.g. 0.2 €/kWh for purchase and 0.1 €/kWh for feed-in). For this case, heating with an electric heater from 55 °C to 60 °C with PV electricity, after the HP has reached the required hygienic temperature of 55 °C, leads to financial losses. For a DHW storage that is sized to cover only 50% of the average daily DHW demand, i.e. the storage must be charged several times a day, the minimum ratio of tariffs above which the electric heater does not lead to a financial loss is between 3:1 and 4:1. If the DHW storage is sized to cover the average daily DHW demand (100%), the ratio must be higher than 5:1. With other words: if the purchase tariff is 0.2 €/kWh, feed-in tariff must be lower than 0.04 €/kWh before an economic advantage can possibly result from the electric heater.

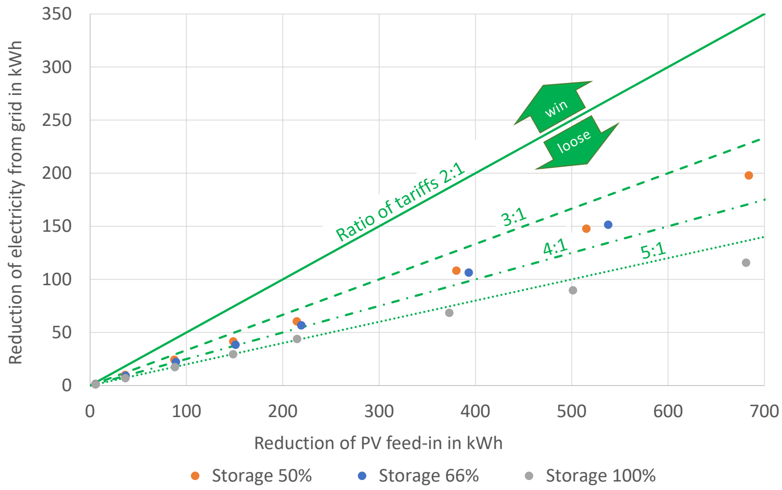

Figure 5: Reduction of electricity from the grid, depending on reduction of PV feed-in, achieved by heating the storage from 55 °C to 60 °C with an electric heater after HP charging (i.e. after 14:00), whenever sufficient PV electricity is available, for storage sizes that cover 50%, 66% or 100% of the average daily DHW demand.

3.2 Combi-system

For the combi-system, the results for the share of grid consumption (SGC) are shown for all simulated variants in Figure 6. As expected, SGC is decreasing with increasing PV size and increasing storage volume. Compared to the reference system (Ref), where overheating of the TES is only done with the HP, SGC can be improved (=decreased) by additional overcharging with the electric heater. The extent of the improvement depends on the available storage volume and the max. temperature to which the el. heater is allowed to overheat the TES. Higher temperatures allow a stronger decrease in grid consumption and, therefore, SGC. However, the reduction in SGC is only a few percent at most. For the system with a radiator heating system (Figure 6, right) the reduction is higher than for the floor heating system. This is due to the lower storage capacity available for overheating with the HP with higher space heating temperatures, which leads to higher savings in grid consumption if additional storage capacity is activated with the electric heater. Moreover, the difference in COP between heat provision by the HP and the electric heater (COP ~ 1) is lower for the radiator system due to higher heat sink temperatures.

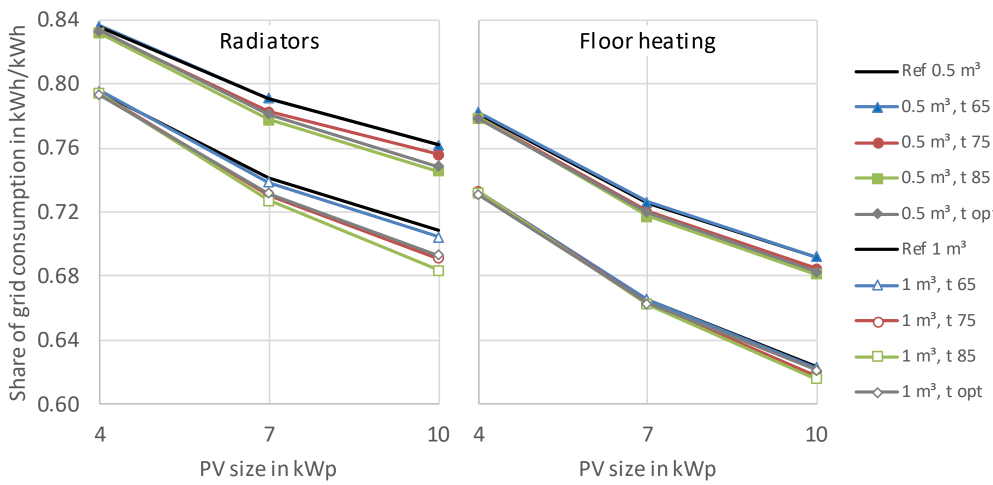

Figure 6: Share of grid consumption (SGC) as a function of the PV size for heating the TES from 60 °C to different max. temperatures (e.g. "t 75" means max. electrical overheating to 75 °C) with an electric heater after HP charging; storage sizes 0.5 and 1 m³, PV sizes 4, 7 and 10 kWp; "Ref" is the reference system without additional electric overheating.

Monthly and annual electric energy balances of three system variants with 7 kWp of PV, a TES volume of 1 m³ and the radiator heating system are shown in Figure 7. The top-most figure shows the reference system with overheating of the TES by the HP only. Here, there is also a very small amount of electric heating in the winter months, which is only due to the HP not being able to operate at very low ambient temperatures. If the electric heater is used with max. overheating to 75 °C (Figure 7, centre), heat provision from the electric heater increases to 1’931 kWh. This increases the total el. consumption of the system from 5’697 kWh to 7’064 kWh. While the consumption from the grid decreases by only 59 kWh compared to the reference system, the feed-in of PV electricity decreases strongly by 1’426 kWh. It is quite obvious from the results in Figure 7 (centre) that with this strategy a lot of overheating occurs during the warmer transitional period. Here, a lot of PV yield is available, but on the other hand there is only a small heat demand.

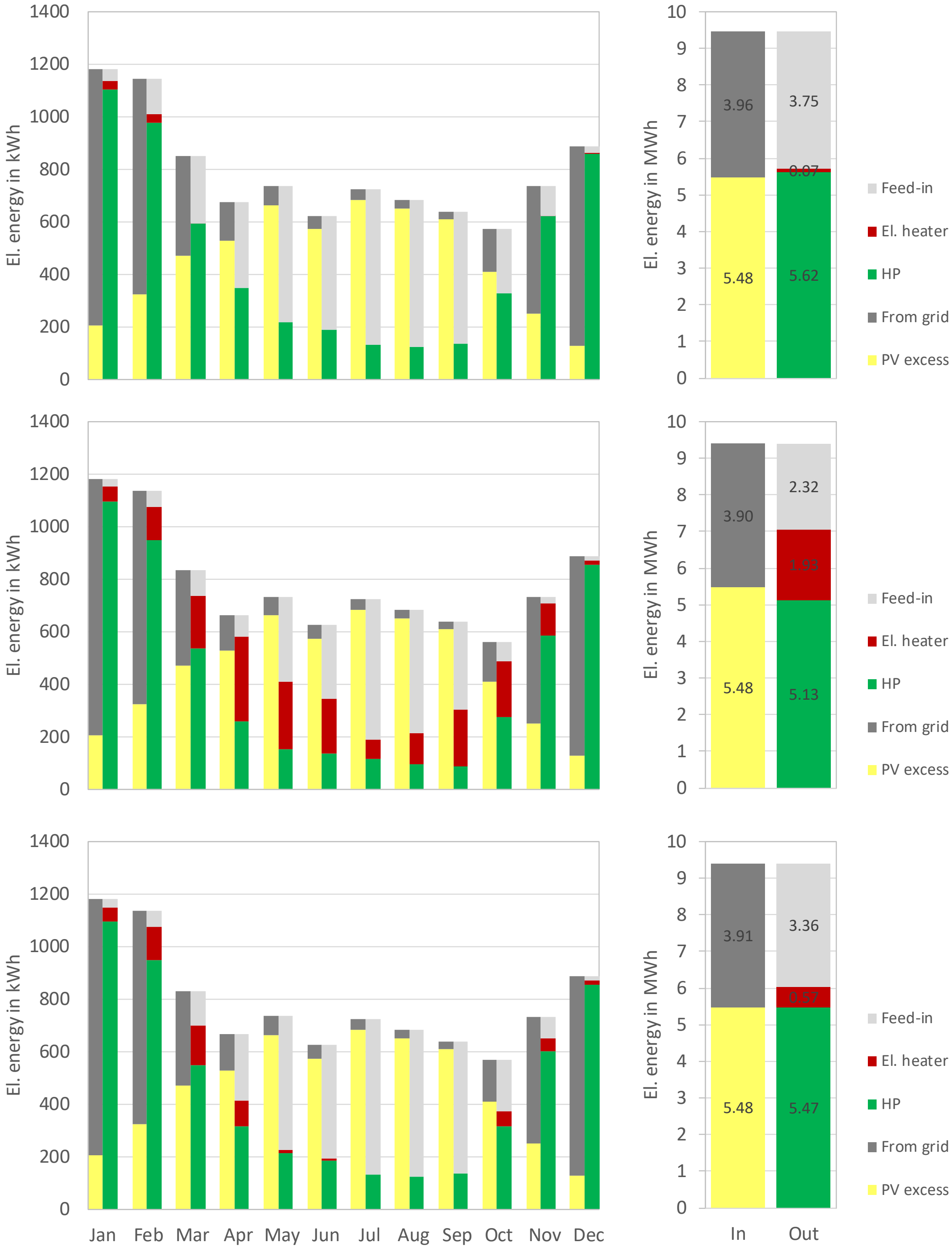

Figure 7: Monthly (left) and annual (right) energy balance of the combi-system with radiator heating system, 7 kWp of PV and a TES volume of 1 m³; Top: no additional overheating with electric heater (Ref); Centre: overheating to max. 75 °C; Bottom: demand oriented overheating (“t_{opt}”)

Therefore, the demand oriented overheating strategy (“t_{opt}”) was implemented (see section 2.2), with the results shown on the bottom of Figure 7. Using this strategy, heat provision by the electric heater is reduced mostly during the transitional period, where the heat demand is low. The consumption of the electric heater decreases to 573 kWh and the overall system consumption to 6’039 kWh. Compared to the reference system, overall grid consumption is reduced by 52 kWh and PV feed-in by 394 kWh. These results are more promising than with max. overheating to 75 °C. However, with a significantly higher reduction of the feed-in compared to the grid consumption, the question remains, if there can be an economic benefit compared to the reference system.

This is addressed in Figure 8, in the same way as before for the DHW-only system in section 3.1 (Figure 5). The results show, that, due to the strong increase in system electricity consumption and a very high reduction of feed-in, for most considered configurations the ratio of tariffs has to be higher than 20:1 in order to achieve a financial benefit compared to overcharging with the HP only. Some of the simulated configurations even show a slight increase in grid consumption of a few kWh. With a radiator heating system, the results are better than with a floor heating system (Figure 8, left vs. right) for the same reasons as discussed for Figure 7. The different max. temperatures used for the electric heater show a massive reduction of PV feed-in with increasing temperatures due to increased PV self-consumption and system electricity consumption. However, increasing the temperature can nevertheless lead to a better (but still bad) financial result (e.g. “t 65” vs. “t 75” in Figure 8 left). The best results of all variants with additional electric overheating are achieved with the demand-oriented optimized control (“t_{opt}”). However, e.g. with radiator heating, a TES volume of 1 m³ and 7 kWp of PV, still a tariff ratio of 7.5:1 or higher is necessary to achieve a financial benefit. Thus, considering current tariffs, no configuration could be found in which the additional use of electric heating could economically compete with using only the HP to optimize PV self-consumption.

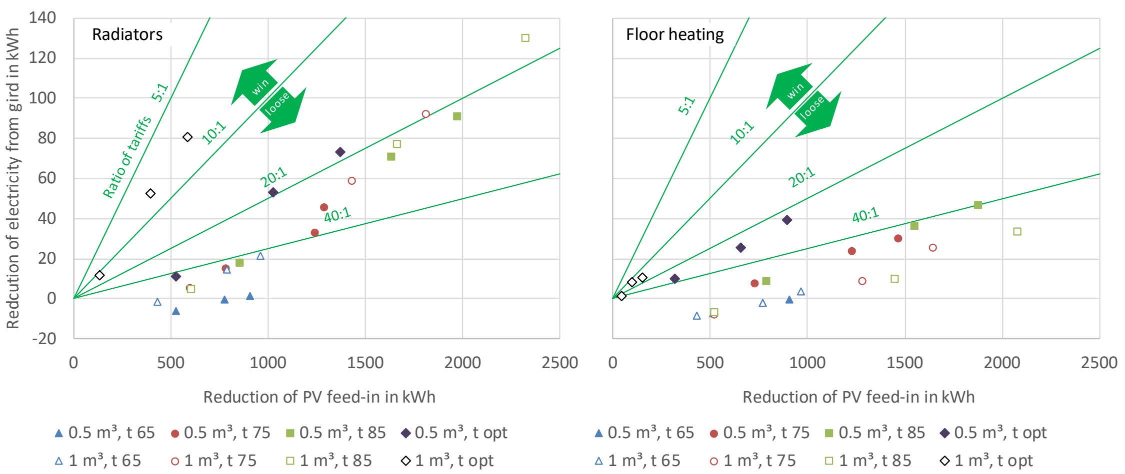

Figure 8: Reduction of electricity from the grid, depending on reduction of PV feed-in, achieved by heating the storage from 60 °C to different max. temperatures (e.g. “t 75” means max. electrical overheating to 75 °C) with an electric-heater after HP charging; storage sizes 0.5 and 1 m³, PV sizes 4, 7 and 10 kWp (PV size increases from left to right).

4. Summary and Outlook

Hot water and space heating are increasingly being provided by photovoltaics in combination with heat pumps. Due to PV feed-in tariffs being quite lower than the grid purchase tariffs of electricity in many countries or regions, an increase of PV self-consumption and decrease of grid purchase can be achieved by letting the heat pump operate more than usual and use PV electricity instead of feeding it to the grid. Since in this case the momentary heat generation is higher than the demand, heat is stored either in a technical thermal storage or in the thermal mass of the building itself. Thus, thermal storages reduce the need of electrochemical batteries that could be used with the same goal. When thermal storages are charged with a heat pump, the efficiency of the heat pump is generally decreasing with increasing state of charge, since condenser temperatures increase in parallel to the temperatures of the heat storage. However, despite this loss of efficiency, the use of thermal storage in combination with heat pumps to optimize self-consumption, when properly done, is of economic benefit and interest for the end-user. This has been shown e.g. by Battaglia et al. (2017), Thür et al. (2018), and Heinz and Rieberer (2021), and is also confirmed by the work presented in this publication.

The simulations of the two systems that are presented in this article were carried out with two different simulation tools and different experts carrying out the simulations independently from each other. It has to be mentioned that the assumptions concerning the maximum temperature to which the heat pump is able to heat the storage (55 °C in the study for the DHW-only system and 60 °C in case of the combi-system) were different. This may have some influence on the results, but an adjustment of the assumptions would probably not change the basic statement and conclusions of this work. While some might criticize the approach of merging results from two different studies that were carried out independently, it may also be seen as an advantage, since it leads to more robust conclusions where they match between the two studies. Results are less prone to be influenced by specifics of a tool or a team or expert's influence on the settings and parameterizations used.

While the optimization of thermal storage management by the HP has been shown clearly to be advantageous already before, this work also presents results on the additional use of an electric heaters for increasing the PV self-consumption. The electric heater is used to heat DHW-only storages or combi-storages for DHW and space heating further, after the heat pump has charged the storage to the maximum temperature it is capable of, and locally produced PV electricity is still available in abundance. This mode of operation is tempting, since self-consumption of PV electricity can be increased substantially, which was confirmed by our results. However, results also show that while self-consumption increases, grid-purchase does not decrease nearly in the same way. For DHW systems the decrease of grid purchased energy stayed 3.5 to more than 5 times lower than the increase of PV self-consumption. For the combined DHW and space heating systems the ratio between increase of PV self-consumption and decrease of grid-consumption was more than 7.5 for systems with radiators for space heating, and more than 20 for most systems with low temperature floor heating. One of the reasons for this is the fact that the electric heater is, depending on the temperatures needed, 3-6 times less efficient than the heat pump. Thus, it is hardly imaginable that the ratios between the increase of PV self-consumed and the decrease of grid purchased energy is lower than 3, even if the electric heater consumes only PV electricity and the heat pump would have had to provide this heat exclusively using electricity from the grid. However, in many cases also the heat pump could have provided this heat – at a later time when storage temperatures have dropped again - using PV electricity. This is e.g. the case for a DHW storage tank that has been charged by the heat pump at mid-day and is then able to cover the demand of 24 hours if the next day is again a sunny day. In this case, the use of an electric heater after heat pump charging on day one does not lead to any reduction of grid purchased energy, but only to an increase of PV self-consumption. An increase of PV self-consumption is at the same time a decrease of PV feed-in by the same amount. If there would have been a financial reimbursement for the PV feed-in, the use of the electric heater is a financial loss for the owner, even if the heater and its control were for free. If additional CAPEX cost must be accounted for the electric heater and its control, the result will be even worse from an economic point of view.

Finally, it can be stated that for the current situation in Austria and Switzerland, where PV feed-in tariffs are in most cases about 2 to 3 times lower than the tariffs for grid purchase of electricity, the operation of an electric heater after heat pump operation that reaches the hygienic temperature, cannot be recommended due to its inefficiency and the resulting financial loss for the owner. Only when feed-in tariffs are 3.5 – 5 times lower (DHW system) or 7.5 – 20 times lower (combi-system) than the grid purchase tariffs, our results show a potential financial benefit for the owner. However, even in the unlikely cases where the owner could profit financially, the question must be raised whether this kind of inefficient use of PV electricity is beneficial from a socio-economic point of view, since there is likely more efficient and more meaningful use for this renewable energy in the neighborhood or in the country's energy system.

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