THERMAL STORAGE TANKS AND THE BUILDING AS STORAGE FOR LOCALLY GENERATED RENEWABLE ELECTRICITY

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1 Abstract

The growing share of volatile and decentralized electrical energy generation in Germany leads to enormous challenges for the balance of energy generation and demand. Therefore, different strategies are proposed. Beside the direct electrical storage of electricity, it can also be saved as thermal energy by using electrical heating systems. Hereto the available thermal storages are ideally charged when renewable energy sources can be used and discharged when not. This process is referred to as load shifting in this study. Besides hot water tanks, the building itself can be additionally a part of the total thermal storage capacity. Therefore, in this study the effect of load shifting with a heat pump along with a PV system on the primary energy consumption, the CO_2 emissions and as well the operation costs have been evaluated. Additionally, the building's thermal mass on load shifting and the resulting temperature dynamics in the building were studied in detail. Therefore a control strategy for load shifting with heat pumps, hot water tanks and additionally the building as storage has been implemented in a simulation model and evaluated.

Keywords: Storage tank, Thermal mass, Heat pump, Load shifting

2 Introduction

The energy generated from PV systems in Germany increased from 1 GWh in 1990 to 29700 GWh in 2013 and this number is expected to increase further in the future [1]. This fast growth was accompanied by a dramatic price reduction of PV systems. Therefore PV systems in combination with electrical heating systems became a legitimate competition to heating systems combined with solar thermal collectors.

Nowadays in general most of the energy generated by PV systems in single family houses is supplied to the grid, due to the mismatch of the energy demand and generation. To increase the overall autonomy (household and heating) in the building, storage technologies are discussed. Beside the storage of the electrical energy in batteries, it is possible to transform the electrical energy to heat and therefore store it much cheaper as in batteries. The generated heat will then be used later in the evening, reducing the electrical consumption for heating in these times. The generated heat can be stored in hot water tanks and/or in the thermal mass of the building construction.

In this study the effect of the load shifting with an air to water heat pump system on the overall system efficiency and the resulting comfort in the building has been evaluated. Different storage tank volumes and building constructions (varying the thermal mass) have been taken into consideration.

3 System and simulation set up

3.1 System simulation

Figure 1 depicts the scheme of the evaluated air to water heat pump system.

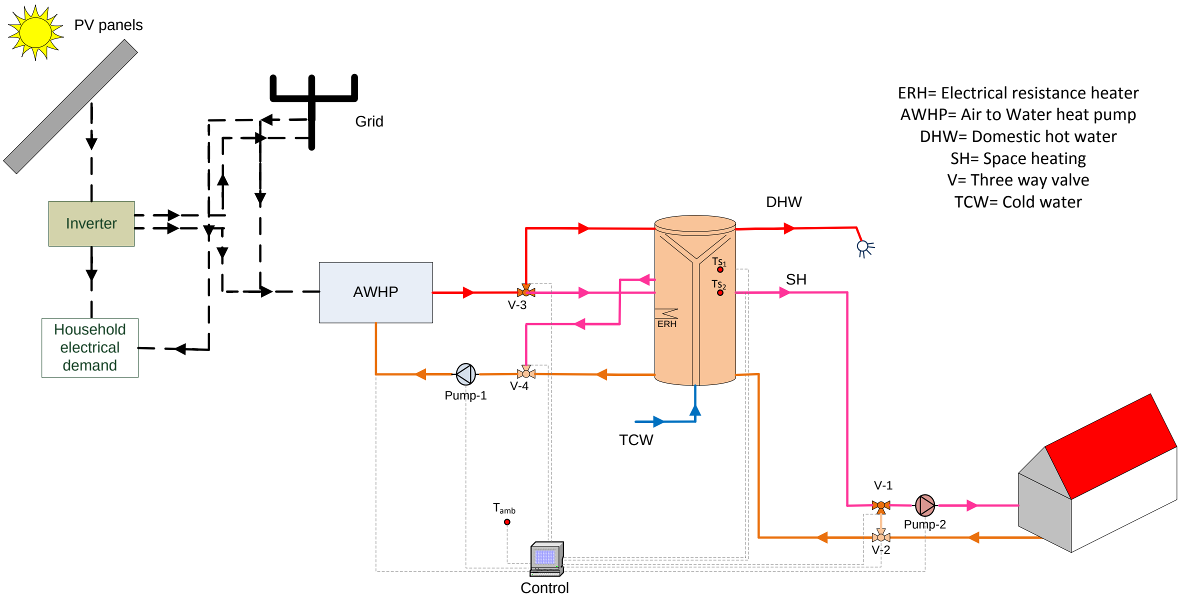

Figure 1: Scheme of the evaluated air to water heat pump system.

The heat pump supplies the storage tank with hot water on the upper part for domestic hot water (DHW) and on the lower part for the heating demand. The DHW is generated via an internal heat exchanger in the storage tank. The building is utilized with a floor heating system, which is supplied with hot water from the middle of the storage tank. The set point of the inlet temperature to the floor heating is calculated by a heating curve, and the flow temperature is adjusted to the set point with a mixing valve. A simulation model of the system in figure 1 has been developed. Table 1 summarizes the boundary conditions of the reference simulation model.

Table 1: Boundary conditions of the reference simulation model.

Simulation model	Reality	Modeling in TRNSYS [9]
Location	Würzburg, Germany	Meteonorm dataset
Building type	Residential building	Type 56
Heated living area	180 m²	Building model from [2]
Yearly overall heat demand	9450 kWh/a	
Total domestic hot water requirements	2050 kWh/a	Profile according to IEA Task 44 [3]
U-values of roof / exterior wall / floor / window	0.24 / 0.16 / 0.35 / 1.4 [W/m²K]	Type 56
Occupancy	3 persons	
Household electricity consumption	4141 kWh	Profile based on VDI 4655 [4]
Hot water storage	1000 ltr. (Consolar Solus II)	Type 340 [10]
Air-water heat pump	8 kW (Dimplex LA8PMS)	Type 401 [5]
PV module	Conergy E185P - Modul; 8.32, 5.5, 3.3 kWp	Type 94a, orientation South, inclination 40 °
Hysteresis room temperature control		Type 2b

To realize building constructions with different thermal storage capacity, the thermal mass of materials used in the building has been adapted in the varying simulations of this study (see chapter 4.2). The storage tank volume also has been varied in this study (chapter 4.2.3). The heat loss coefficient was hereto adapted with a linear function in dependence of the storage tank surface.

3.2 System control strategy

3.2.1 Basic heat pump control

The storage tank temperatures in the upper and the lower part are controlled with a hysteresis controller (Type 2 in TRNSYS). The heat pump operation for DHW is dependent on the following control:

$$u_{HP,DHW} = 1 \quad \text{IF} \quad (T_{S1} < 52\,°\text{C} - 5\text{ K}) \quad \text{AND THEN UNTIL} \quad T_{S1} \geq 52\,°\text{C}.$$

For the space heating demand it depends on

$$u_{HP,SH} = 1 \quad \text{IF} \quad T_{S2} < T_{set} \quad \text{AND THEN UNTIL} \quad T_{S2} \geq T_{set} + 3\text{ K}.$$

T_{S1} and T_{S2} are measured temperatures in the storage tank (see fig. 1) and T_{set} the set temperature of the water supply to the building calculated via the heating curve. The heating curve is a nonlinear function of the ambient temperature (see [3]).

3.2.2 Load shifting without the building as storage

The energy generated by the PV panels is at first supplied to the household demand, then to the air-water heat pump (AWHP) and finally to the grid. The load shifting is achieved by operating or using the AWHP as often as possible when more PV-power is available than required by the household. Hence, the AWHP will always run when:

$$u_{HP,LS} = 1 \quad \text{IF} \quad \text{PV}_{\text{surplus}} > PV_b \quad \text{AND} \quad T_{S2} < T_{max}$$

Where T_{max} is the maximal allowed temperature in the storage while load shifting and PV_b the boundary PV surplus power, at which the load shifting process starts. Both are control parameters and have been varied in the simulation study (65 °C cannot be exceeded for T_{max}, due to the maximum available temperature with the heat pump).

3.2.3 Load shifting with the building serving as a storage

In order to use the building as a storage in the load shifting process, a coupling of the load shifting logic to the room hysteresis controller has to be implemented. To make the building utilizable as a storage, the interruption of the mass flows in the floor heating circles has to be avoided, while the heat pump runs for load shifting (see chapter 3.2.2). Therefore the set points of the room temperature hysteresis controller are elevated between 2.5 and 4 K (dependent of the room, see [3]), while the heat pump runs for load shifting. To realize this in practical applications, modern single room controllers have to be used that can communicate with the central heat pump controller. Additionally to the adaption of the single room controller, the temperature set point of the supply water is adapted according to:

$$When \ \text{PV}_{\text{surplus}} > PV_b \, , T_{supply} = T_{set} + 7\,K.$$

3.2.4 Electrical resistance heater control

As auxiliary heating source, a 6 kW electrical resistance heater (ERH) which is installed inside the hot water storage, has been used. The ERH will work if the AWHP cannot process the temperature demand for space heating and DHW. Therefore, the ERH will run when:

$$u_{ERH,SH} = 1 \quad \text{IF} \quad (T_{S2} < T_{set} - 4\text{ K or } T_{S1} < 52\,°\text{C} - 8\text{ K})$$

The ERH will then work until the following conditions are met:

$$u_{ERH,SH} = o \quad \text{IF} \quad (T_{S2} \geq T_{set} \text{ or } T_{S1} \geq 52\,°\text{C})$$

3.3 Thermal storage capacity of the building

The thermal mass of the building has a major influence on the thermal comfort in the space, especially in damping room temperature fluctuations caused by external (e.g. solar radiation) and internal disturbances. The thermal mass of the building denotes the overall effective heat capacity of the building. When the building is used as a storage for converted heat from PV electricity, the thermal mass of the building influences not only the thermal comfort in the rooms, but simultaneously the storage capacity. The thermal capacity is therefore a main factor in the evaluation of the load shifting control strategy. For that reason the building model has been adapted. The thermal mass of the building construction has been calculated according to DIN V 4108-6 [6]. It is dependent on the characteristics of the building materials (density, heat capacity), the thickness of the layers and the building size. Table 2 summarizes the adaptations of the building model in [3] and the resulting thermal mass values according to DIN V 4108-6 for the heaviest building with 80 Wh/ m³K (reference building C_b=38 Wh/ m³K). The overall U-Value of the outer walls were kept constant with the changes.

Table 2 summarizes the adaptations of the building model in [3].

Construction	Component layers	Thickness [m]
Outer wall	Plaster	0.02
	Concrete	0.24
	Mineral wool	0.15
	Plaster	0.01
Inner wall	Plasterboard	0.012
	Limestone	0.24
	Plasterboard	0.012

3.4 Performance indicators

To evaluate the effect of load shifting different performance indicators based on the simulation results are calculated:

The **Autonomy** is defined as the ratio of the total locally used energy from PV panels to the total electrical energy demand in the building (both household demand and heating):

$$Autonomy = \frac{\sum PV_{Local}}{\sum el.Total}$$

The **self consumption** is defined as the ratio of the total locally used energy from the PV system (household demand and heating system) to the total energy generated from the PV system per year.

$$Self\ Consumption = \frac{\sum PV_{Local}}{\sum PV}$$

The **primary energy consumption** and **CO_2 emissions** are calculated according to standards EnEV 2009 and prEN 15203 [7, 8]. The primary energy factor was chosen to 2.6 and the CO_2 factor to 0.617 [kg/kWh]. These factors are multiplied with the total electrical energy demand from the electrical grid:

$$Q_{PE} = Q_{el,grid} * 2.6; \quad \mathrm{CO_2 - emissions} = \ Q_{el,grid} * 0.617$$

The **system operation costs** are calculated to estimate the economic effect of different control parameterizations. Here two different price structures were assumed. One with current price and feed-in tariffs (Price: 25.7 €cent/kWh, Feed-in: 15 €cent/kWh) and one with assumed tariffs in the near future, because of the actual rapid changes (Price: 35 €cent/kWh, Feed-in:

7 €cent/kWh). This assumed future price tariff gives an impression on the effect of load shifting in future. The operation costs are calculated according to the following equation:

$$Operation\,Cost = Cost\ of\ purchasing\ energy - Cost\ of\ selling\ energy\ to\ the\ grid$$

4 Results

4.1 Load shifting without the building as storage

For the load shifting control the two parameters PV_b and T_{max} have to be adjusted. At first the parameter PV_b has been evaluated. Figure 2 depicts the locally used PV energy for heating for different months and different values of PV_b (3,33 kWp PV system, T_{max} = 55 °C).

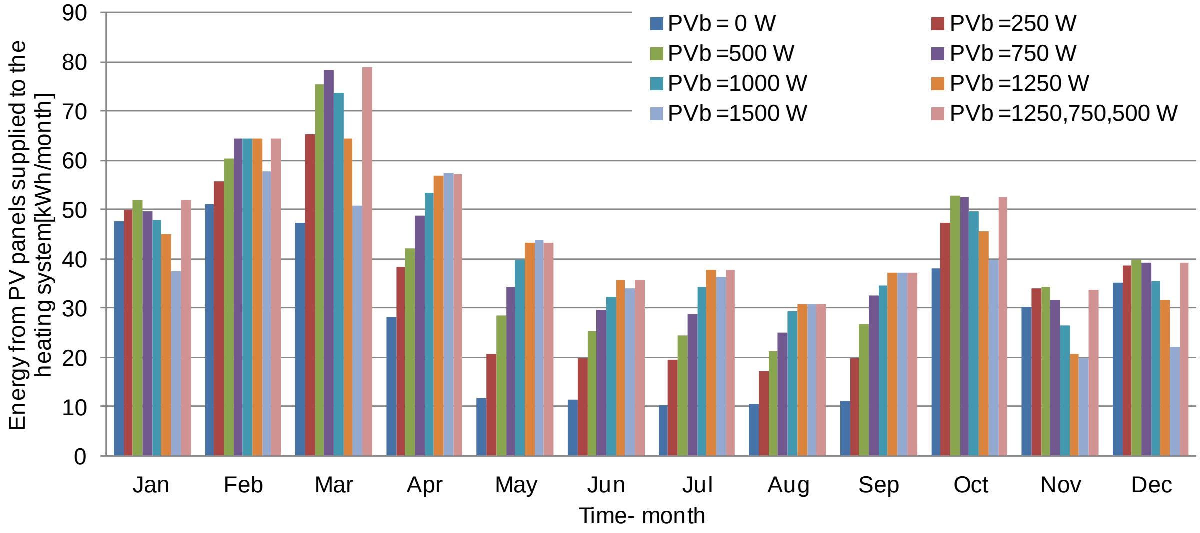

Figure (2): PV energy usage in the heating system

It can be seen that in the winter months an earlier start at lower PV power surplus (PV_b = 500 W) leads to higher usage of PV energy, whereas in the summer months a later start of the load shifting is desirable. Therefore a varying PV_b dependent on the season has been introduced. Between January, November and December PV_b is set to 500 W, between February, March and October PV_b is set to 750 W and from April to September to 1250 W.

The second control parameter is the maximum temperature, to which the hot water storage will be superheated while load shifting. Figure (3) depicts the primary energy consumption and the CO_2-emissions for different values of T_{max} .
The minimum primary energy can be obtained with T_{max} 62 °C. This parameterization leads to a reduction of the primary energy consumption and the CO_2-emissions of 8.4 % compared to the reference case without load shifting. Also here the optimum temperature depends on the installed PV peak power, the storage tank volume and the heating demand.

Three peak powers have been tested in this study: 3.33, 5.55 and 8.32 kWp to evaluate the effect of load shifting in dependence of the PV system size. The proposed cases (3.33, 5.55 and 8.32 kWp) were simulated with a 1 m³ storage tank and T_{max} = 62, 62, 64 °C respectively, PV_b ≥1250, 750, 500 W for 3.33 and 5.55 kWp, PV ≥ 750, 1000, 2250, 2750, 1250 for 8.32 kWp. Figure (4) depicts the primary energy and operation cost reduction compared to the reference case (without load shifting) in dependence of the PV system peak power.

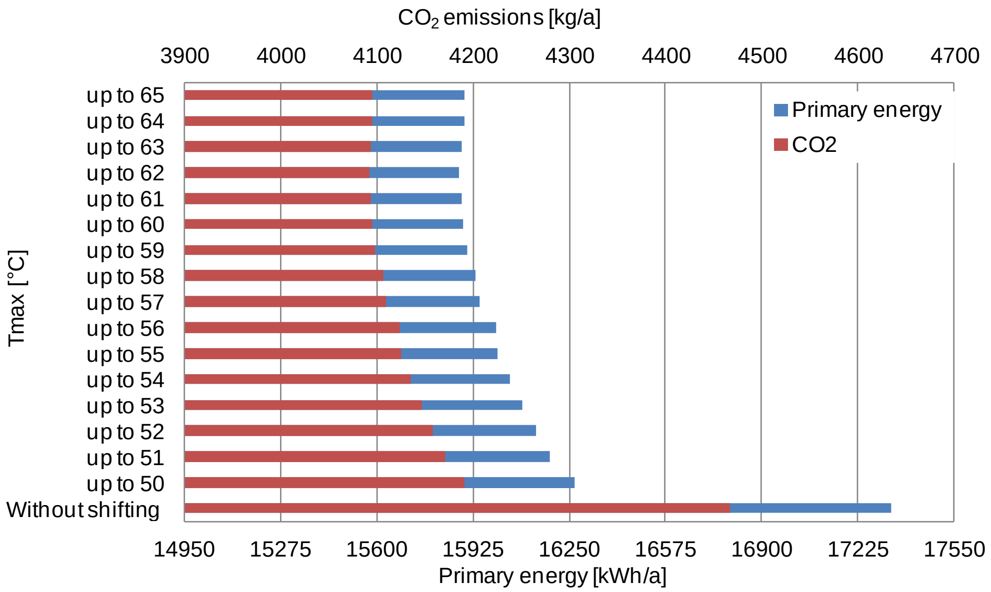

Figure (3): Primary energy consumption and CO2-emissions in dependence of T_{max} .

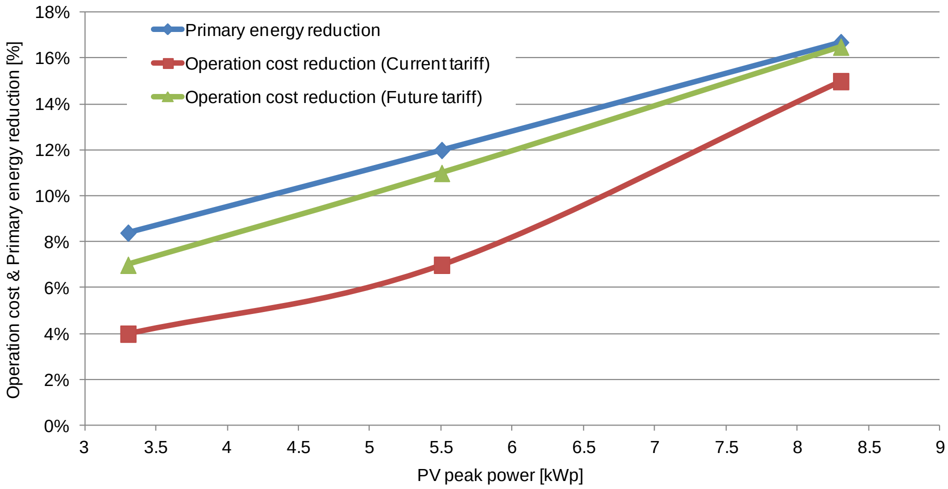

Figure (4): Primary energy reduction and operation cost reduction for different installed PV system sizes (hot water storage volume in all cases 1 m³).

4.2 Load shifting with the building as a storage

In contrast to the load shifting with the storage tank, the load shifting with the building as a storage can be done more efficiently, because the storage can be supplied with lower heat pump temperatures compared to the overheating of the storage tank (section 4.2.1). When the building is used as a storage the thermal comfort of the residents could be impaired. Therefore, beside the overall efficiency of the load shifting control, also the resulting thermal comfort in the building has to be evaluated (section 4.2.2).

4.2.1 System efficiency with the building as a storage

Figure (5) depicts the reduction (compared to the reference simulation without load shifting) in primary energy, the operation cost reduction and the increased autonomy with different control strategies and building constructions. All these cases were simulated with 8.3 kWp PV power and the savings are relative to the reference case without load shifting.

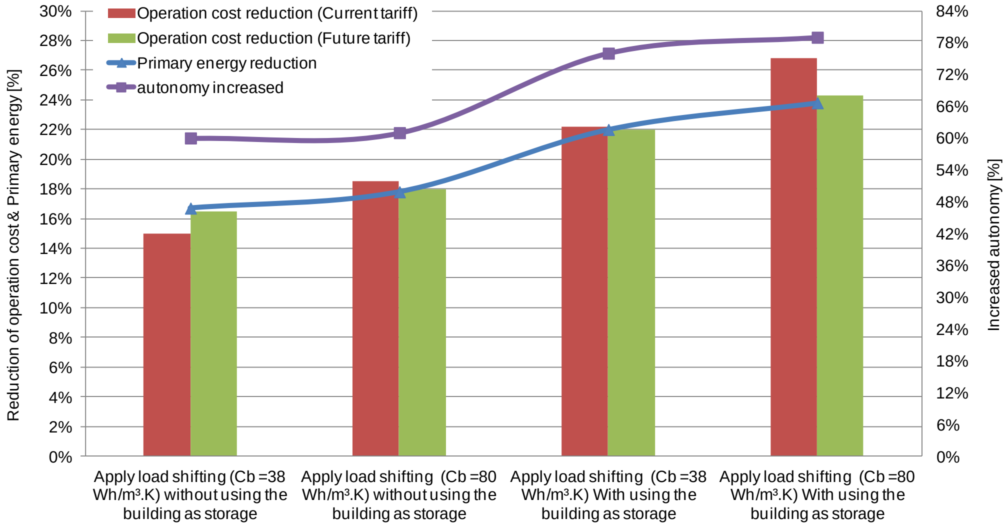

Figure (5): Reduction in primary energy, operation cost and increase of the autonomy for different cases compared to the reference case without load shifting (all cases with 8.32 kWp installed PV power; C_b denotes the thermal capacity of the building).

In the first two cases the building wasn't used as storage, while in the second two cases it was used. The reduction of the primary energy consumption compared to the reference is in case 1 16.7 % and in case 2 17.8 %. This corresponds to a 1.1 % increase (case 1 to case 2), due to an overall lower heating demand of 3.1 % of the building with the higher thermal capacity. In the step from case 1 to case 3 the direct effect of using the building as a heat storage in the load shifting strategy can be seen. A 5.3 % further primary energy reduction and a 7.5 % further reduction in operation cost are achieved. If the thermal mass of the building is increased only a small further effect can be achieved (case 3 to case 4). This is due to the fact that the storage capacity of the storage tank + the (light) reference building is already big enough. With bigger storage capacities the storage losses exceed the benefits. Figure (6) summarizes the primary energy reduction by load shifting with the building as a storage in dependence of the building's thermal mass.

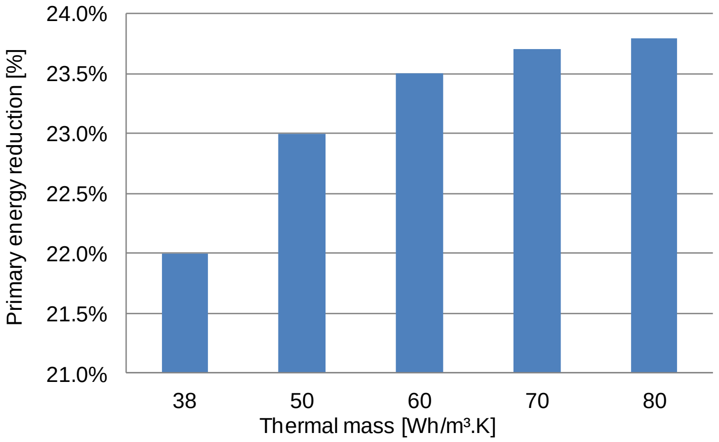

Figure (6): Primary energy reduction in dependence of the thermal mass with load shifting and the building as a storage.

As already stated the effect of the thermal mass of the building itself on the system efficiency is relative small, because already a light building allocates enough storage capacity. Figure (7) depicts the achievable monthly self consumption and autonomy (5.55 kWp, 1 m³ hot water storage, thermal capacity of the building C_b = 80 Wh/m³.K used as storage) for two different electricity household demand profiles. The yearly self consumption and autonomy with a 4141 kWh household demand results in 48 % and 36 % respectively, while with the 2070 kWh/a household demand in 40 % and 39 % respectively.

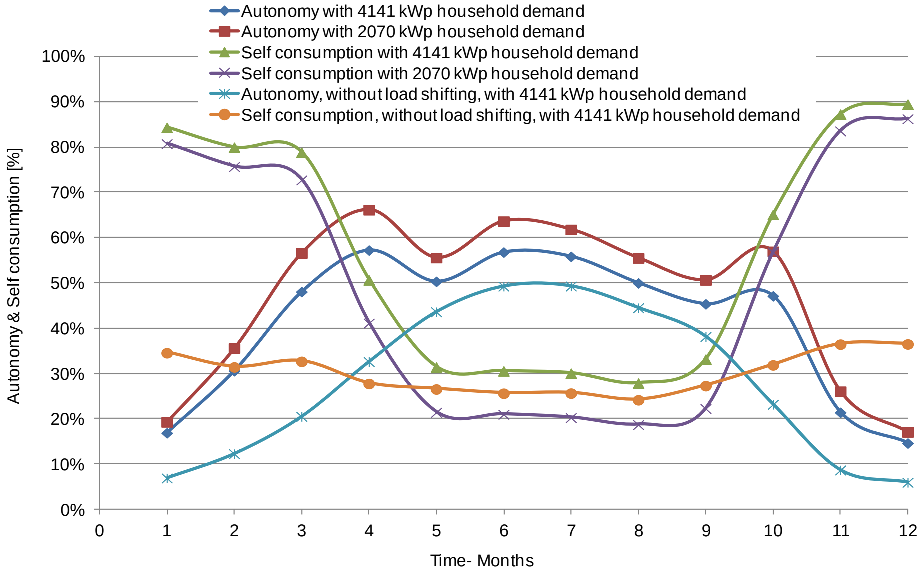

Figure (7): Monthly self consumption and solar fraction.

Figure 8 depicts the primary energy reduction compared to the reference case in dependence of the PV peak power. An interesting result is that the primary energy reduction can either be achieved by using the building as a storage or by increasing the hot water storage size (here from 1 to 3 m³). When these two actions are combined no further reduction can be achieved (see chapter 4.2.3). The effect of the load shifting on the primary energy reduction increases with the PV system size. This is due to the effect, that when the PV system size is small, most of the produced PV energy in the heating period is consumed by the electrical household demand and therefore cannot be used for heating. With growing PV system size this effect diminishes, because more PV surplus energy is available.

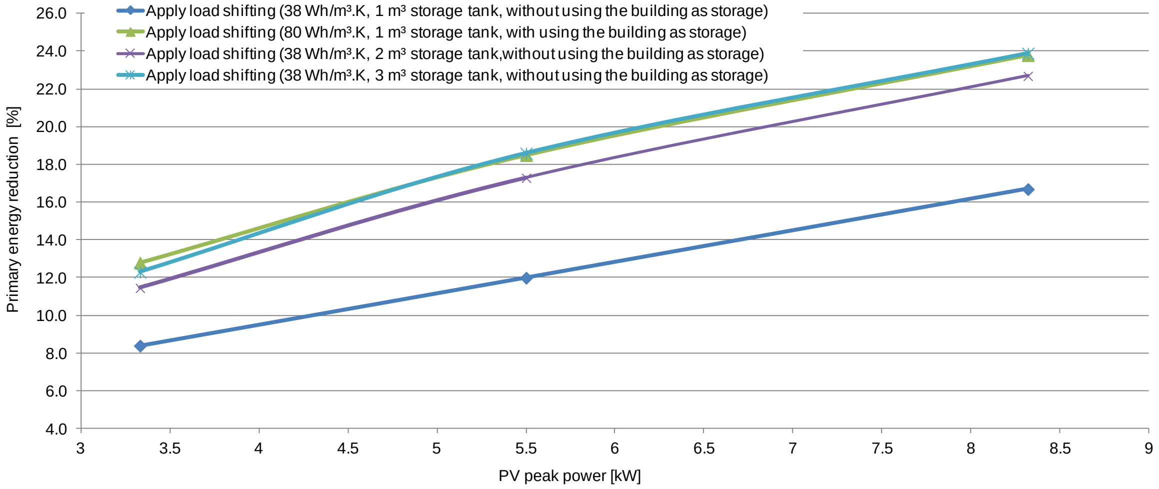

Figure (8): Primary energy reduction in dependence of the installed PV peak power for different simulation cases.

4.2.2 Thermal comfort with using the building as a storage

When the building is used to store heat, this leads to higher fluctuations in the room temperatures as usual. Figure (9) depicts the effect of the building’s thermal mass on the room temperatures with and without using the building to store the heat. Using the building to store the heat causes higher amplitudes of the fluctuations (green line). When the load shifting with the building as a storage is active, the heating in the building in the morning starts approximately 5 hours later (see red circles) than in the case where the building is not used as a storage. This is due to the overheating to higher room temperatures.

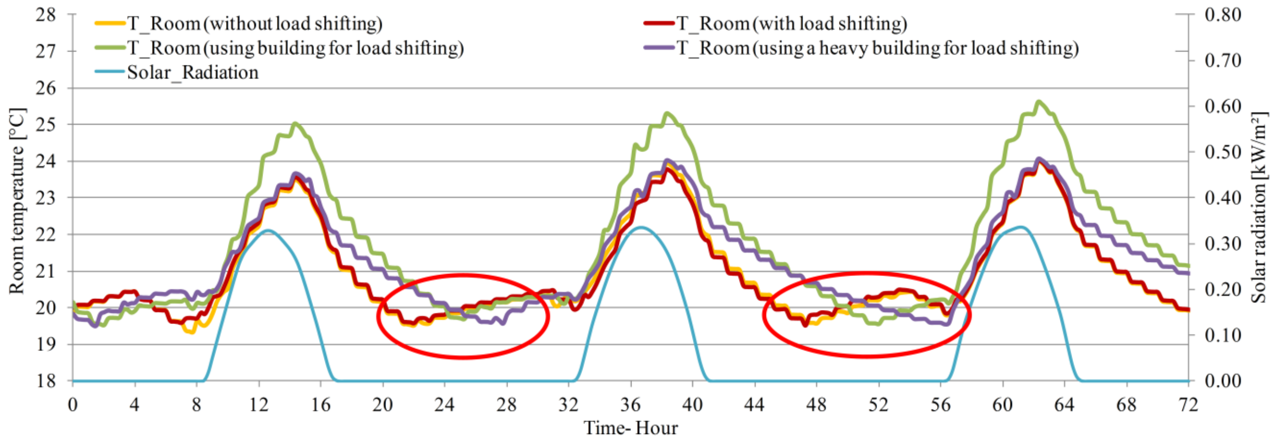

Figure (9): Temperature in a south room for three sunny days in February with different control cases (case 4 purple: C_b = 80 Wh/m³.K, all other cases C_b = 38 Wh/m³.K)

If the thermal storage capacity is increased (purple line), the heating starts approximately 7 h later, due to the bigger storage capacity. Furthermore, it is important to notice that no higher temperature peaks occur in the building with a higher thermal capacity compared to the reference case without load shifting. This means that the thermal comfort is not impaired.

Figure (10) depicts simulated room temperatures (3 example days in March) with load shifting (building as a storage) for a building with different thermal capacities.

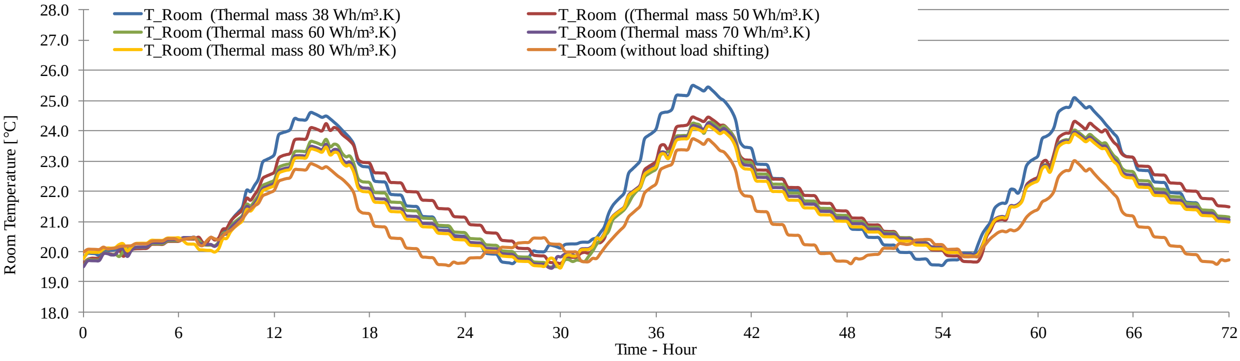

Figure (10): Simulated room temperatures for three example days in March.

Already with a thermal mass of the building equal to 50 Wh/m³.K the temperature peaks in the case where the building is used as a heat storage, don't exceed the peaks of the reference case (C_b = 38 Wh/m³.K, without load shifting).

4.2.3 Effect of the hot water storage tank volume

Different storage tank volumes with and without the additional use of the building as a storage have been tested. Figure (11) depicts the primary energy reduction and operation cost reduction in dependence of the storage tank volume for different cases (all cases PV peak power = 8.32 kWp). When the building is not used as an additional storage, an increase of the hot water storage volume leads to significant improvements of the efficiency and operating costs (blue lines).This is mainly due to two effects: (1) An increase of the heat storage capacity and therefore higher autonomy in the heating period. (2) A reduction of the hot water storage temperatures while load shifting. Whereas, when the building is already used as a storage, an increased hot water storage volume doesn't lead to further significant improvements. This is due to the fact, that with the building already enough thermal capacity is available. Therefore it can be stated, that in practical applications either the building should be used in the load shifting strategy or the hot water storage size should be increased. It can be disregarded to combine both actions.

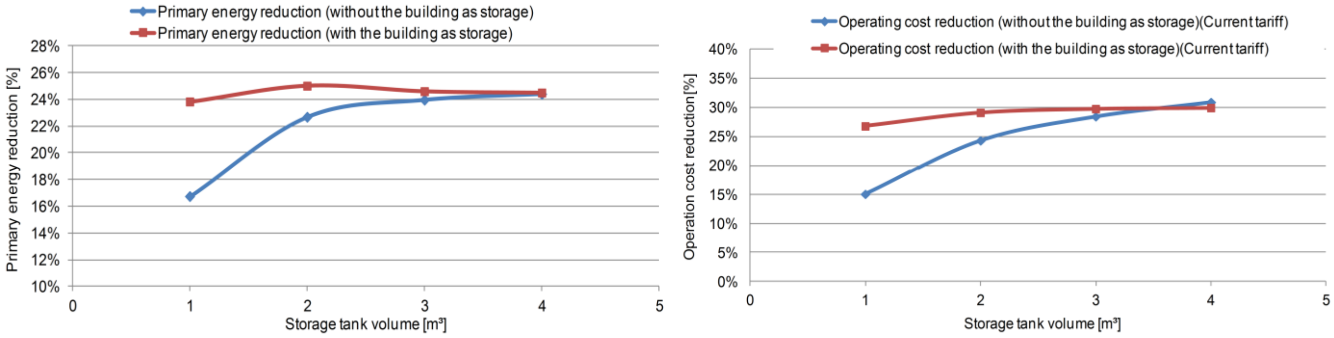

Figure (11): Primary energy and operation cost reduction in dependence of different storage tank volumes.

5 Conclusions

In this study the storage of locally generated PV energy as heat in hot water storages and in the thermal mass of a building has been evaluated. This process is called load shifting in the paper. The building's overall autonomy (heating demand and household) could be increased with load shifting from 24 % to 38 % (1 m³ hot water storage, without the building as a storage, 8.32 kWp PV power), When the building additionally was used as a heat storage (thermal capacity of the building between 60 and 80 Wh/m³.K, 1 m³ hot water storage, 8.32 kWp PV power), the overall autonomy was increased to 43 %. The latter case led to a reduction of the primary energy consumption and operation cost of 24 % and 27 %, compared to the case without load shifting.

By an enlargement of the hot water storage the same effect as with the usage of the building as a storage could be achieved. Therefore in practical applications only one action has to be taken: either the usage of the building as storage or the enlargement of the hot water storage. It could be shown in the study that the usage of a building with a high thermal storage capacity doesn't lead to higher temperature peaks as in a building with lower storage capacity without load shifting.

6 Literature

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