100 % Solar Heating with Seasonal Thermal Storage, Solar Thermal Collectors, PV, and Heat Pump

[1]Florian Ruesch, [1]Fabio Lichtensteiger, [1]Kanchan Bohara, [2]Luca Brauchli, [2]Sebastian Ammann, [2]Willy Villasmil, [2]Jörg Worlitschek and [1]Michel Y. Haller

[1]SPF Institute for Solar Technology, Eastern Switzerland University of Applied Sciences (OST), Rapperswil (Switzerland)

[2]Institute of Building Technology and Energy, Lucerne University of Applied Sciences and Arts (HSLU), Horw (Switzerland)·

Abstract

In this contribution, the concept of 100 % solar-heated multifamily buildings with seasonal water storage is analyzed and optimized. Simulations of the system have been implemented in TRNSYS and were calibrated with measured data from the first winter of a real building with 160 m^2 of solar thermal collectors and a water seasonal thermal energy storage of 110 m^3. In a second step, this system has been complemented with photovoltaics and a heat pump with different heat sources. Parameter variations to optimize sizing of the collector field, the PV area, the storage volume, and the heat pump size were carried out and the corresponding investment costs were estimated. Furthermore, shower heat recovery systems were included in the simulations to estimate their potential to further reduce the size of the storage tank.

The most promising combination of solar thermal collectors, PV-system, heat pump, and shower heat recovery resulted in a 40 % reduction of the required storage volume compared to the original standard system and reduced the investment cost by about 15%. This "combined system" not only covers the heat demand of the building but is also able to cover part of the electricity used by households and feed some excess electricity into the grid.

Replacing all solar thermal collectors by PV and combining the PV and heat pump system with direct electrical heaters was not favorable compared to the combined system described above and was only possible with larger tanks and heat pump sizes. But when increasing the hypothetic solar roof area from 160 m^2 to 210 m^2, PV only systems became attractive. With increased PV sizes combined with heat pumps and direct electrical heaters, the needed storage volume could be further reduced to 33 m^3 and the investment cost to 65.6 % compared to the original standard system. However, contrary to the combined systems, no excess electricity was fed to the grid in the case of 100 % PV system configurations.

Keywords: Seasonal thermal energy storage, thermal autarky, solar thermal, PV, heat pump, shower heat recovery

1. Introduction

The energy strategy 2050 that was issued by the Federal Council of Switzerland requires a tremendous increment in renewable heat and electricity supply to meet the demand of different end-use sectors. The final energy consumption of Switzerland in 2020 was 747.9 PJ of which around 29.3 % was consumed by the private household sector (Bundesamt für Energie, 2022). Out of that total energy consumed by private households, around 80 % of the energy was consumed to meet the demand for space heating and domestic hot water, and almost half of the energy demand in private households (49.6 %) was met by the supply of fossil fuels (mainly heating oil, natural gas, and coal) (Kemmler and Spillmann, 2021). The replacement of these largely fossil-based heat supply systems is a main concern of the energy strategy 2050. Renewable energies, such as solar energy, are considered to have a high potential in this context. However, solar energy shows a pronounced seasonality with a high supply in summer and a low supply in winter. Therefore, the coincidence of low solar energy generation and high heating demand during the winter season leads to the requirement for affordable seasonal thermal energy store (TES) technology.

There are several examples of fully solar heated multifamily buildings MFB in moderate climates, which use solar thermal collectors (STC) only. Contrary to the widely reached net zero electricity concepts, thermal autarky can only be reached with seasonal TES. Large seasonal water storages, the state of the art for such concepts, induce elevated levelized cost of energy storage (LCOES). Additionally, for the concept investigated here, they occupy

doi:10.18086/eurosun.2022.03.01 Available at http://proceedings.ises.org

valuable space within the building. In such systems, STCs are used to heat the TES to temperatures close to 100 °C in summer. However, the efficiency of thermal collectors in winter is strongly reduced due to low irradiation and cold outdoor temperature. In order to still achieve significant winter heat production, collector fields are usually sized in a way that the TES is already fully charged in spring. This leads to heat rejection or stagnation in summer. On the other hand, PV modules deliver electricity also with low irradiation conditions, profit from cold temperatures in winter, and reach similar area-specific efficiencies for producing heat when combined with heat pumps (HP). Since standard heat pumps are not able to reach elevated temperatures to fully charge the TES in summer, a combination with STC for this purpose is advantageous.

Along with that, energy efficiency measures like the shower or drain water heat recovery (HR) systems result in a significant saving in hot water demand. There is a possibility of reducing the useful energy expenditure for shower water heat by at least 30 % under standardized boundary conditions (Passivhaus Institut, 2020).

This contribution analyzes and optimizes the cost and storage volume of fully solar heated MFB by combining STC, PV, and HP. Furthermore, the potential of HR to optimize these systems is analyzed. Additionally, these combined STC, PV and HP systems are compared to PV systems with HP and direct electrical heating (DEH).

2. Methodology

The analysis was based on a real multifamily solar home, built by Jenni Liegenschaften AG in Huttwil, Switzerland. It consists of four floors with two apartments on each floor (total living area of 1100 m^2), seasonal TES with 110 m^3 volume, and 160 m^2 of roof area used for STC. This building was monitored and served as a reference case for the dynamic simulations.

4.1. Simulations

The simulation software TRNSYS was used to model the building as well as the thermal system. The modelling of the building was done with “Type 56” (SPF-OST, 2021). Some simplifications of the geometry were done by implementing the building (see Fig. 1). In addition, the window opening and shading behavior were taken from the reference building described in detail in (Mojic et al., 2019).

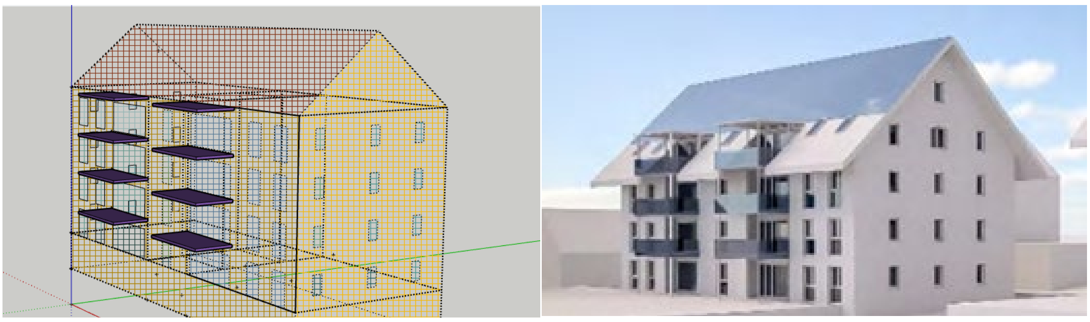

Fig. 1 Simplified building model in TRNSYS3d/Sketchup (left) compared to the detailed architectural representation (right, source: Jenni Liegenschaften AG)

Hot water profiles, household electricity consumption and internal thermal gains were used from the same reference MFB, which was created based on the monitoring data and the results of the ImmoGap project (Mojic et al., 2018). A detailed piping model was simulated with short timesteps in order to estimate the reduced consumption of DHW during showering when a HR system was present. The combination of the real piping sizes of the building and the measured parameters of a good central shower heat recovery unit (Passivhaus Institut, 2020) resulted in a reduction of 23.6 % of the total DHW consumption. Adapted DHW profiles were used to implement this reduced DHW demand into the annual simulations. Weather data from the village of Wynau (the closest SIA weather station near Huttwil) in Switzerland was used in the simulations. These combinations resulted in space heating demand of 10.2 MWh and a DHW demand of 12.9 MWh.

Fig. 2 is based on the hydraulic scheme of the reference MFB in Huttwil with the solar loop (yellow) the DHW preparation (blue) and the floor heating loop (purple). The existing system of Huttwil was complemented for simulation purpose with a heat pump (green). Different sources such as outside air, ground collector, Air PVT and an activation of the foundation plate of the building were simulated. The hydraulics with the foundation activation is shown in brown color. For the simulation of a simpler system, some of the loops were kept inactive.

The following models were used for the simulation:

- Solar collectors were modelled using an adapted version of the "dynamic collector model by Bengt Perers" (Haller, 2012) with $\eta_0 = 0.825\ [-]$, $a_1 = 3.13\ [W/(m^2K)]$ and $a_2 = 0.0152\ [W/(m^2K^2)]$. Collectors were south oriented with an inclination of 40°.
- A stratified plug flow model by (Haller and Carbonell, 2013) was used to model the TES.
- The energy system was coupled to the building by detailed floor heating model (Battaglia, 2017). The same floor heating type was coupled to a simplified 2D ground model, to model the foundation plate as source for the HP.
- A characteristic curve-based HP model (Haller, 2015) was used and linearly scaled for variable sizes. Parametrization was done based on a real HP with a COP of 4.47 (A0W35) for air source and 4.79 (B0W35) for brine source HPs. In both cases the HP was limited to 60° water supply temperature from the condenser.

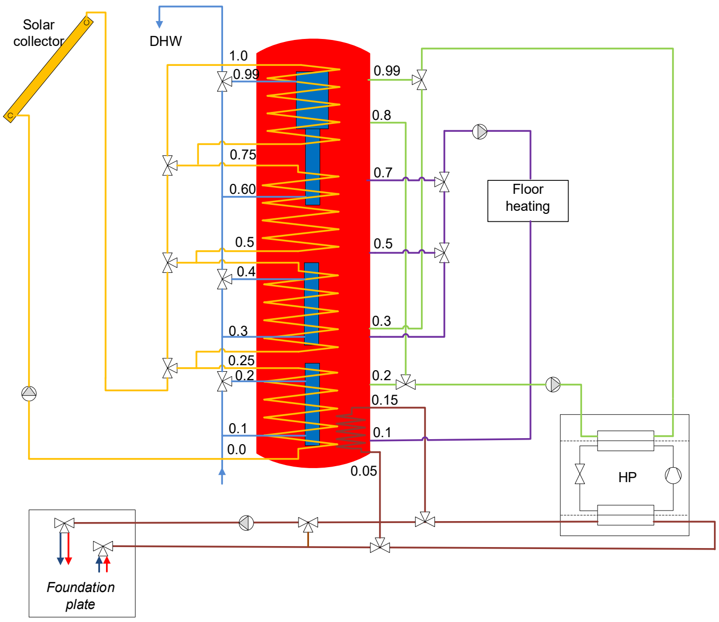

Fig. 2 Hydraulic scheme used for system simulations, a variant with foundation plate as a heat source for brine-to-water HP and as a sink for excess thermal gains in Summer

For the solar charging of the TES, the heat exchanger that is lowest in the tank was used with priority and further exchangers were added in series when the return temperature of the collectors increased over the TES temperature at the according height. In the reference system, an hourly volume flow rate of 43 $l/(m^2h)$ was used, respective to the collector area. Because of the increasing pressure drop, when several heat exchangers were operated in series, the flow rate was lowered down to 25 $l/(m^2h)$. The heat pump was controlled by the PV production and was only operated with self-produced PV electricity. Therefore, the HP was modulated. Like the STC system a priority was set to the charging of the lower storage volume. Only when the temperature in the top of the TES dropped below 55 °C the HP switched to DHW mode.

3. Results

4.2. Comparison of monitoring and simulation

A monitoring system was installed in the MFB in Huttwil, monitoring the main energy flows and the temperatures in the seasonal storage in detail. In the first year of operation, only one of the eight apartments was inhabited, wherefore the DHW and, to some extent, the heating demand was not yet comparable to the designed use case. Nevertheless, monitoring data of the first year of operation was used to validate the simulations of the seasonal water storage. For this purpose, the measured load for DHW and floor heating and the inputs of the solar collector were integrated into the simulation. By simulating only the TES and the connecting hydraulics, a high agreement of measured and simulated data was confirmed (see Fig. 3).

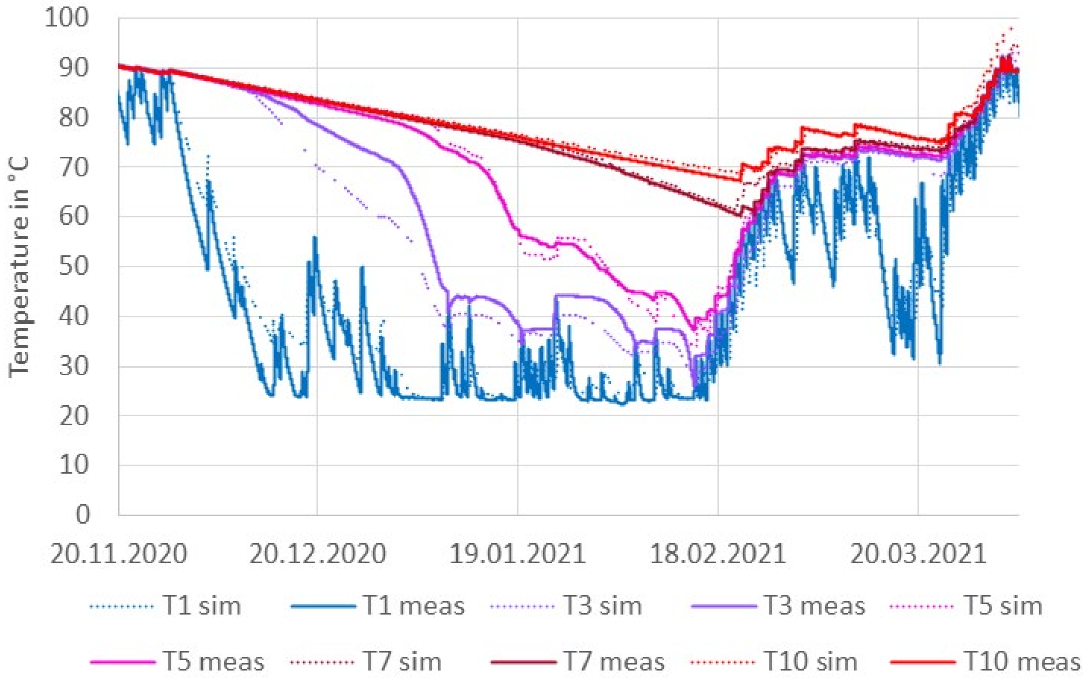

Fig. 3 : Comparison of measurements with a simulation of the TES combined with measured loads. Positions T1 to T10 are equally distributed from the bottom to the top of the tank

4.3. Reference system with only solar thermal

In Fig. 4, the temperature evolution in the seasonal TES is given for the standard system with 160 m^2 STC and a TES volume of 110 m^2. For the selected boundary conditions, in combination with the weather data of the location Wynau the standard system needed an additional (virtual) auxiliary energy input of 135 kWh (<0.5 % of the final energy demand) to fulfill the requirement of always reaching 55 °C DHW temperature (as required by the Swiss standard (SIA 385/1, 2020) at the outlet of the TES. For the evaluation of other system variants, this 99.5 % instead of 100 % solar fraction was taken as a benchmark. When the virtual auxiliary need was lower than this benchmark, the system variant was selected to be equivalent or better than the standard system.

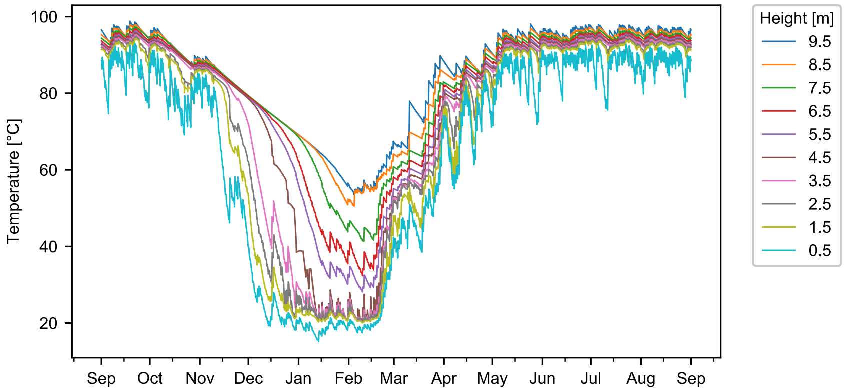

Fig. 4 Temperature evolvement at different heights of the seasonal TES from the simulation of the standard system with solar thermal collectors only

Based on the findings from the OPTISAIS project (Villasmil et al., 2021), a low flow controls (12.5 l/(m^2h)) was used to optimize the reference system. With this low volume flow strategy, the storage volume could be reduced to 99 m^3 (-10% compared to reference TES volume). However, permanent low flow control also can cause incomplete loading of the storage during the summer months. Therefore, a combined control strategy was implemented, with high flow in summer, but switching to low-flow when the temperature at the bottom of the TES dropped below 60 °C. With this combined control strategy (a low-flow in winter and a high-flow in summer), the storage volume could be reduced by 20 % (to 88 m^3) without increasing virtual auxiliary demand compared to the reference system (see Fig. 5).

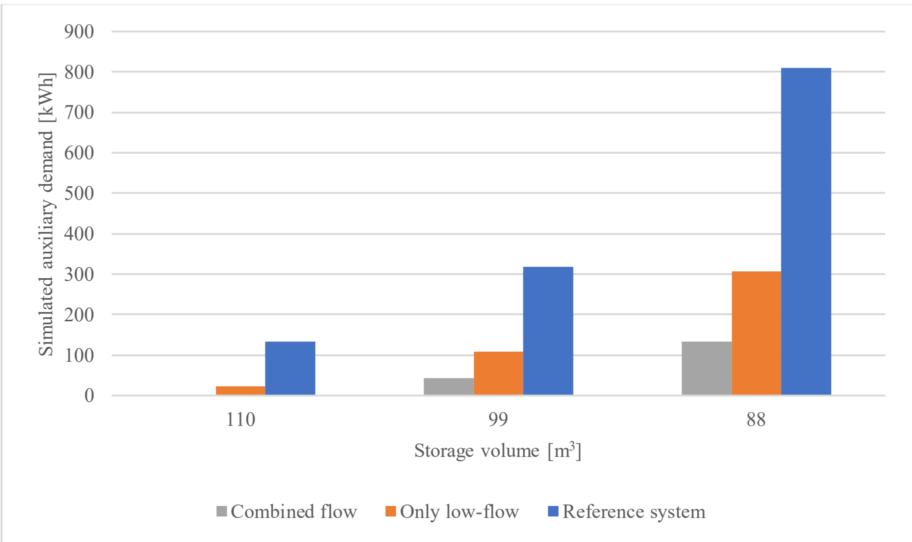

Fig. 5 Comparison of simulated auxiliary demand with different control strategies of the volume flow rate, depending on the storage volume

4.4. Solar thermal, PV, and air-source HP system

Based on the reference system with optimized control, a PV system, coupled to an air-to-water HP, was added to the system and different parametric studies were performed. The constraint on useable roof area of 160 m^2 was kept constant and shared between PV and STC. However, the PV roof area share, different HP sizes and the TES volume were varied. All the systems with virtual auxiliary demand of less than the benchmark of 135 kWh are performing better than the reference system with standard control and are therefore valid alternatives. For the combination with an air-source heat pump, the storage volume could be reduced by a maximum of 30 % (77 m^3) with 40 m^2 PV, 120 m^2 of STC, and 10 kW HP (see Fig. 6). This system not only delivers more than 99.5 % of the heating demand of the building based on local solar resources, but also directly covers around 19% of the household electricity and additionally feeds more than 2 MWh of electric energy to the grid.

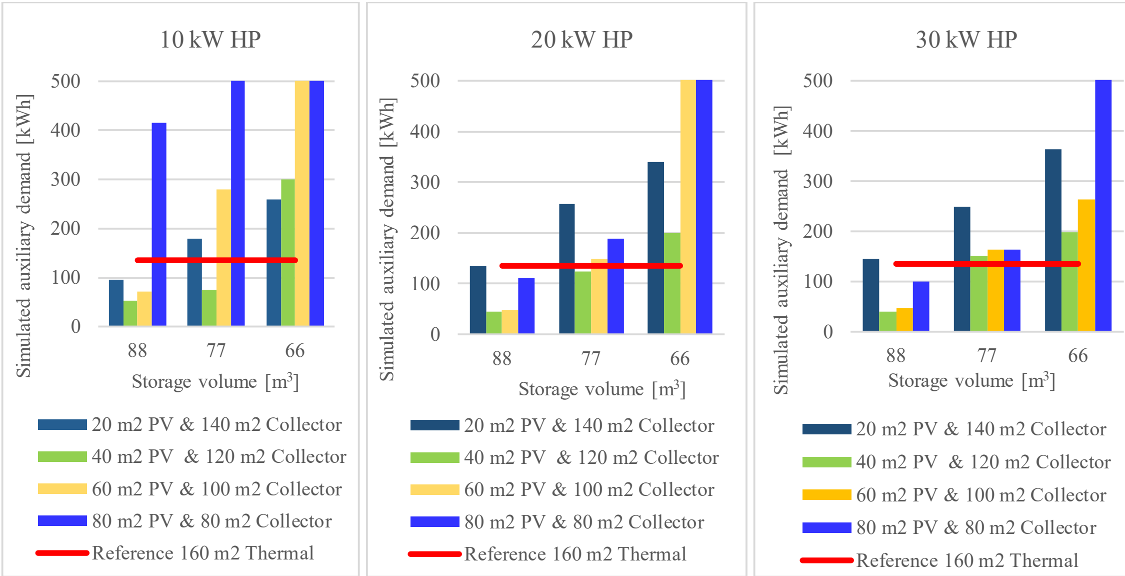

Fig. 6 Simulatedauxiliary demand of the reference system implemented with PV and air-to-water HP with different storage volumes and without HR unit.

4.5. Solar thermal, PV, and HP with foundation plate as a heat source

The combination of the original system with a HP which uses the thermally activated foundation slab of the building as a source was simulated as an alternative to the air-to-water HP system. The foundation plate must be actively regenerated with the unused solar heat during summer months to prevent it from cooling down in the long term. In this case, only systems which achieved a regeneration >100 % were considered as long-term stable system. Systems with less than 100 % of regeneration are likely to face a decrease of their performance under long term operation and were not considered for the comparison.

Fig. 9 shows the maximum possibility of reducing the storage volume as a result of different combinations of PV, STC and HP sizes, when the constraint on the roof area of 160 m^2 is maintained. With brine-to-water HP and foundation slab source, the storage volume could be reduced to 77 m^3 (30 %) using 60 m^2 PV, 100 m^2 STC and a HP of 10 kW. This system covers not only more than 99.5% of the heating demand, but also directly 23 % of the electric household demand, and additionally feeds 4.1 MWh of electrical energy into the grid.

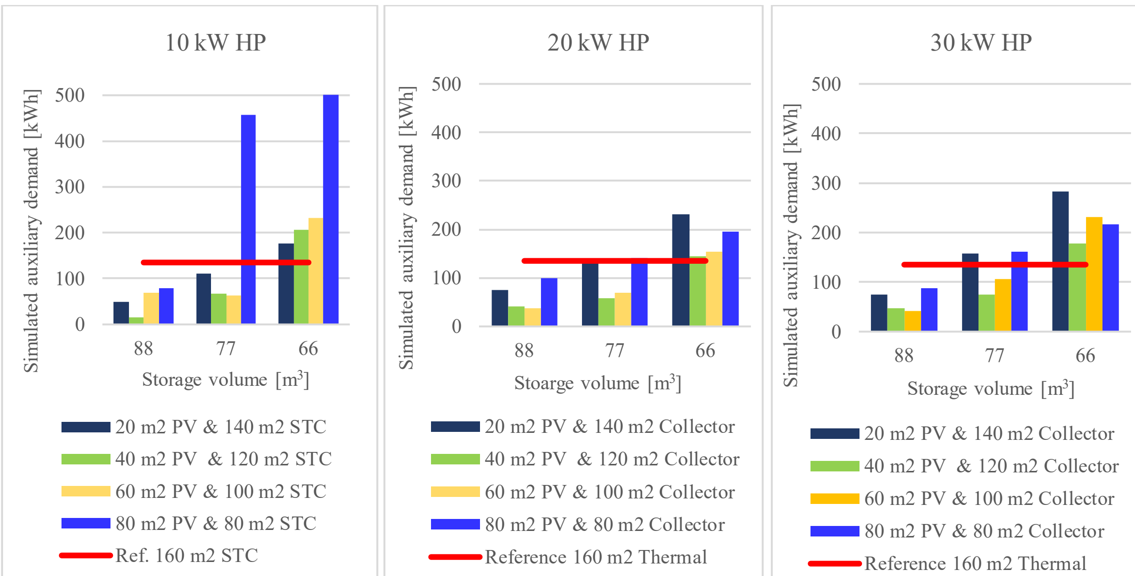

Fig. 7 Simulated auxiliary demand of the reference system implemented with PV and brine-to-water HP with the foundation plate together with different storage volumes, without HR unit.

4.6. Heat recovery

By including a DHW HR unit, the storage size for the combined systems could further be reduced. In the case of a combination with an air source system, a reduction to 66 m^3 was possible only in the case of a 10 kW HP, 40 m^2 of PV and 120 m^2 of STC (see Fig. 8). Similar results were obtained for the system with a HP and the foundation plate as a source. In this case a reduction of the storage size to 66 m^3 was possible for different combinations, where a 20 kW HP, 60 m^2 PV and 100 m^2 STC was the most promising one (these graphs are not shown in this paper).

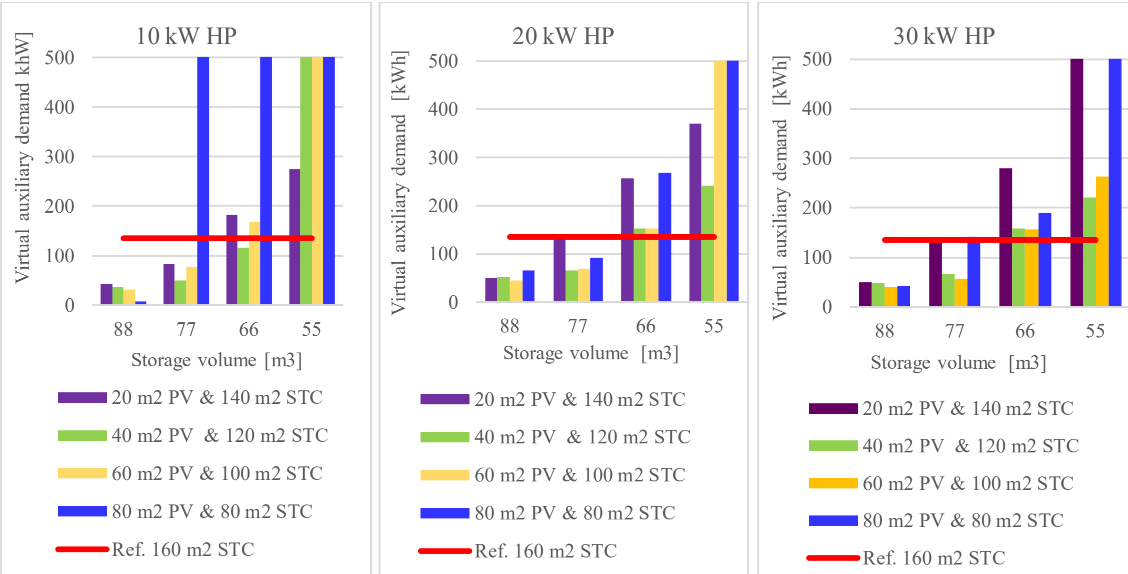

Fig. 8 Simulated auxiliary demand of the reference system implemented with PV and air-to-water HP with different storage volumes, with HR unit.

4.7. PV and direct electrical heating

When the PV roof area is constrained to 160 m^2, the TES volume cannot be reduced as there is always an additionall auxiliary heating demand above the reference benchmark. However, when such a system was implemented with a HR unit and when the size of the air-source HP was further increased to 50 kW, the reference benchmark could just be reached with a storage volume of 99 m^3. Systems with a foundation plate source HP and only PV as solar input reached the benchmark already with smaller HP sizes, but were not able to fully regenerate the ground. Therefore, these systems are not considered for comparison.

4.8. PV and direct electrical heating, increase of building surface used for solar

As the analyzed building has the potential to increase the solar area to about 210 m^2, parameter variations with larger PV fields were carried out. When changing the constraint of the solar area, a direct system comparison is no longer valid. However, systems with large PV installations can drastically reduce the size of the needed TES volume. As shown in Fig. 9, the storage volume can in this case be reduced to 33 m^3 when using 210 m^2 of PV installation and a 40 kW HP.

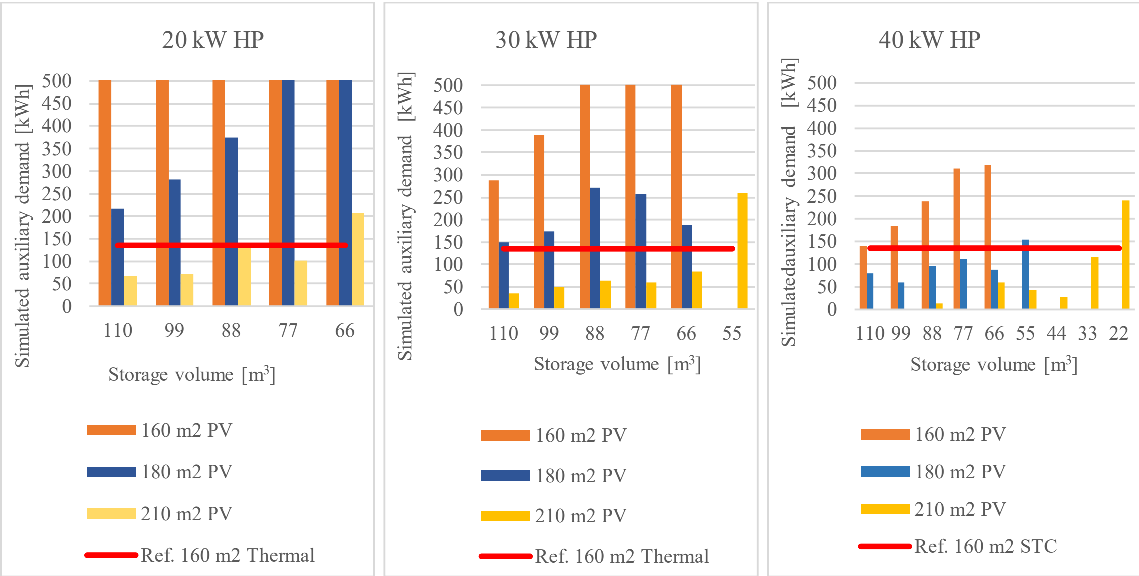

Fig. 9 Aimulated auxiliary demand of the system with only PV, direct electrical heating and air-to-water HP with different storage volumes without HR unit

4.9. Investment cost analysis

The financial analysis was limited to investment cost, as the systems don't use external energy and therefore don't generate external energy cost. Running cost are dominated by capital cost, which depend directly on investment cost. A precise estimation of operational cost, which are for these systems dominated by maintenance cost, is difficult. Simplified maintenance cost estimations are given as percentages of the investment and are again directly dependent on investment cost. Therefore, an estimation of running cost doesn't bring added value for fully solar heated systems.

Based on real cost from the constructed building and further indicative offers of the company Jenni Energietechnik AG, investment cost estimations for different system combinations were carried out. These cost estimates cover investment and installation cost. Planning cost were excluded from the analysis, as standard planning cost cannot be applied for such pilot systems. On the other hand, similar planning cost can be expected for all analyzed systems. Fig. 10 provides a comparison of the investment cost for different system configurations. For all system types, the sizing with the lowest investment cost is chosen for this comparison. As some system configurations can provide part of the household electricity and feed excess PV electricity to the grid, the financial returns from this additional PV production (for a period of 20 years) are also given for comparison in Fig. 10. Electricity cost for Huttwil 2021 (consumption: 0.175 CHF/kWh and feed in: 0.07 CHF/kWh) were used for this analysis. When reducing the storage size, living area in the building is gained. The financial benefit of this effect is difficult to quantify and strongly depends on the location and other parameters. Therefore, the return from the gain of living area is not given precisely but is represented by a bar with a color that is fading out.

It can be seen that the combined systems have lower investment cost than the standard STC system. Especially when the financial gains of the PV production are accounted for, the system with the foundation plate HP is economically most attractive.

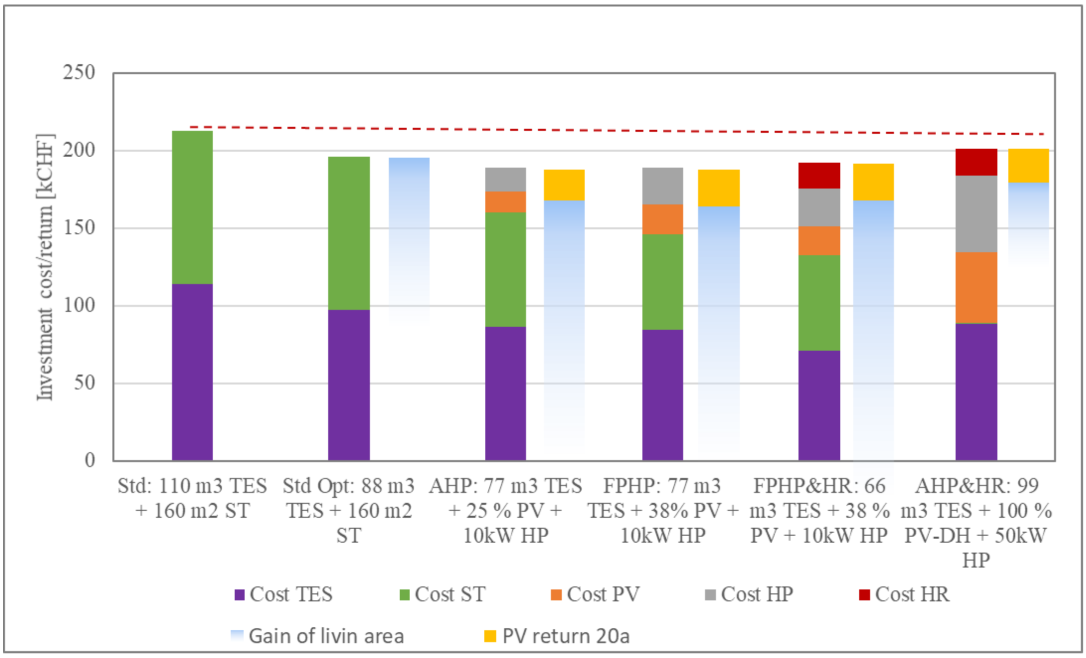

Fig. 10 Investment cost for different system configurations compared to the return from produced PV electricity and the virtual return from the gain of building volume when reducing the size of the TES

By increasing the solar roof area, investment cost increased for the case of the combined systems but decreased in the case of PV only systems on the other hand. This can be seen in Fig. 11 (Annex), where the system with optimized control (standard reference system) and the best combined system with a solar field size of 160 m^2 is compared with various system combination with a solar field of 210 m^2.

4. Conclusion

In comparison to the reference system with only solar thermal, the combined system with PV and HP has both energetic and economic advantages. The additional costs of the HP can be compensated by the savings in the storage tank size and the lower cost of PV compared to STC. Systems without STC but with PV and direct electrical heaters are only possible in combination with a large HP and shower heat recovery. These systems are therefore more expensive than the best combined systems.

With the combined system, almost all the heat demand of the building can be covered and part of the electricity demand of the building can be supplied with the PV electricity. In summer, some systems even feed excess electricity to the grid. Financial benefits of this PV production and benefits from the gain of living area from the size reduction of the TES make the combined systems even more attractive. Using the foundation plate of the building as a source for the HP is economically the most attractive of the analyzed solutions, especially when the gains are accounted for.

5. Acknowledgements

We would like to thank Mr. Josef Jenni from Jenni Energietechnik AG for enabling the measurements on the MFB in Huttwil as for providing technical and economic information's. Further, we would like to thank the Swiss Federal Office of Energy (SFOE) who supported this work within the projects SensOpt and 100%SolarLCA.

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7. Annex

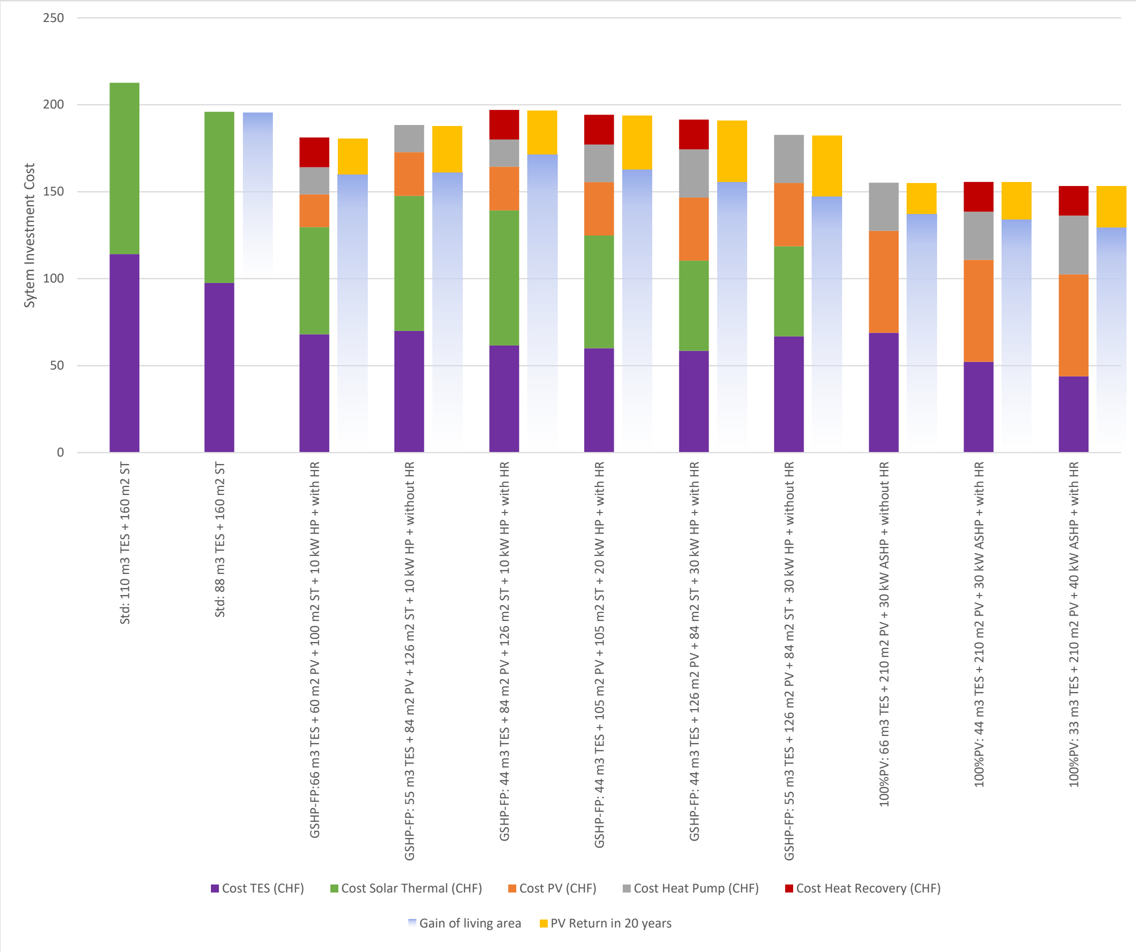

Fig. 11 Investment cost for different system configuration with larger solar areas compared to the return from PV electricity production and the virtual return from the gain of building volume when reducing the size of the TES