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HpCosy - Heat Pump Comfort System

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Abstract

In the project HpCosy the base for a decentralized brine-water heat pump system for flats in multi-family houses is developed and investigated. It encompasses the functions heating, cooling and domestic hot water preparation. Its control shall enable the consideration of availability of on-site produced photovoltaic electricity as a single unit within a swarm of all heat pumps within the building.

The comparison between a centralized and several decentralized heat pump systems clearly shows great advantages of the decentralized solutions (savings up to 31% of electric energy). However, the largest share of the energy saved is due to the elimination of DHW circulation.

The measurement of a HpCosy-unit in realistic and dynamic working conditions showed that an individual adjustment of the control of the individual swarm participants in response to a swarm signal is technically feasible and already leads to a reduction of the grid consumption in the selected and tested week.

The final simulations of the overall system show that - in addition to the savings achieved through the use of decentralized systems - an additional reduction in grid consumption of up to 5% can be achieved by increasing self-consumption by 11% to 17% with a swarm signal, indication whether there is a positive on-site energy production or not.

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1. Introduction

Heat for the provision of domestic hot water (DHW) will become more relevant than heat for heating due to increasingly better building insulation and therefore decreasing space heating demand. Cooling applications will be increasingly realized because of increased comfort demands and not least also due to the advancing climate change. In this context, it makes sense to use the same heat pump to generate both cooling and heating of hot water in the summer, and to operate it as far as possible with self-generated electricity from photovoltaics (PV) or to be able to react to tariff incentives for load shifting (demand side management).

Decentralized heat pump systems for heating and DHW provision in multi-family houses (MFH) with individual units per residential unit offer decisive advantages over central heat pumps. DHW circulation is not required, distribution losses can be avoided, and the lower requirements for DHW storage temperatures in accordance with the Swiss SIA 385/1 [1] standard will increase the efficiency of the provision of DHW. As a result of having several small units, the electrical power drawn can be more finely adjusted to the PV electricity produced.

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When combined with geothermal probes as heat sources and heat sinks, the system is expected to have major advantages from both an energetic and an economic point of view.

2. Project goals

The main objective is to develop the basis for a new heat pump system, which has the following characteristics:

- Increased efficiency (30% less electrical energy demand) compared to current solutions with the same hygiene assurance (legionella protection) [2].
- Increased comfort by offering free cooling and/or active heat pump cooling function
- Increased flexibility of the brine circuit, which can be coupled with geothermal probes, energy networks, air heat exchangers or other heat sources.
- Development of a so-called swarm control for skillful consideration of the local PV electricity production.

3. Market potential

In a first step, the market potential for the application was analyzed and the requirements for a decentralized heat pump and storage unit defined, such as the necessary heating and cooling capacities, the power controllability, the necessary communication requirements, and the size of the DHW storage tank.

According to the Federal Statistical Office (FSO), there were a total of around 1.76 million buildings with residential use in Switzerland in 2019 [3]. Of these, around 1.48 million are purely residential buildings, divided into 1.0 million single-family houses (SFH) and 0.48 million MFH, of which around 0.25 million have between 3 and 9 flats. The number of residential buildings with secondary use and 3 to 9 dwellings is about 0.06 million. A first rough estimate for the HpCosy system potential results in about 0.31 million buildings with 6 dwellings on average, which would mean 1.86 million decentralized heat pumps.

A market survey of suitable heat pumps with DHW storage systems showed, that the devices for the application are already available. Of the 27 analyzed models with inverter drives, 13 are with heating powers in the range of 1-10 kW, which is regarded to be sufficient for the individual flats. Heating buffer tanks are not required for part load operation, as the output can be adjusted to a very low demand. The heating power ranges of the 13 selected models are shown in Fig. 1.

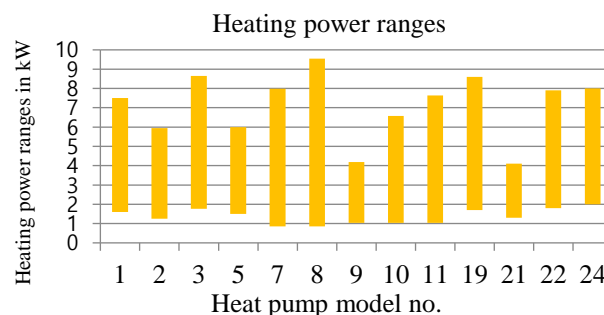


Fig. 1: Heating power ranges of suitable, available heat pumps/storage systems

4. Comparison of centralized and decentralized heat pump systems

A combination of building simulations with the software TRNSYS and spreadsheet calculations for the heating system was used to compare a central with a decentralized heat pump system in an MFH. The modelling was done with the "Type 56" building model in TRNSYS. The modelled building is a three-storey renovated apartment building with six residential units: three residential units on the east side and another three on the west side [4]. Both the internal loads of the flats and the hot water demand are considered via individual user profiles. The location is the city of Zurich. The total heat demand of the flats is shown in Fig. 2 as the sum

of the space heating (SH) demand with ideal heating to a setpoint temperature of 21 °C and the hot water demand.

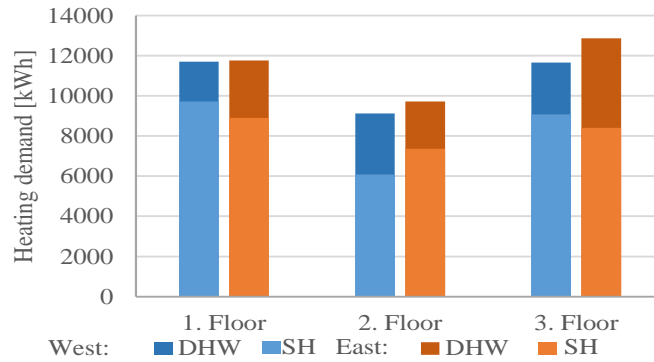


Fig. 2: Heat demand in the MFH

The heat supply of the building is either with a central heating system consisting of an inverter-controlled brine-to-water heat pump, two 600 liter DHW storage tanks and an 850 liter buffer tank for space heating, or six decentralized brine-to-water heat pumps, each with an integrated 220 liter DHW storage tank.

4.1. Centralized heating system

In the central system according to Fig. 3, the room heat is distributed by means of a central heating circuit pump and one line per residential unit. Each apartment is equipped with a room temperature controlled thermostatic valve. An overflow valve is integrated into the heating circuit system to keep the pressure constant and prevent the pump from working against closed valves. The DHW distribution is kept warm by hot water circulation.

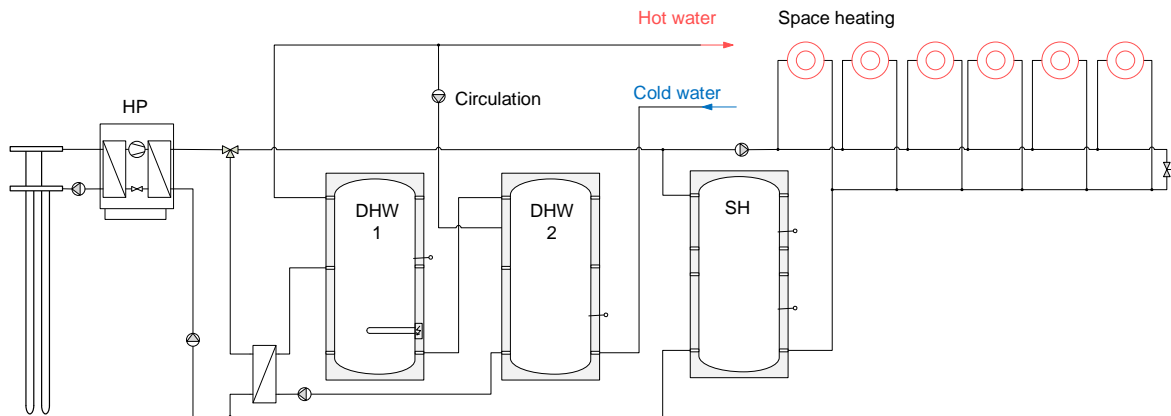


Fig. 3: Hydraulic scheme of the centralized heating system

4.2. Decentralized systems

The decentralized systems shown in Fig. 4 were modeled as compact units with integrated DHW storage tanks (220 l) and direct connection to space heating without an SH buffer tank. The set temperature in the DHW tank is 55°C (SIA 385/1:2020 for systems without DHW recirculation), which can be achieved by the heat pump without the use of an electric heating element; the space heating curve can be set individually in each unit according to the preferences of the occupants and the heat loss rate of the apartment, which is higher for apartments just under the roof or in contact with the basement.

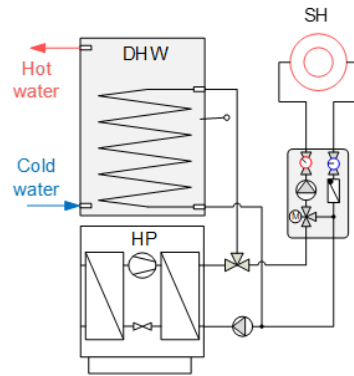


Fig. 4: Hydraulic scheme of a single decentralized unit

The parameterization of the heat pumps for calculating the electricity consumption was carried out according to two models of the company CTA AG:

- Optiheat Inverta 17e for the central system, and
- Optiheat Inverta DHW for the decentralized systems.

The dimensioning of the heat pump for the central heating system was based on the heat demand of the building described above. The aim of the design was a model that can cover the heat demand with 2500 full load hours. The total space heating demand (including losses) in the building is about 58 MWh. Considering the full load hours of 2500 for the heat pump operation, the heat pump capacity is 23.11 kW. The Optiheat Inverta (OHI) 17e model from CTA AG with an output of 25.6 kW at a compressor speed of 70 rps was selected as the basis for the calculations. The COP values of the two HPs were calculated as a function of the condenser outlet temperature and the compressor speed.

The decentralized systems supply the heat directly to the respective heating circuit. For the distribution of DHW, a circulation system with 60/55 °C in the flow and return - and a correspondingly high setpoint temperature in the storage tank - is integrated in the central system; the decentralized systems can operate without the circulation, which is why a temperature of 55 °C in the individual storage tanks is sufficient (SIA 385/1:2020).

Comparing the heat balances of the variants on **Error! Reference source not found.** the difference between the centralized and the decentralized system is relatively small. For space heating, only 1.5 MWh of losses occur in the central system, with a heat demand of 49.6 MWh. For DHW, the losses from storage and distribution amount to 7.4 MWh, with a demand of 17.3 MWh. For the decentralized systems, the only losses are the heat losses from the domestic hot water storage tanks. These amount to a total of 2.9 MWh, which can be credited to the space heating of the respective zone.

However, the comparison of the electricity demand shown in Fig. 6 discloses a big difference between the centralized system and the 6 decentralized systems. It becomes clear that the greatest difference lies in the DHW preparation and distribution.

With a target room temperature of 21°C in each flat, the decentralized systems could save 12% of the electrical energy used for space heating. For hot water production, the total saving, i.e. including coverage of heat losses from circulation, is as much as 53%.



Fig. 5: Heat demand for SH and DHW including losses and inefficiencies, for a centralized heating system compared to 6 decentralized systems.

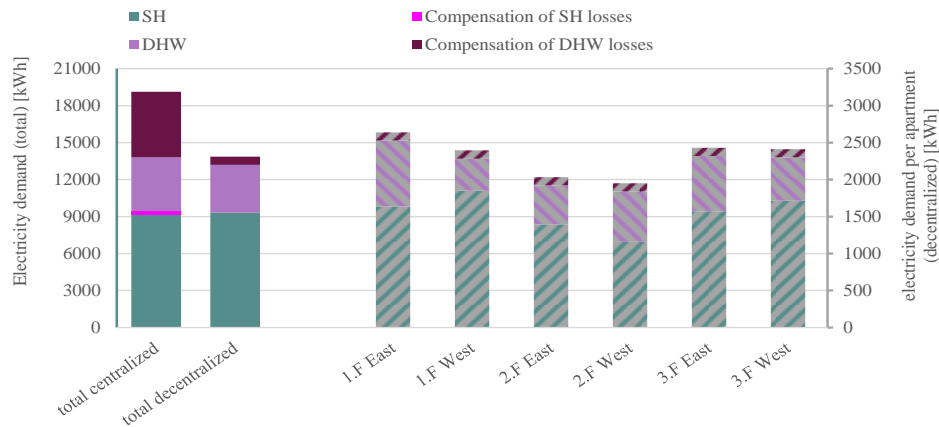


Fig. 6: Electricity demand to cover SH and DHW and the respective extra-electricity for covering losses and inefficiencies, for a centralized heating system compared to 6 decentralized systems.

5. Swarm signal

The comparison of centralized and decentralized systems in a MFH revealed already a significant advantage of the decentralized systems with a control strategy that is based on the individual demand. The next step was to investigate the potential benefits in terms of self-consumption of the locally generated PV power of an aggregation of the 6 HP systems into a swarm. The individual HP system has its own controller which also listens to a guide signal, the so called “swarm signal” to rather consume electricity or not. Therefore, a signal is to be calculated and communicated to the individual entities, whose reaction to the signal is programmed to their controllers. There are different concepts of guide/swarm signals feasible:

- A locally generated by regarding the PV production and electric consumption of the building itself
- A remotely generated by the electricity supplier (using tariff models, regarding demand and supply)

For the tests, a locally generated swarm signal was used. The central unit records the target value, namely the difference between local PV power generation and the consumption of all participants for household appliances and the operation of the heat pumps. The aim of the swarm control is to minimize this difference. The difference S is transmitted as a unidirectional signal to the individual HpCosy units. The transmission is linked to the production of the local PV system. Only from a threshold value of 200 W produced PV electricity, the swarm signal processing is enabled. Otherwise, the HP control is purely demand driven.

The signal S is limited to the peak power of the PV plant in kW: $-P_{PV}$ in kWp ... S ... P_{PV} in kWp.

6. Laboratory setup and measurements

A sample of a HP and DHW system from the company CTA AG was measured in the FHNW "hardware-in-the-loop" test stand according to Fig. 7 for the provision of DHW, space heating (SH) and cooling; its functionality was tested and its efficiency evaluated. In the background of the HP, the emulators for the building heating and the geothermal probe are visible, which are operated in a simulation-coupled manner. The DHW tapping takes place in real according to the SN EN 16147:2017 tapping profile L [5].

Fig. 7 shows the schematic of the laboratory measurement with the emulators (highlighted with color). The other five heat pump/storage systems of the other flats are just virtual in the simulation. Temperatures for all supply and return lines, tank layer temperatures, volume flows and electrical powers are recorded.

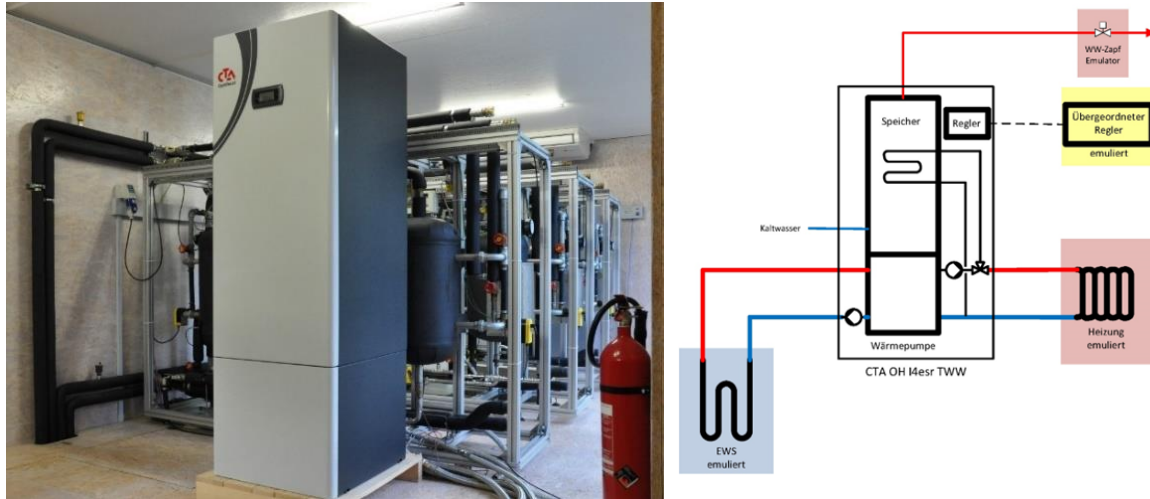


Fig. 7: Laboratory setup of the heat pump system Optiheat Inverta TWW - CTA AG and the according schematic

A total of three different dynamic 7 day test sequences were measured with this setup:

- only DHW preparation and tapping for 4 days and standby mode for 3 days
- heat demand for SH and DHW with a purely demand-driven control without PV power
- heat demand for SH and DHW with the specification of a swarm signal for the measured unit

6.1. DHW Storage Tank CTA Optiheat DHW

Fig. 8 shows the storage tank temperatures measured at 400, 700, 1000 and 1300 mm above the bottom of the tank (Tww1 ... Tww4) and the volume flows of the heat pump (HP) charging (Vdot_HP) and hot water tapping (Vdot_DHW) during a 24-hour cycle of the measurement. The storage tank has a total height of 1300 mm. The power-weighted mean flow temperature of the HP during this cycle was 44.5 °C, the power-weighted mean flow temperature of the DHW was 51.4 °C.

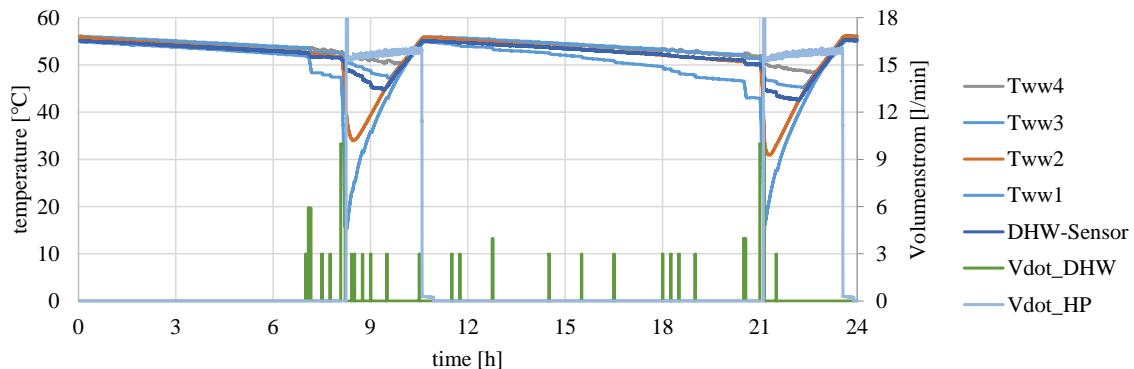


Fig. 8: DHW tank, temperatures and tapping flow rates

For efficient DHW production with the HP, it is particularly important to keep the flow temperature of the HP as low as possible by avoiding mixing in the storage tank. Any mixing of fluids of different temperatures means exergy losses, which must be compensated again via the HP, with the corresponding negative effects on the efficiency of the HP. The temperature curve in Fig. 8 shows the unavoidable mixing processes in the lower part of the storage tank due to the internal heat exchanger. However, the temperatures in the upper part of the storage tank remain unaffected during charging.

The HP had to deliver in total 13.2 kWh to cover the heat demand of 11.9 kWh. The average charging temperature was 44.7 °C, the DHW was delivered with an average temperature of 51.5 °C. The electricity demand of the HP was 4.1 kWh, leading to a power factor (PF) of 3.3 respectively 2.9 considering the thermal losses. The source temperature was held at 5 °C throughout the test.

6.2. Testing of the HP system with demand control (Test 007) and swarm signal control (Test 011)

The developed swarm signal control strategy was transferred to the system installed in the laboratory, but not activated/enabled for the initial tests.

As a reference base, the purely demand controlled system setup was tested (Test 007). The whole building was simulated in advance in detail to generate the time series of the five other heat pump systems of the building. The electric power rates of the five simulated heat pump systems were fed into the real-time simulation running during the laboratory test. The data collected from the “hardware-in-the-loop” measured from the heat pump system were also used to form a swarm of totally six heat pump systems within the simulation.

Further tests were performed to verify the correct function with the swarm signal control (Tests 008, 009 and 010). During Test 011 the swarm signals for power and control enabling were calculated in the real-time simulation and processed by the heat pump controller.

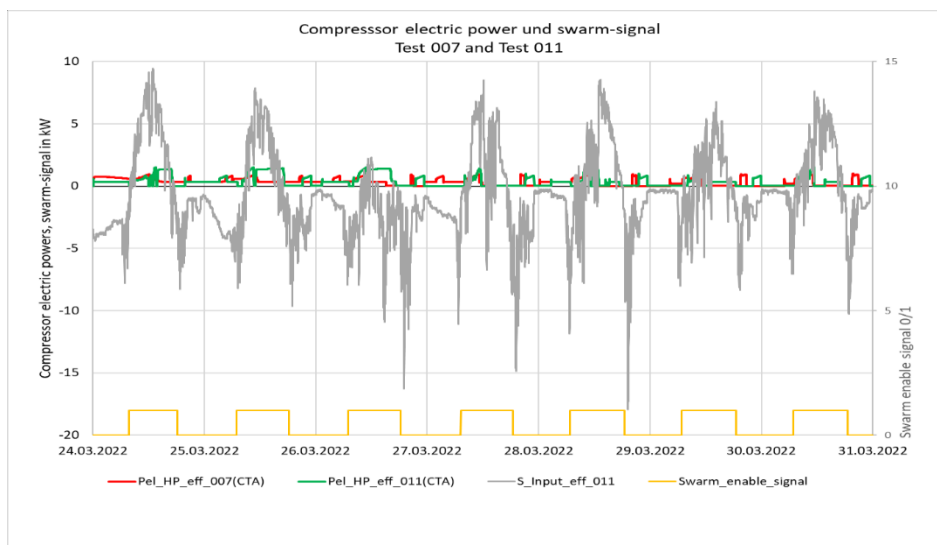


Fig. 9: Compressor electric power and swarm-signal

Comparing the compressor electric powers of test 007 and 011, it can be seen in Fig. 9, that the compressor of the swarm signal controlled system (green curve) runs higher and more during the times with a positive swarm signal.

The HP controller reactions to the swarm signal were:

- Rising or lowering the SH supply temperature setpoint as an offset +/- 5K of the heating curve value
- Rising or lowering the DHW temperature setpoint up to max. 58°C / down to min. 48°C and rising or lowering the compressor speed during DHW preparation nom/min/max 44/30/65 Hz

Fig. 10 shows the time series of the two test 007 and 011 for the simulated and measured week of 3/24 - 3/30. This week was selected because it had sufficient PV power, days of SH requirements and days without. Shown are the SH, DHW, electric compressor energies and the generated swarm signals during test 011.

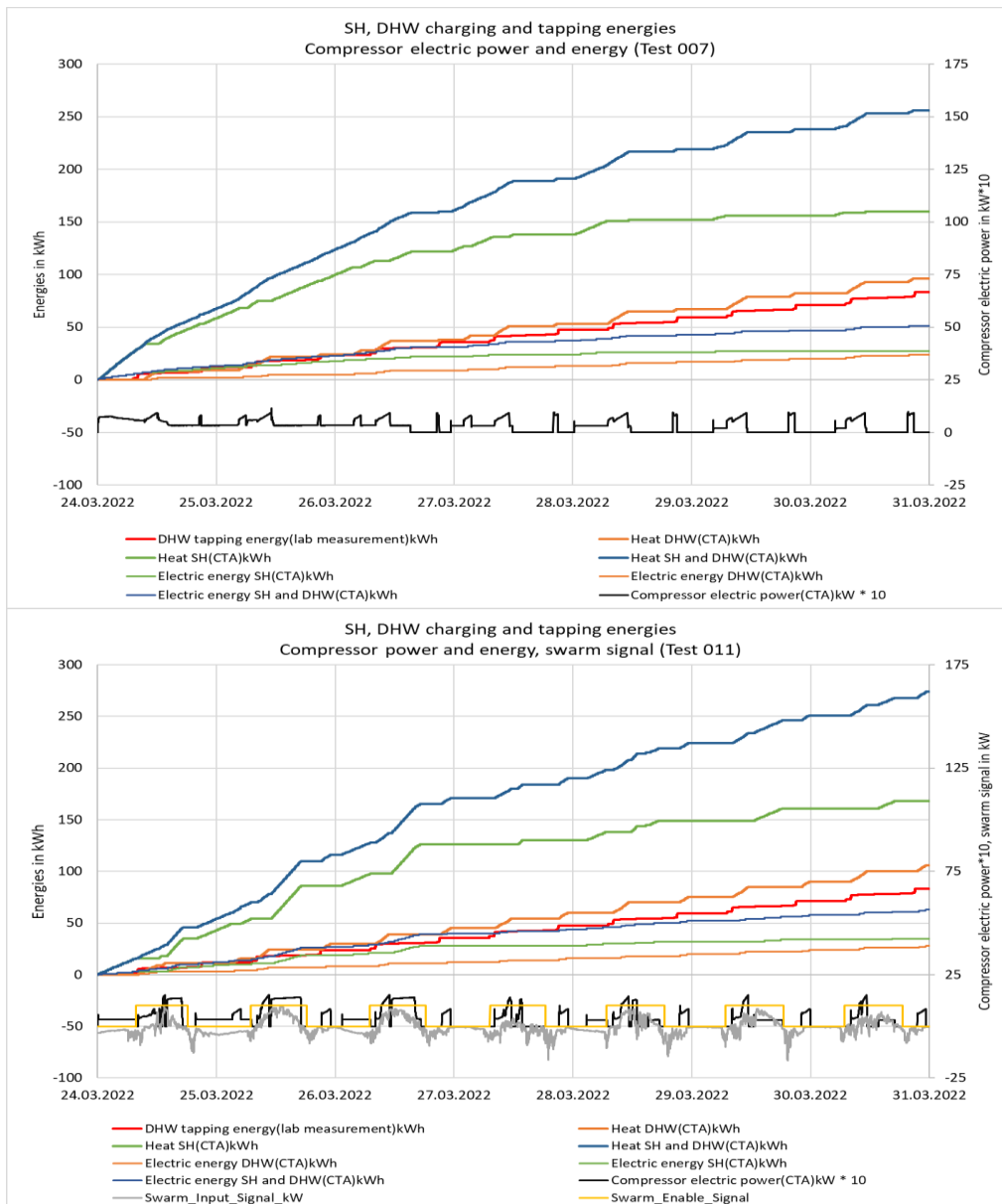


Fig. 10: SH, DHW charging and tapping energies, compressor electric power and energy and swarm input signals

6.3. Comparison of the energy consumption from the grid and PV for the tested week

Table 1. shows the final energies and the average COP values after 7 days of testing. Test 011 showed higher energy values for the SH and DHW and lower values for COP. The swarm signal controlled system had higher temperature setpoints for SH and DHW in average, so the efficiencies were in total 13% less compared to the demand controlled system. On the other hand, the swarm signal controlled system reduced the grid consumption from 36 kWh to 31 kWh (-14%) by enhancing the PV power consumption. With the chosen swarm signal concept, yearly results were evaluated with a series of test-validated simulations in paragraph 7.

Table 1. Comparison of the test 007 and test 011 during week 3/24 – 3/30

Value	Unit	Test 007			Test 011			Change Total	Change Grid / PV electricity
		Demand Total	Grid electricity	Self-consumed PV electricity	Swarm Total	Grid electricity	Self-consumed PV electricity		
Heat for SH	kWh	160			168			+5%	
Heat for DHW	kWh	96			106			+10%	
Heat for SH+DHW	kWh	256			274			+7%	
Electric Energy SH	kWh	27	22	5	35	18	17	+30%	-18% /+240%
Electric Energy DHW	kWh	24	14	10	27	13	14	+17%	-7% / +40%
Electric Energy SH+DHW	kWh	51	36	15	62	31	31	+24%	-14% /+107%
COP avg SH	-	5.93			4.80			-19%	
COP avg DHW	-	4.00			3.79			-5%	
COP avg SH+DHW	-	5.02			4.35			-13%	

The influence of the swarm signal control on the operation can be seen in Fig. 11. The tested week has sufficient PV power, so the during the day, the DHW storage was loaded to higher temperatures. Also, the SH supply temperatures were raised in test 011 and the operations shifted to daytimes with PV power.

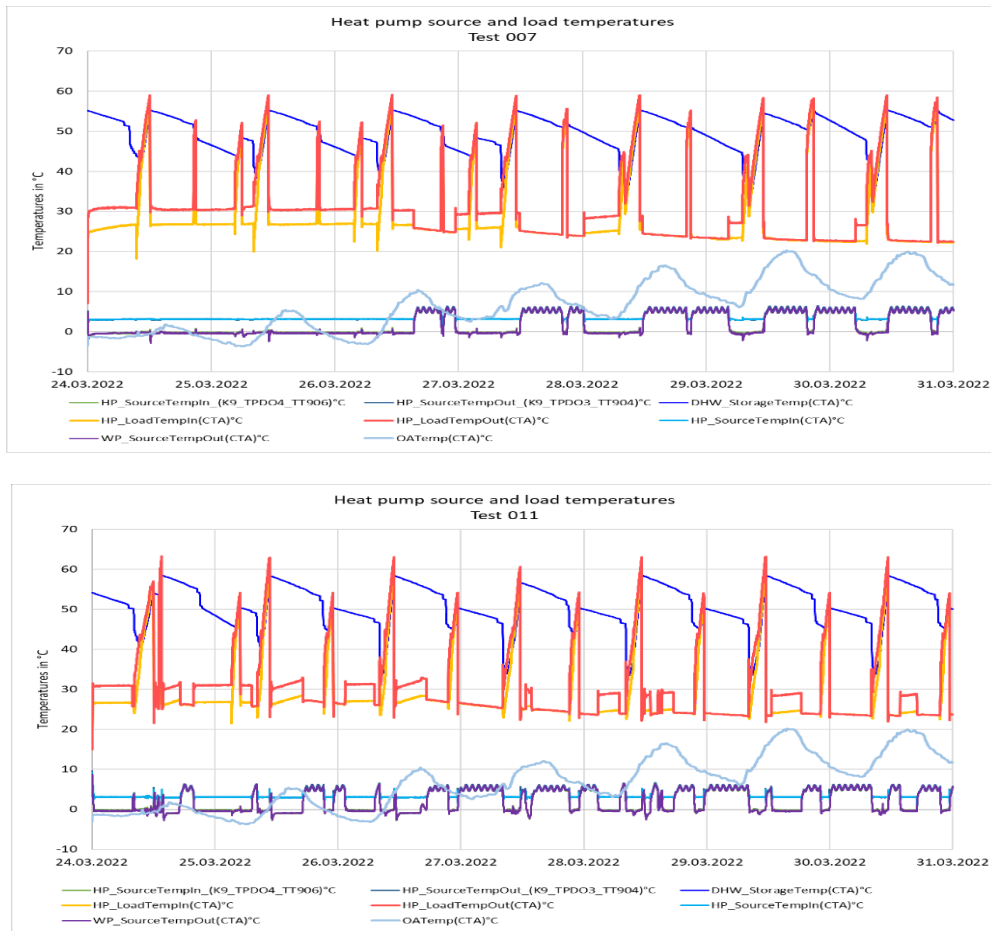


Fig. 11: Heat pump source and load temperatures

7. Annual simulations

Annual simulations of the selected swarm control strategy of the decentralized units with the aim of using PV electricity as efficiently as possible were conducted with a simulation model that has been re-parameterized according to the performed hardware-in-the-loop measurements to obtain viable results.

Figure 12 shows the energy balances with swarm control for different PV areas on a monthly basis. The goal of the simulations is to minimize the term “GridtoHP”, the electric energy from the grid to the HP, and maximize “PVtoHP”, the electric energy from the PV system to the HP. The term “ELfromGrid” is the electric energy from the grid as an input (IN) to the system, “GridtoHH” is the electric energy from the grid used for the household appliances as an output (OUT), in the sense of where it comes from and what it is used for.

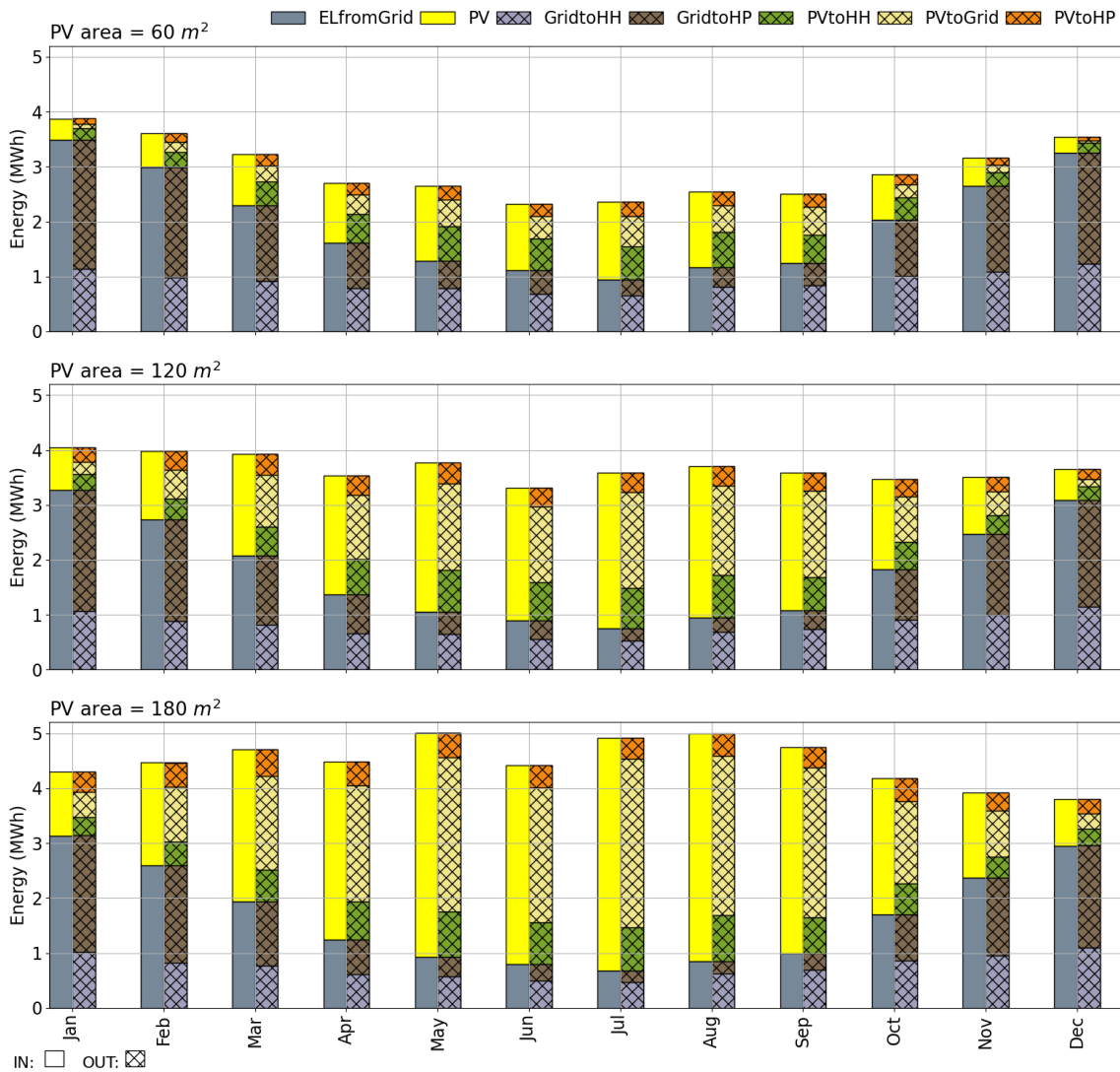


Fig. 12: Energy balance of the complete system with swarm control strategy and different PV areas.

As the swarm signal strength is a function of the PV kWp sizing compared to the totally rated electric consumption of the building, three PV areas 60, 120 and 180 m² of specified PV modules were simulated and compared with the base case of purely demand controlled HPs. The grid consumption could be reduced up to 5% and the self-consumption increased by 11 to 17%.

Figure 13 shows the grid purchase and the grid feed-in of the systems with swarm control compared to those with purely demand-based control. The comparison was carried out for different PV system sizes. As expected, the reduction of the grid consumption (blue numbers in the graphic) is smaller than the reduction of the grid feed-in (green numbers). This is due to the reduction in efficiency with forced operation at higher supply temperatures. The ratio of saved grid consumption to lost feed-in is between 2.2 (with 60 m² PV area / 11.3 MWh PV yield) and 1.9 (with 180 m² PV area / 23.8 MWh PV yield).

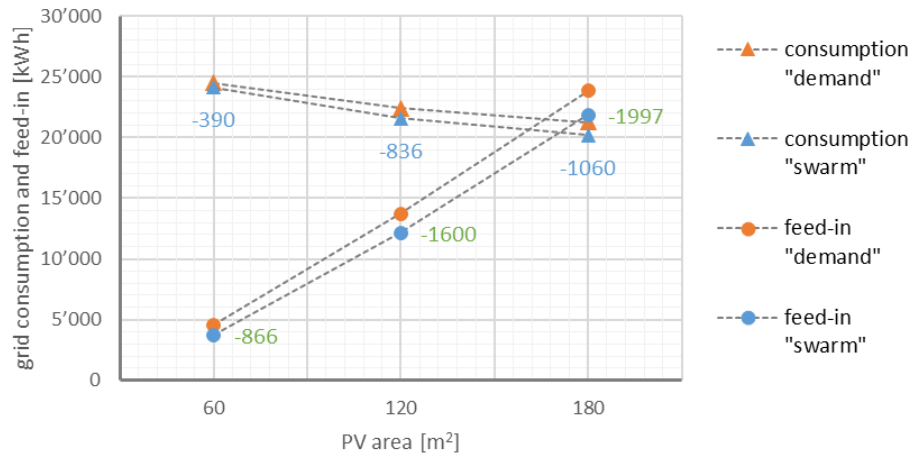


Fig. 13: Grid consumption and feed-in of the demand controlled and the swarm controlled systems for different PV areas.

8. Summary and conclusion

The comparison between a centralized and several decentralized heat pump systems clearly shows great advantages of the decentralized solutions, even in a purely demand controlled operation without taking PV electricity or a swarm control into account.

The savings in the base case with a room set temperature of 21 °C are 28% in electric energy. The variation of room set temperatures revealed that the savings could increase up to 31% when only one of the apartments demands a high room temperature. However, the largest share of the energy saved is due to the elimination of DHW circulation.

The measurements showed that an individual adjustment of the control of the individual swarm participants in response to a swarm signal is technically feasible and already leads to a reduction of the grid consumption in the selected and tested week.

The final simulations of the overall system show that - in addition to the savings achieved through the use of decentralized systems - an additional reduction in grid consumption of up to 5% can be achieved by increasing self-consumption by 11% to 17%.

Acknowledgements

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References

- [1] Norm SIA 385/1. Anlagen für Trinkwarmwasser in Gebäuden - Grundlagen und Anforderungen
- [2] Vetsch B, Gschwend A, Bertsch A. “Warmwasserbereitstellung mittels Waermepumpen in Mehrfamilienhaeusern”; 2012
- [3] Bundesamt für Statistik BFS. «Allgemeine Übersicht «Gebäude» 2019» Bundesamt für Statistik. 10. Oktober 2020. <https://www.bfs.admin.ch/bfs/de/home/statistiken/bau-wohnungswesen/gebäude.assetdetail.17924951.html>
- [4] Mojic I, Crameri S, Caflisch M, Carbonell D, and Haller M. “Reference Frame-work for Building and System Simulations: Multifamily Reference Building.” SPF Institut für Solartechnik, HSR Hochschule für Technik Rapperswil; 2019
- [5] Norm SN EN 16147:2017. Waermepumpen mit elektrisch angetriebenen Verdichtern - Pruefungen, Leistungsbemessung und Anforderungen an die Kennzeichnung von Geräten zum Erwaermen von Brauchwarmwasser
- [6] Haller MY, Haberl R, Persdorf P, Reber A. “StorEx – Theoretische und experimentelle Untersuchungen zur Schichtungseffizienz von Waermespeichern.” Rapperswil: SPF Institut für Solartechnik; 2015
- [7] Haberl R, Tuerk O, Bohren A, Haller MY. “DHWStrat – Methode zur Bestimmung der Schichtungseffizienz von Warmwasserspeichern. ” Rapperswil: SPF Institut für Solartechnik; 2021