Modular Refurbishment of multi-family Houses with PVT-PCM Heat Pump Systems and self-learning Energy Management

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Abstract

This paper presents a retrofit concept, especially for multi-family houses, where the two retrofit measures are decoupled in time. The heating system is based on a hybrid system with a PVT-driven heat pump and an energy management system that ensures the dynamically optimized use of the different energy sources in terms of minimized CO_2 emissions and costs. The renovation concept consists of supplementing an existing gas boiler with a heat pump with SOLINK PVT collectors in the first step. If necessary, the gas boiler can also be replaced with a small investment. In a typical dimensioning, the heat pump capacity is 50 % of the maximum heating capacity, but supplies - partly in parallel operation - about 80 % of the heating energy over the year. If the building envelope is renovated in a second step, the share of the gas boiler can be reduced to zero. However, no energy management solutions are yet available on the market with which optimized and monitored operation with minimized grid power consumption can be realized in a simple manner, especially in multi-family houses and quarters. Hence a predictive and self-learning energy manager has been developed and implemented as cloud-based service. The functionality of the energy manager is investigated and proven on the basis of three properties. In a simulation study, a typical renovation process of a multi-family house is shown in two steps.

Keywords: modular refurbishement, PVT, heat pump, predictive energy management

1. Introduction

According to the Paris Climate Agreement, climate neutrality is required for Germany by 2035 (Rahmstorf, 2019). In Germany, buildings and quarters account for around 35 % of energy consumption, of which over 90 % is used to provide heat (BMWK, 2022). In particular, the three million medium-sized multi-family houses (3 - 12 housing units) are responsible for about 37 % of about 105 million t CO2 emissions of the German residential building stock (Mauch, Greif, 2021). Overall, only 13.6% of all German buildings are fully renovated or new buildings (Metzger et al., 2019). In order to achieve the climate target in this sector, a significantly greater and more consistent renovation rate is required above all. This involves, on the one hand, the replacement of fossil-fuel heat generators and, on the other hand, the insulation of the building envelope. However, the switch to an efficient low-temperature heating system with a high proportion of renewable energies often fails because the building would first have to be renovated to reduce the heat demand and the temperature level of the heating circuit. Coupled with the lack of suitable energy management, this leads to high coverage shares of fossil or purely electrical redundancy systems.

The paper is structured as follows: In section 2 the two-stage refurbishment concept with PVT is presented. The impact on energy savings and CO2 emissions is discussed by means of simulation results. Some first impressions from real world application of the concept are shown. Section 3 focuses on the predictive, self-learning energy manager. Results from the cloud based implementation in properties are discussed.

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2. Two-stage refurbishment concept with PVT

2.1 General concept

Besides the problem of missing low-temperature heating systems, the use of heat pumps often fails, especially in densely built-up urban areas, because ground probes or ground heat exchangers are not possible or desired, while air-source heat pumps are not target-oriented due to noise emissions and/or high-power consumption. Special PVT heat pump collectors (SOLINK) with heat transfer surface on the back side can be used as a sole, efficient, and silent heat source for heat pumps due to their high heat transfer capacity to ambient air (Leibfried et al., 2019). At the same time, they produce electrical power - due to the cooling on the back side with higher yield than pure PV modules.

The renovation concept consists of supplementing an existing gas boiler with a heat pump with SOLINK collectors and the substitution of the sensible thermal energy storage (TES) by a TES using phase change materials (PCM) in the first step. If necessary, the gas boiler can also be replaced with a low investment volume. In a typical dimensioning, the heat pump capacity is 50 % of the maximum heating capacity, but supplies - partly in parallel operation - about 80 % of the heating energy over the year. If the building envelope is renovated in a second step, the share of the gas boiler can be reduced to zero. The renovation concept is sketched in Fig. 1.

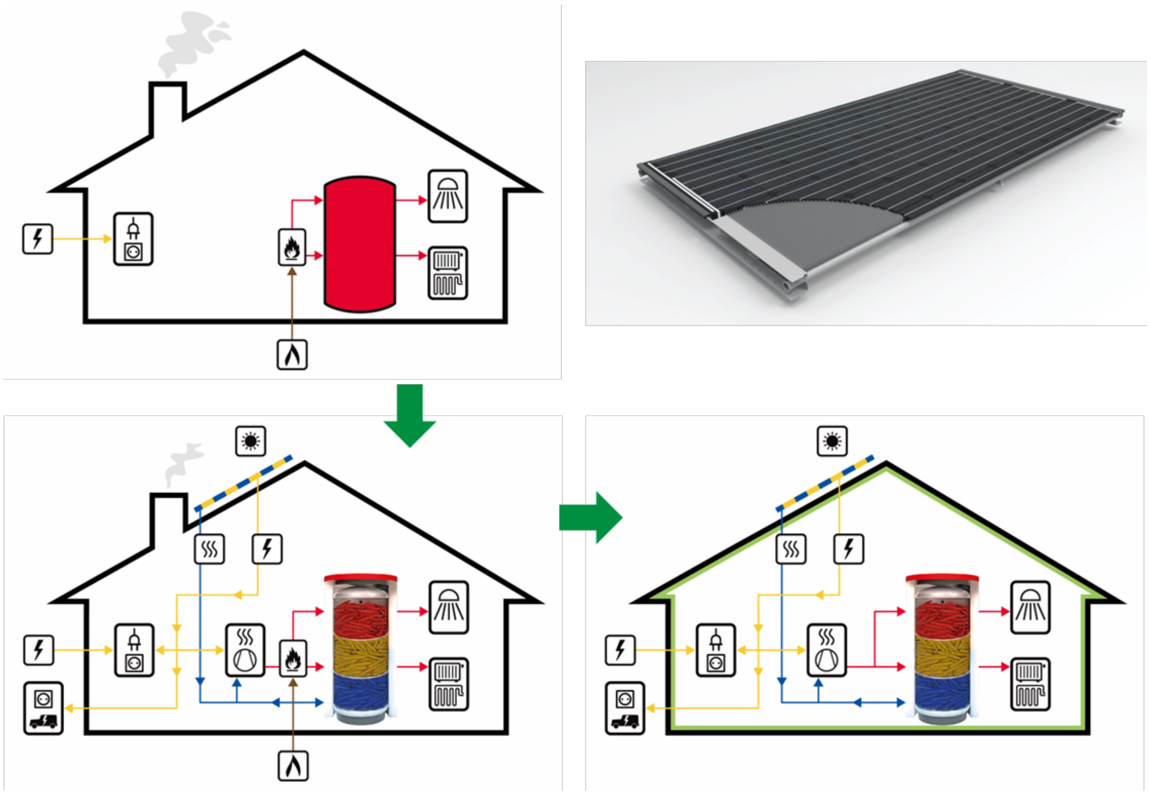

Fig. 1: Two-stage refurbishment:
left: uninsulated building envelope, SOLINK heat pump combined with peak-load gas boiler;
right: insulated building, full supply with SOLINK.

SOLINK heat pumps represent a third class of heat pump systems, now proven in over 1000 installations, alongside ground-source/groundwater-coupled heat pumps and air-source heat pumps. SOLINK systems ensure that the decarbonization of heating technology is accompanied by the necessary increase in renewable electricity production.

The use of PCM-TES instead of sensible TES has the following advantages: (1) A high specific storage capacity allows the installation of storage units even in small installation spaces. In this way, energy management can be used to selectively shift heat pump operation to favorable times and to temporarily store the heat that is not needed. (2) In contrast to conventional water-based buffer TES, the temperature of PCM storage tanks does not rise significantly, so that the efficiency of the heat pump remains consistently high. A narrow temperature window is particularly relevant because in existing buildings even higher flow temperatures are required in the heating system. (3) Different temperature levels can be realised in one storage tank, for example for radiator or surface heating on the one hand and for domestic hot water supply on the other.

As part of the SOLINK project funded by the DBU, it was shown that SOLINK heat pumps in single-family and multi-family homes achieve comparable, and in some cases better, economic efficiency than air-source or ground-source heat pumps combined with a PV system. The PVT collectors, when typically sized, produce in a year the electrical energy that the system consumes. Although most of the electricity is produced when there is no demand for heating but hot water, with appropriate load management with heat and battery storage, 50% or more of the electricity demand can still be met directly. In the previous studies and in the following ones, the use of self-generated electricity for households/tenants in multi-family houses has not yet been taken into account, as the current bureaucratic requirements for this are a deterrent for many landlords. The economic efficiency can therefore be improved even further if households/tenants also use their own electricity.

2.2 Simulation of a step-by-step redevelopment

In a simulation study, a typical renovation process of a multi-family house was mapped in two steps. Tab. 1 shows the boundary conditions on which the simulation study was based.

Tab. 1: Ambient conditions, building and heat generator for simulation study

Redevelopment stage	Unit	unrenovated	hybrid system	Renovated building without gas
Location		Würzburg	Würzburg	Würzburg
heated living space	m²	800	800	800
Heating demand	kWh/a kWh/(m² a)	77400 97	77400 97	43000 54
Warm water withdrawal Warm water heating demand	l/d kWh/a	1450 22080	1450 22080	1450 22080
Orientation / inclination collector field		-	South / 40°	South / 40°
General electricity (uses PV yield) [1]	kWh/a	6000	6000	6000
Hot water preparation		Central WW heating, 60°C circulation	Four-wire network, decentralized Fresh Water, 50 °C circulation	Four-wire network, decentralized Fresh Water, 50 °C circulation
Heating circuit temperatures FT/RT	°C	60/50	60/50	40/35
Gas boiler power	kW	40	40	-
Heat pump capacity (two-stage) for B0/W35 / B-15/W35	kW	-	34 / 23	34 / 23
Area of SOLINK PVT collectors	m²	-	79	79

[1] General electricity excludes the household electricity in the appartments

In the fully refurbished Stage 3, a reduction in the heating requirement of 45 % is assumed. The existing heating surface then only has to transmit significantly less power, so that the flow and return temperatures can also be reduced. The simulations were performed with Polysun. Fig. 2 and Fig. 3 show the hydraulics modeled in each case. In all three cases, a 1000 l buffer tank is provided for the heating circuit and another for the hot water preparation.

Annual simulations were used to calculate the reductions in consumption costs and CO_2 emissions caused by the heating system. The following assumptions were made:

- Energy price heat generator (gas): 6 cents/kWh
- Energy price heat generator (electricity): 22 cents/kWh
- Energy price auxiliary energy (electricity): 29,2 Cent/kWh
- Feed-in tariff: 9,03 Cent/kWh
- CO_2 factor electricity: 537 g CO_2eq/kWh
- CO_2 factor gas: 202 g CO_2eq/kWh

When calculating the costs, the feed-in tariff was deducted from the consumption costs. For CO2 emissions, on the other hand, the CO2 credit from PV feed-in was not taken into account.

Fig. 4 shows the annual CO_2 emissions and operating costs of the three stages. The first renovation stage reduces CO_2 emissions by 37%, the second by 65% compared to the baseline. This does not take into account CO_2 avoidance by feeding PV electricity into the grid. The cost savings - here considering the feed-in tariff - are similar: 39% in the first stage, 67% in the second. This corresponds to CO_2 emissions of 11.2 kg CO_2 per m2 of living space and thus achieves the target value of ≤ 12 kg CO_2/m2 for residential buildings in the existing stock which corresponds to the target of maximum global warming of 1.5 °C.

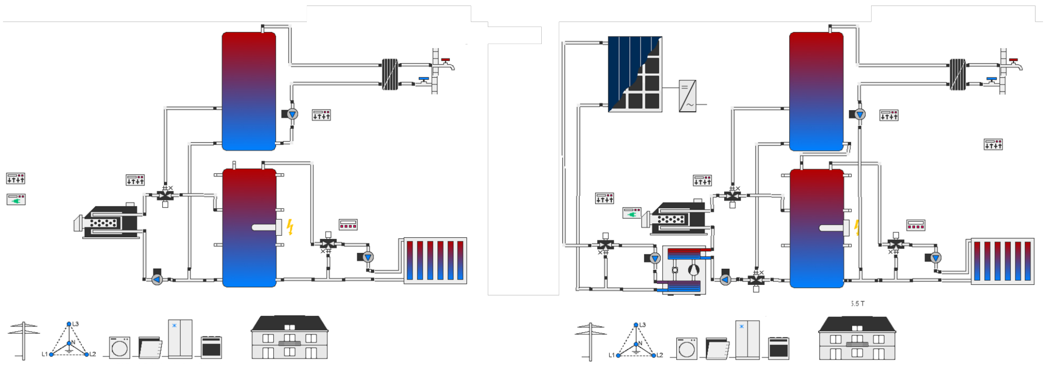

Fig. 2: Hydraulic schemes shown in simulation: left unrefurbished with gas boiler, right with hybrid system: heat pump with SOLINK PVT collectors and gas boiler connected in series.

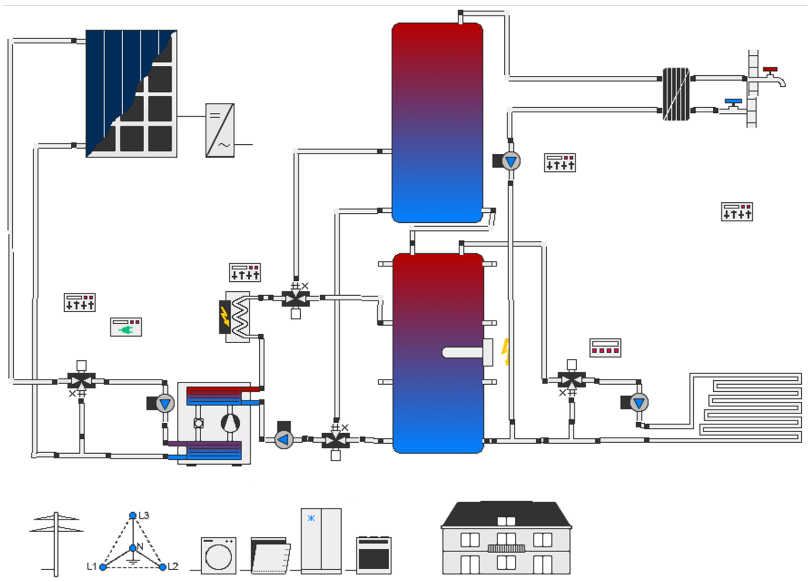

Fig. 3: Hydraulics of the second renovation stage for monoenergetic heat pump operation. The return of the circulation line for hot water preparation is connected to the heating buffer tank at the bottom. Due to this optimized connection, the heating buffer tank can also be used for energy management, i. e. storage heating in case of PV surplus, in summertime hot water operation only.

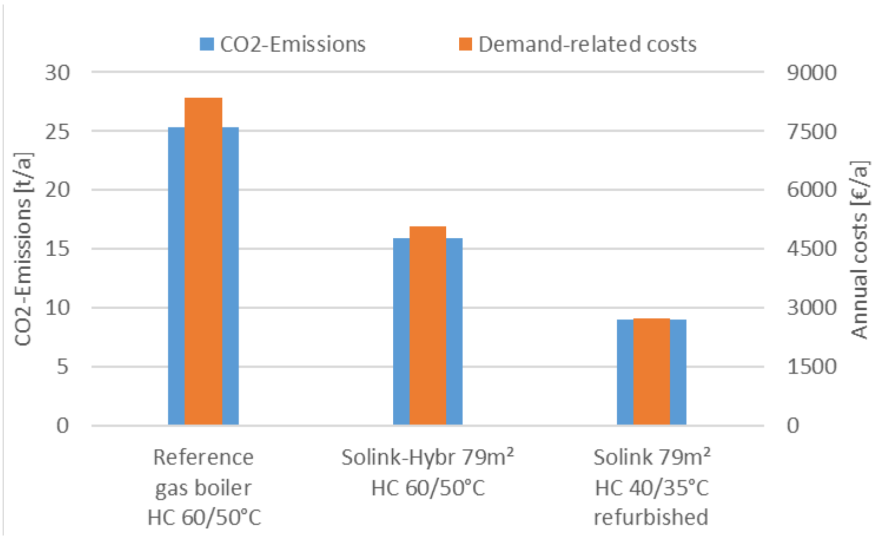

Fig. 4: Costs and CO_2 emissions of the baseline condition and the two refurbishment stages.

In the first refurbishment stage, the gas boiler supplies only 22 % of the annual heat demand, 78 % comes from the SOLINK heat pump. The reason that the costs and emissions in the fully refurbished stage do not decrease further compared to the first stage is that the total heat demand is not halved, but still accounts for 65 % of the consumption in the first refurbishment stage. Heating consumption drops to 55%, but hot water consumption remains the same. Also, the better thermal insulation leads to a reduction of the heating operation in the transition period - i.e. the times that could also be supplied very efficiently with heat pump and PVT.

Fig. 5 shows the energy consumption of the three variants in detail as well as important key figures. The self-consumption shares of stage 2 and 3 is about 40 % in each case, i.e. almost half of the electrical energy produced by the SOLINK collectors is used directly for the heating system or for general electricity. If the PV yield were also used directly for households, this share and thus also the economic efficiency could be increased even further. The prerequisite for this to be implemented in practice is that the German government fulfills its obligation to adapt the EEG in this respect in conformity with European law, so that electricity produced in a building can be used directly without bureaucratic hurdles and levies. The German government is currently (early 2023) in the process of changing the rules so that all electricity consumed by all households can initially be covered by that produced locally, without triggering a huge amount of bureaucracy.

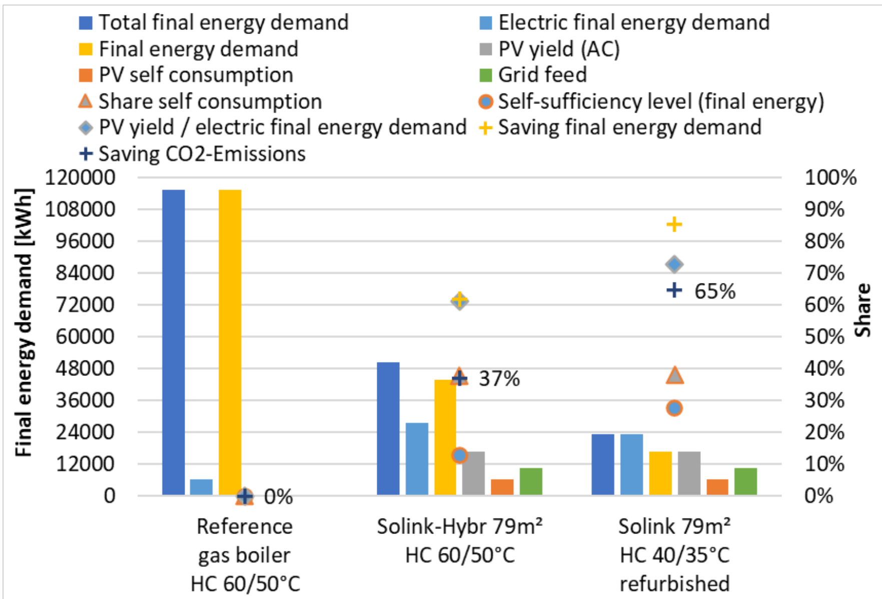

Fig. 5: Energy consumption and key figures of the three variants (see also Table 1)

Total final energy demand	Total consumed energy (electricity and gas)
Final energy demand	= Total final energy demand - PV Self consumption
PV Self consumption	Part of the energy produced by PV which has been directly consumed
Share self consumption	Relation PV Self consumption to total PV yield
Self-sufficiency level (final energy)	The share of the annual final energy consumption that is directly (simultaneously) covered by PV output
Saving final energy demand	Savings in relation to the reference, the gas boiler (electricity and gas added).

Table 1: Definition of the key figures shown in Fig. 5

The result of bivalent systems, here the partially renovated "Solink Hybrid" variant, depends strongly on the control concept in terms of cost and CO_2 savings. Here, a bivalence point dependent on the outdoor temperature with parallel operation was applied: the boiler is only enabled in addition to the heat pump below 0 °C ambient temperature. Furthermore, a simple non-predictive energy management is implemented: If the PV grid feed-in exceeds a threshold, the set temperature of the heat pump, with which it heats the buffer tank, is raised.

2.3 Real application

The heat supply of an apartment building of the Volkswohnung Karlsruhe, which was built in 1963 and renovated in the 80s and 90s, was renovated in 2020 with a SOLINK heat pump and a peak load gas boiler. The brine heat pump has an output of 43 kW_{th} (B0/W35), the peak load gas boiler has an output of 60 kW_{th}, and the SOLINK collector array has an area of 200 m2. Fig. 6 provides an impression of the SOLINK PVT collectors.

The system is metrologically supported by Fraunhofer ISE as part of the *Smart Quartier Karlsruhe-Durlach (SQ-Durlach)* project.

Fig. 6: Transport of SOLINK collectors to the roof of the apartment building (left). SOLINK collectors installed on the roof (one half of the roof and one half of the field) (right)

2.4 Summary and conclusion

SOLINK PVT heat pump systems enable the use of efficient heat pumps even in densely built-up urban areas. The decisive advantages over an air-to-water heat pump with PV system are the higher system efficiency and the absence of noise pollution. Compared to ground-source heat pumps, there are no restrictions due to space requirements or geological prerequisites for drilling. In connection with a temporally decoupled renovation of heating technology and building envelope, they open new possibilities for the energetic renovation of existing buildings.

3. Predictive, self-learning energy manager

Previous control concepts for heating systems are not designed to operate various components in a network or in a quarter in a holistically energy-optimised manner. In order to ensure energy-efficient operation and the highest possible degree of energy autarky even with changing utilisation concepts or energy demands - for example, after thermal insulation - a self-learning energy management system is presented in this work. For this purpose, the energy manager developed in the project dynOpt-En (dynOpt-En, 2022) is to be used locally in the individual properties.

3.1 Concept of the energy manager

The basic concept of the optimizer is illustrated in Fig. 7. The energy manager uses a prediction algorithm to optimise heat generation in buildings and quarters. For this purpose, the optimisation continuously calculates consumption forecasts from the meter data available for energy billing in combination with weather forecasts and other sensor data. These are used to optimally match different heat generators to each other, in addition to heat pumps and gas boilers, also CHP units, each combined with PV or solar heating systems.

The optimisation algorithm requires no complex and individual programming and only a small number of sensors. The basic algorithmic principle of the optimizer is nonlinear model predictive control. The single components of the energy system (PV(T), heat pump, CHP, heat/electricity storage) are modeled by simple static equations resp. 1st order storage models.

The optimizer has an internal prediction horizon of e.g. 36 hours. The internal time sample time of the predictor is 1 hour. The optimization calculation typically takes less than a minute and is updated e.g. every 10-15 minutes.

It is important to note that the optimizer does not replace the basic control of the aggregates. The result of the optimizer are "activation commands" for the individual aggregates (heat pump for heating or cooling, CHP, battery charging). For modulating heat pumps, the activation level is also optimized. The activation commands are also transmitted to the metering service provider via Internet interface. The latter implements the activation commands via its connection to the actuator system in the property. This is done, for example, via relays or, in the case of heat pumps, via a Smart Grid Ready interface (SG Ready interface for short)

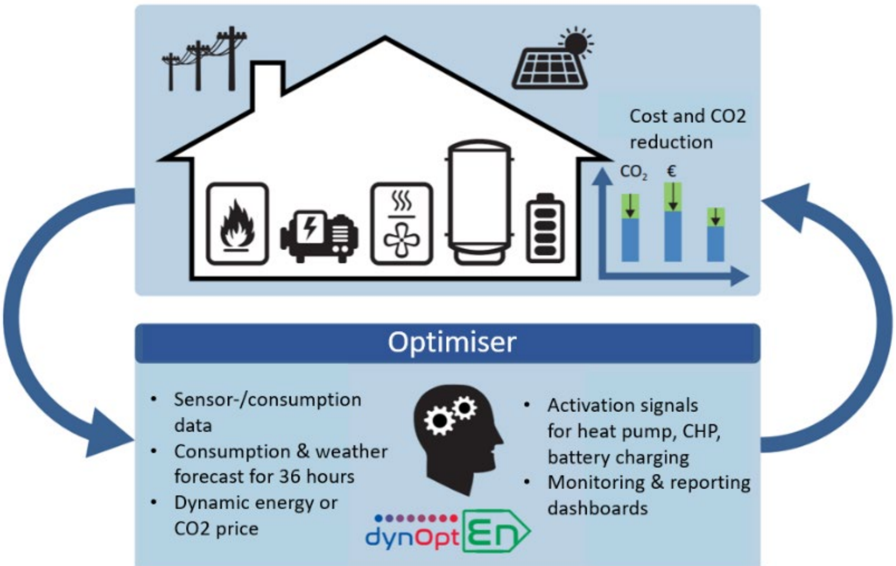

Fig. 7: Basic concept of the predictive energy manager

3.2 Cloud-based implementation of the energy manager

The consistent design of the energy manager as an online cloud service means that hardly any on-site installations are necessary. All data are available via data interface (e.g. REST API). Via a gateway, the data from the meters already available for consumption billing are transferred in 15-minute resolution to the energy manager, which runs on an external server. Via the gateway and interfaces provided for this purpose, such as the SG-Ready interface of a heat pump, the operating request for the heat generators is also set. For this purpose, either gateways can be used as a plug-and-play solution or already installed data collectors and controls can be integrated. Energy management can thus be offered as a service of the metering service. As a further service, the monitoring of energy consumption and costs can take place with a comparison of the real values with those expected for the respective weather conditions.

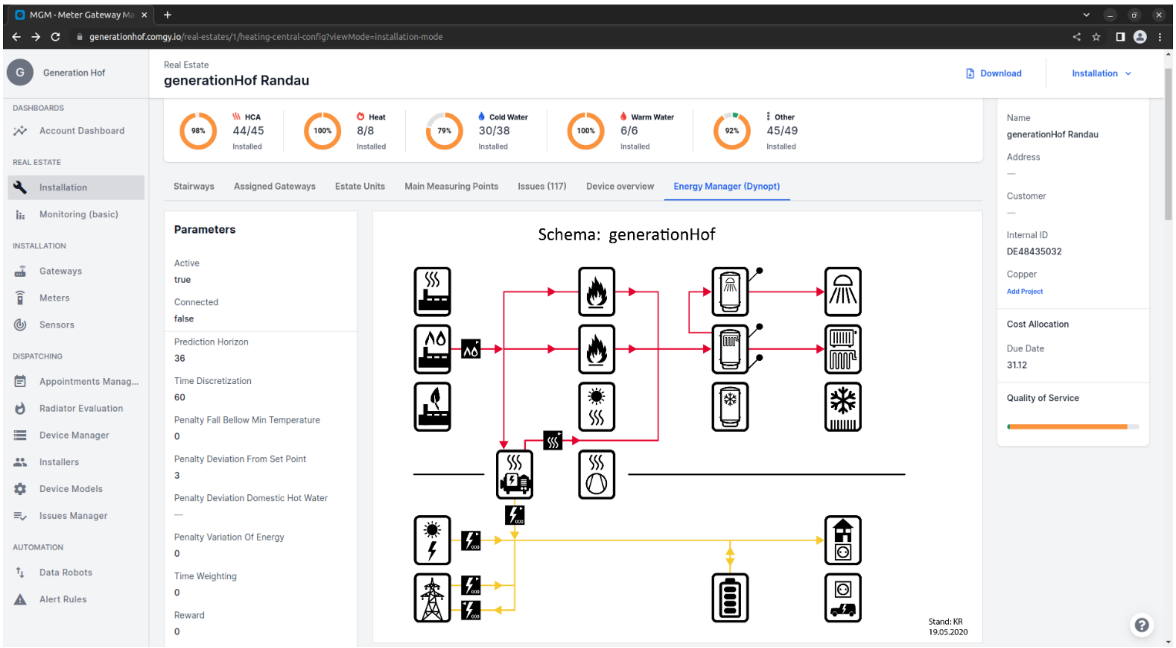

Fig. 8: Cloud-based portal for plant configuration and parameterization of the optimizer

The plant structure of the properties can be stored with graphic symbols via a web-based portal (Fig. 8). Here, the physical and control linkage of the energy generators with the energy storage systems and the main consumers is mapped - thermal and electrical in each case. Via the graphical user interface, meters and sensors are linked to the optimizer. Furthermore, it is possible to adjust parameters of the plant (e.g. volume of the thermal storage) and the optimizer directly at runtime. The suitable communication with the optimizer takes place via a REST-based interface. For this, the configuration model and the external functions of the optimizer have been defined in the form of the Energy Manager API and described in the open standard OpenAPI (OpenAPI, 2022).

Communication with the optimizer is encrypted, since the optimizer API is only accessible via HTTPS. To control access to the assets created in the optimizer, clients - such as the configuration portal - must authenticate themselves with predefined bearer tokens (IETF, 2022). At this point it is important to emphasize that the optimizer only returns "recommended actions" (e.g. setpoints; activation of the heat pump etc.) via the API. The client installed in the property implements these. The optimizer therefore never intervenes directly in the system control.

3.3. Results of the application of the predictive energy manager

The energy manager dynOpt-En is primarily intended for commercial properties such as multi-family houses and quarters in which several components such as heat pumps, PV systems, solar heating systems, gas boilers or CHP units are operated in conjunction with each other. Furthermore, dynOpt-En monitors energy consumption and costs and compares the real values with those expected for the respective weather conditions. In this way, malfunctions can be detected promptly and signaled via a clear visualization. In the project, the functionality of the energy manager was tested on the basis of 3 properties with different system configurations (including PV, heat pump, CHP, thermal and electrical storage; heating and cooling operation was investigated).

In annual simulations it could be proven for an exemplary property with PV and heat pump that by using the predictive energy manager compared to a non-predictive energy manager, the operating costs and also CO2 emissions are reduced by approx. 15% per year. The self-consumption fraction (i.e., the ratio of PV energy used to operate the heat pump to the electrical heat pump energy required) was increased by about 20%.

Thus, the use of the predictive energy manager makes economic sense for larger properties. An essential prerequisite for the performant use of the energy manager is a sufficiently large thermal storage. Especially for the operation with heat pumps, a clean separation between a zone with higher temperatures for water heating and a zone with lower temperatures for heating is necessary. As part of the dynOpt-En project, Consolar Solare Energiesysteme developed a new type of two-zone heat pump storage tank for this purpose (Leibfried et al., 2022).

Fig. 9 shows data from a real property in Lörrach/Germany (period 17 - 24.5.2021). In this property the operation of heat pump has been optimized. A web-based dashboard has been implemented, which visualizes all relevant data (outdoor climate, sensor data, optimizer calculations, activation of heat pump), see Fig. 9.

Furthermore, a live visualization of the "internal optimizer view" was realized. From the monitoring dashboard, the prediction of the optimizer at this point in time can be displayed in a simple way (right mouse click on any point in time). This is shown as an example in Fig. 10. From the selected point in time, the visualization shows the prediction over the next 36 hours. In Fig. 10 it can be seen that the activation of the heat pump is done in an optimized way, so that no activation of the heat pump is necessary during the next day.

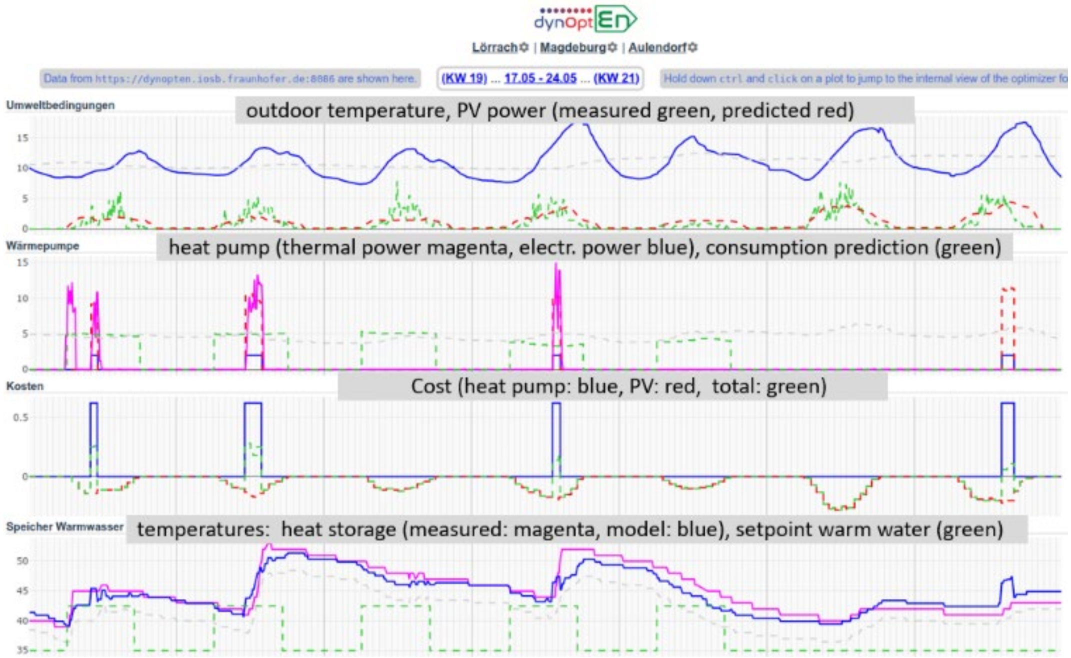

Fig. 9: Data from a real property in Lörrach/Germany with optimized operation of a heat pump (period 17 - 24.5.2021)

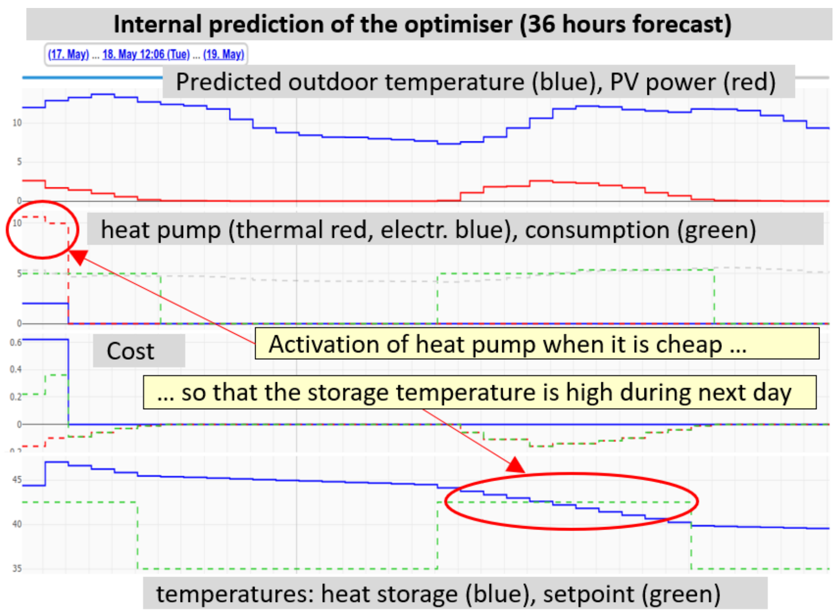

Fig. 10: Internal prediction of the optimiser (data from a property in Lörrach/Germany, period 17 - 18.5.2021)

3.2 Monitoring of key performance and efficiency indicators

For monitoring, a distinction is made between evaluations and presentations for the operator (e.g. housing association) and the end customers. Algorithms for the provision of performance and efficiency indicators have been developed and implemented in clearly arranged dashboards. The key figures (e.g. costs, CO2 emissions, thermal/electrical energy consumption or energy provision) are output in daily, weekly or monthly aggregation. Fig. 11 shows a dashboard for visualizing monthly averages of costs per thermal kilowatt hour, CO2 emissions per thermal kilowatt hour, CO2 emissions of the heat pump and outdoor temperature of a property. From Fig. 11, it can be seen that only in the months of December, January, and February of the study period 2020/2021 does non-renewable energy need to be purchased. During the rest of the period, the predictive energy manager ensures that the thermal energy is provided regeneratively and thus free of charge.

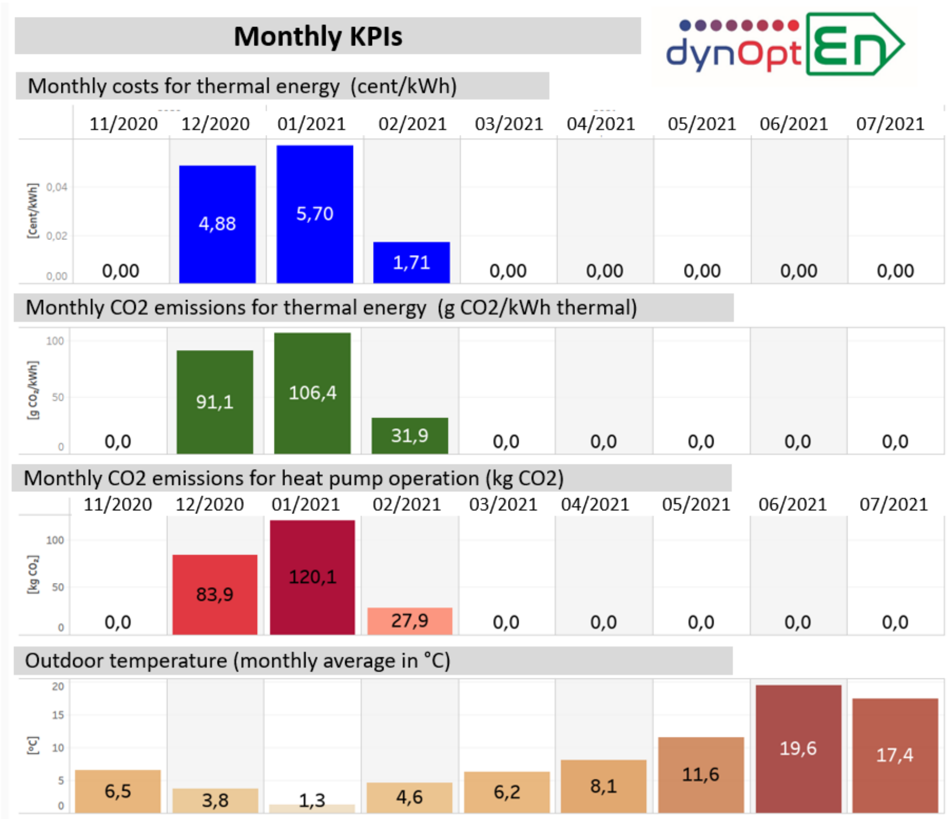

Fig. 11: Dashboard visualizing monthly average values of a property in Lörrach/Germany in the period November 2020 - July 2021

4. Summary and Outlook

4.1 Summary

In this paper we have presented a two-stage refurbishment concept with PVT. In a simulation study, a typical refurbishment process of a multi-family house is shown in two steps: status quo - hybrid operation - full refurbishment. First real results of a multi-family house refurbished with PVT heat pump and gas peak load boiler are presented. Furthermore, a predictive and self-learning energy manager has been developed and implemented as cloud-based service. The energy manager has been deployed in 3 larger properties with different system configurations (including PV, heat pump, CHP, thermal and electrical storage). It has been shown that with the cloud-based service, maintenance-friendly and robust operation is possible. According simulation and experimental results the energy savings of typical properties are approximately 15 %. The energy self-consumption of PV power has been increased by approx. 20%.

4.2 Outlook

To reduce expansion of grids and costs, the autarky of quarters must be increased. This requires a superordinate instance having knowledge about the storage levels, renewable electricity generation potential of the individual properties and about energy prices. In addition, further research is required in the selection and development of PCM suitable for the required temperature range, in optimised heat transfer and in the monitoring of the storage charge level for optimised operation. Therefore, the aim of a planned project is to develop a central energy manager that minimises the energy consumption of the individual properties with regard to electricity grid purchases. For this purpose, the central energy manager of one quarter communicates with the local energy managers of the multi-family-houses and gives incentive signals based on forecasts for generation, demand and electricity price. The central energy manager shall detect changes in user behaviour and energy demand in the quarters (e.g., through refurbishment) and shall adapt the parameterization of the model in a self-learning manner without any extensive adjustments in the central control system. Moreover, the central energy manager shall work on the principle of predictive control with a powerful optimiser. Weather forecasts and predicted consumption (electricity and heat) of the properties are considered. Methods for automated consolidation of measurement data need to be developed to ensure optimal use for the data-driven models. Two-level energy management will then be practically investigated in a multi-family house and virtually tested in a quarter via software-in-the-loop simulation with realistic load cases and scenarios. In addition, the new project aims to reduce the transaction costs of modular refurbishment by digitally supporting the inventory, pre-design, parameterisation of predication models and commissioning.

5. Acknowledgement

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