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Potential assessment of coupling PV electricity with district heating supply of building

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Abstract. The energy transition in Germany is leading to an increasing decentralized generation of electrical energy. In Fact, the feed-in of electrical surplus of PV systems causes a higher load on the electrical grid. Increased local use prevents this. Significant potential for the integration of produced electrical power of PV plants for this purpose exists in the heat supply. This paper describes the development and evaluation of a system solution from the cross-sectoral use of surpluses from PV plants and district heating. The latter is often used to supply urban apartment buildings. According to research on the market situation, independently controlled heating rods are available for converting electrical power of PV plants into heat. However, a coordinated operation of these heating rods with district heating is not possible so far. In this paper different approaches for combining these two heat sources with various hydraulic concepts and system controllers will be developed and evaluated. As a potential assessment, a parameter study on influencing factors (e.g. user behaviour, power size of the components, building characteristics) was carried out by numerical simulations. As one result, the highest potentials arise from the use of a forecast-based charging control of a combi-storage tank. The charging control can be realised with different techniques, either through simple if-then decisions or a model predictive control. This can only use slightly more produced electrical power of PV plants, as it is limited due to the time lag between PV surpluses and heat demand. Predictions of future energy flows are necessary for both approaches but these have relatively high errors for individual consumers and PV systems. The results of the paper shows, that more complex forecast approaches (demanding large data sets) do not perform significantly better than simple forecast approaches (which can deal with smaller data sets). Model predictive control requires a higher forecast resolution and is therefore also more error-prone, thus it is not recommended. The desired relief of the electrical grids can be achieved through local consumption. In addition, the economic implementation and the carbon footprint of such a concept are analysed under local and global (whole energy-system) aspects.

Keywords. district heating, sector coupling, photovoltaic, renewable energies, carbon footprint, model predictive control, residential building forecasts, operation of HVAC-systems
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1. Introduction and boundary conditions

The local use of electrical energy from renewable energy systems is the focus of the implementation of the energy transition due to the limited capacities of the electrical distribution network. This is based on the premise of the decentralization of the energy supply to use if possible the resources locally. Only surpluses (produced power of the PV plant minus household electricity demand) are to be exchanged via an energy network. In the heat supply there is great potential for the local integration of produced electrical power of PV plants, since a large proportion of the final energy requirement is implemented, especially in residential buildings [1]. In the following, an approach for converting PV surpluses into thermal energy to supply heat to an apartment building (fig. 1) is described and analysed with regard to its technical, economic and ecological potential. The investigation builds on the analysis by Altenburger [2]. The parameters of the building, composed of four apartments, are shown in tab. 1. The model building represents a newer building with an energy rating of 44 kWh/m²a.

Tab. 1 – key facts of the building

	value
cross building area	905 m^2
number of apartments	4
heated area per apartment	110 m^2
specific heating energy value	44 kWh/m^2
installed PV power	22 kW
total heating demand per year	19.347 kWh/a
total domestic hot water demand	6.027–8.378 kWh/a
total building electricity consumption per year	11.350-15.800 kWh/a

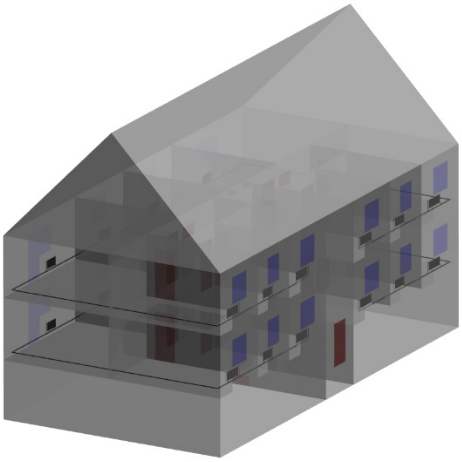

Fig. 1 – apartment building

The aim is to use the PV surpluses as much as possible locally. A district heating supply with central drinking water heating was assumed. Based on the initial analysis and potential assessment of the approach, a heating rod in a storage tank is used to convert the electrical energy. Fig. 2 shows the analysed hydraulic scheme.

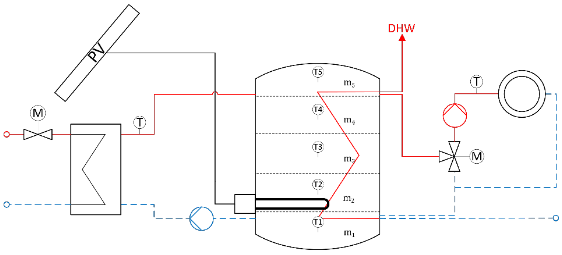

Fig. 2 – analysed hydraulic scheme of this investigation

2. Methodology

To estimate the potential, simulations were carried out with the numerical simulation program TRNSYS-TUD [3]. The model represents a characteristic multi-family house with a PV system, which is installed on the roof, the hydraulic scheme of fig.2 and typical requirement profiles in terms of domestic hot water and household electricity consumption. Variations were made with regard to the orientation of the building and the size of the PV system. As weather data, the test reference year 04, with the reference location of Potsdam [4], was used. An idealized forecast was used to forecast the heat demand. The numerical analyses were carried out with a time step size of $\tau = 60$ s.

3. Control concepts

The integration of PV surpluses in the heat supply requires the implementation of various subtasks in the control. As part of the investigation, the focus was on regulating the heat supply from a district heating station and a heating rod. The flow temperature in the heating circuit is regulated according to the outside temperature. The electronic regulation of the heating element is able to implement the required output immediately. The control concepts to be considered are described below.

3.1 Independent ad-hoc control

At the beginning, a market analysis of the existing systems was carried out. This showed that systems that work independently from each other are available on the market. Based on this knowledge, the approach of the independent ad-hoc controlling system was developed. To do this, it is necessary to set loading limits for the thermal storage tank in relation to minimum and maximum temperatures. These are defined as the maximum temperature of the storage tank and as the minimum flow temperature. If the minimum flow temperature at the storage tank is not reached and the heat supply is restricted, the district heating is used to charge the storage tank (water tank). The charging process ends when the minimum flow temperature is reached at the bottom of the tank (fully charged tank). Regardless of this, the heating rod converts the PV surplus that occurs up to its nominal output into heat. The heating rod is switched off when the maximum storage tank temperature is reached, in addition to a switching hysteresis of $\Delta\vartheta = 3$ K. The control takes place without the use of a forecast.

3.2 Forecast-based ad-hoc control

A further development of the approach described above is the forecast-based ad-hoc control. The aim is to reduce the use of district heating to load the storage tank in order to be able to convert a higher proportion of the PV surplus into heat and to use it. For this purpose, with sufficient forecasted PV power, the switch-off limit for district heating operation is changed so that the charging process is stopped when the minimum flow temperature is reached at a higher temperature sensor. In this consideration, a thermal storage tank with five sensors (see fig. 2) was used. The top sensor

corresponds to the flow temperature and the second highest sensor is used as an alternative sensor for the switch-off point, in this example. Therefore, the storage tank is only charged to approximately 20 % by district heating. As a limit for the adjustment of the charge limits, the ratio between the forecast PV surplus and the heat demand is used. The criterion is defined as $\varphi_{\text{PV sur lim}} = 0{,}1$.
If $\varphi_{\text{PV sur}} > 0{,}1$. The load is adjusted, otherwise the procedure is analogous to the independent ad-hoc control. For the described regulation, forecasts with only daily resolution are sufficient, whereby the regulation is tolerant of incorrect prognoses due to its use as a limit value. A completely combined control with the integration of an optimization is not possible with this approach.

3.3 Model-predictive control

A common approach to regulate systems with temporally variable influences and target values is the use of a model-based predictive control (MPC). With this, it is possible to optimize the schedule within a prediction horizon based on the current system status and the predicted requirements as well as the predicted produced power of the PV plant. The aim of the analysis is to minimize the district heating consumption, as this allows the maximum proportion of the PV surplus to be used. The control concept and the creation of schedules is based on approaches for CHP systems and heat pump systems [5], [6]. The creation of the schedule is carried out on a rolling basis for each time step of the entire prediction horizon. The first time step is always implemented in a subordinate control system, so that after this time step the new (then current) system status can flow in the calculation again. Due to possible forecast deviations, a condition monitoring of the storage tank has to be integrated in the continuous implementation, which ensures the use of the storage within its temperature limits.

4. System assessment

The system assessment shows the technical potential of the different control concepts, presents an ecological and economic evaluation and considers the effects of the system solution on upstream energy systems.

4.1 Comparison of the controller concepts

Overall, different variants for user behaviour (domestic hot water and electricity consumption) were analysed. The evaluation is based on the mean value and the fluctuation range of the results of a selected variant. More information is documented in [2]. The aim of the investigation is to maximize the locally used proportion of electricity (share of self-consumption) as well as the proportion of heat demand generated by PV surpluses. It is also important to analyse what proportion of the PV surplus can be integrated into thermal use. This is in addition to the self-consumption proportion, which also includes the produced power of the PV plant used as household electricity consumption. The results are shown in tab. 2. The values in brackets represents the fluctuation range of the analysed variants in relation to thermal and electrical consumption of the building (Tab. 1).

Tab. 2 – Results of the controller comparison (mean value and range)

concept	PV - quantity of heat in %	el. self-con-sumption quantity in %	usable quantity of PV surpluses in %
indepen-dent ad-hoc control	22,8 (20,1 – 25,6)	69,4 (61,7 – 77,6)	58,0 (51,7 – 65,4)
forecast ad-hoc control	24,9 (21,7 – 28,5)	73,0 (66,2 – 80,8)	63,1 (57,4 – 70,3)
model-pre-dictive control	25,8 (22,2 – 29,5)	75,0 (68,3 – 82,4)	65,7 (59,9 – 72,6)
theo-retical limit	26,5 (22,2 – 30,9)	75,9 (62,5 – 92,2)	67,0 (60,2 – 82,0)

The MPC concept achieves the most efficient local use of the PV surplus. However, the increase compared to the two simpler concepts is small. This is due to the problem of the time difference between the highest PV generation in summer and the highest heat consumption in winter. The concept with the forecast-based ad-hoc control is therefore to be preferred due to the lower complexity.

In order to determine a reference, a theoretical limit case was defined. This describes a daily balance analysis in which the PV surpluses can be used up to the level of the heat demand. The district heating provides the missing energy in the daily heat balance. If the PV surpluses exceed the heat demand, they are fed into the electrical grid. It can be seen that the mpc concept is close to the defined limit case. The deviations are justified by restrictions in the storage tank temperatures, the output of the heating rod or by the use of daily amounts in the theoretical limit. The fig. 3 shows the course of a year and the temporal offset of the heat demand, the PV generation and the PV surpluses. It can be seen that a large part of the PV surplus cannot be used in summer.

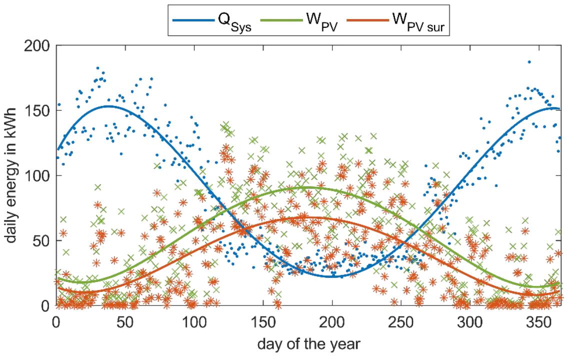

Fig. 3 – annual profile of daily key values

4.2 Carbon footprint / Economic valuation

In the following, the system with forecast-based ad-hoc control is analysed according to its carbon footprint. For a holistic view, the carbon emissions from district heating, the purchase of electrical energy and the PV output were determined. In addition, for the greenhouse gas emissions in the life cycle of the PV system, a credit was used for the feed-in of electrical energy compared to the displacement electricity mix. The boundary conditions for the CO_2 emissions are [7], [8], [9]:

- District heating: 253,2 g/kWh
- PV electricity: 67,0 g/kWh
- Electricity from the grid: 401,0 g/kWh
- Displacement mix: 860,0 g/kWh

The displacement mix refers to the factual displacement of amounts of conventional electricity by renewable energies. This is primary the generation of hard coal and lignite power plants in condensation mode. In relation to the reference variant, there was an average increase in global CO_2 emissions of approx. 150 %. It means that from an environmental point of view, a local use of the PV surpluses in the heat supply is not recommended. This is a contradiction to the goal of decentralizing the energy supply from the necessity of relieving the load on the electrical grid. The reason for this result is the assumption of a significantly higher reduction in CO_2 emissions when feeding into the electrical grid compared to district heating. In the future, a decrease in CO_2 emissions from the displacement electricity mix is to be expected. However, these static assumptions do not cover situations with an oversupply of renewable energy systems, in which these energy sources must also be regulated. This means that if too much EEG electricity is currently being fed into the electrical network, these systems will be switched off. This leads to an improvement in the ecological balance, which was not considered here.

In addition to the technical potential and the ecological consideration, the economic profitability is decisive for the use of such a system. There are various costs for the energy supply of the building, the costs of district heating (energy price), the credit for the feed-in of PV electricity have a special influence. It should also be noted that the system solution creates additional installation costs of around 116 – 200 € per year (annual cost of installation in 15 years of operation). Fig. 4 shows the previous development of the feed-in compensation and the district heating energy prices since 2010. Furthermore, a forecast based on the development since 2014 is assumed for the next few years. For the district heating energy price, the development with rising costs for greenhouse gas emissions is also shown [10].

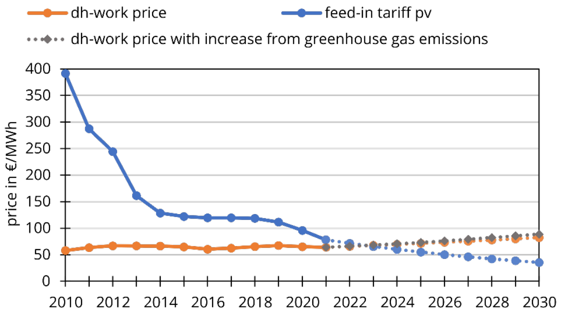

Fig. 4 – previous and forecast of PV and district heating (dh) prices

In order to clarify the knowledge of the necessary relationship between the district heating energy price and the feed-in price, a sensitivity analysis was carried out. The scenarios are shown in tab. 3 and tab. 4.

Tab. 3 – scenarios of district heating energy price.

scenario	energy price in €/MWh	description
current	64,03	mean current price
current + 10 %	70,43	increase of 10 %
current + 25 %	80,04	increase of 25 %

Tab. 4 – scenarios of PV feed-in energy price.

scenario	energy price in ct/kWh	description
1	9,45	status 02.2020
2	7,41	status 02.2021
3	6,63	10 % reduction
4	5,46	25 % reduction
5	3,51	50 % reduction

The result of the sensitivity analysis is shown in fig. 5. In this, the area of the amortization costs of the additional system costs is coloured green. It becomes clear that the system solution will be economical in the next few years with rising district heating prices and falling feed-in compensations. With the current conditions, a positive economic balance is not possible.

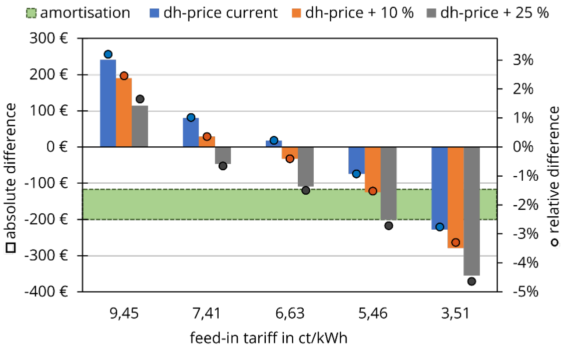

Fig. 5 – relative additional costs in comparison to the reference

But in the next few years, the point of district heating parity will be reached. From this point, the local use of PV electricity to replace district heating is preferred. Based on the relative costs, it can be seen that the resulting saving potential is rather in the low range in relation to the total energy costs.

4.3 Impact on the upstream energy systems

The use of the system solution has effects on the upstream district heating and electricity grid. These are also to be assessed. The investigation relates to the comparison with the reference system based on the consumption or generation profiles.

District heating

With this solution, the total of the annual district heating purchases is reduced by approx. 25 %, as this proportion is covered by the produced power of the PV plant. But the reduction is not evenly distributed. On days with no PV generation, the entire heat requirement must still be covered by district heating. In contrast to this, in summer the district heating requirement is almost completely covered by the PV surplus, which is shown in fig. 6. This results in a higher output fluctuation for district heating between summer and winter.

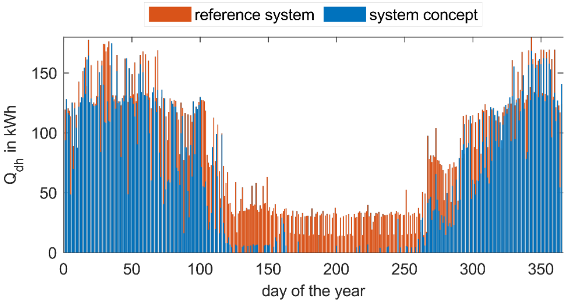

Fig. 6 – comparison of district heating consumption

This reduction leads to a decreasing income of a district heating operator, which creates economic pressure. At the same time, the already existing problem of summer heat surpluses from CHP systems and the competitive situation between various renewable energy sources are exacerbated by the falling district heating sales.

Another point is that the adjusted charge control of the storage tank unit leads to a decrease of the return temperatures in the district heating. This is shown in fig. 7 and results from the shorter charging processes and the reduced consumption of district heating in summer.

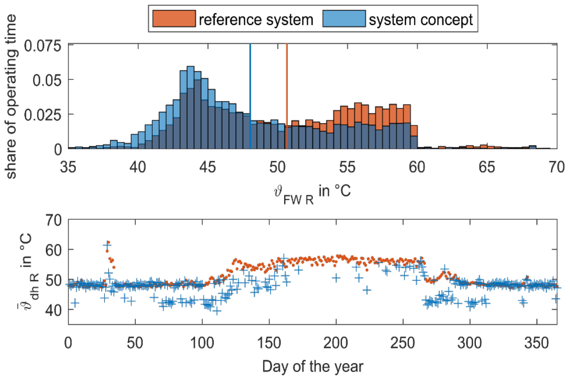

Fig. 7 – effects to the return temperature of the district heating

The figure shows the frequency distribution of the values for the district heating return temperature in 15 minute intervals and their mean values (vertical lines). The annual profile is also shown. The reduction occurs mainly in areas with PV generation. Outside of these times there is no difference in the regulation between the reference system and the system solution. The reduction in return temperatures is positive for the district heating, as the efficiency of energy conversion and energy transport is increased (Lower return temperatures lead to more efficient energy conversion during energy supply).

Electrical grid

There are also effects on the electrical grid. A significant reduction in feed-in can be achieved here through local consumption. This is desired to relieve the distribution in the grid. At the same time, the pre-set system control does not enable a reduction in the feed-in peaks, since local use is only possible with sufficient storage capacity. A time-shifted loading process could solve this problem, but is not implemented in this analysis. Fig. 8 shows the frequency distribution of fed energy in an interval of 15 minutes. The distribution in the annual profile shows that PV surpluses are fed into the grid, especially in summer. In winter, almost the entire PV yield can be used locally.

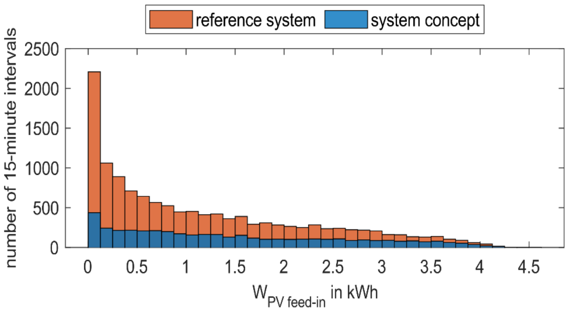

Fig. 8 – Frequency distribution of fed PV energy

As it can be seen, there is a significant reduction in the area of low feed-in of electrical power. This can be explained by the good integration of the PV surpluses in the heat supply in times of high heat demand, if the PV generation tends to be rather low. Nevertheless, the analysis of the feed-in profiles shows that it is possible to reduce the load on the grid.

5. Conclusion

With the combination of a district heating supply using the PV surplus locally and thermally, a cross-sectoral solution for the decentralization of the energy supply and the relief of the electrical grids was analysed. Basically, a model of a representative apartment building was developed, which was implemented in the simulation environment TRNSYS-TUD. From the view of regulation and control, three different approaches were considered. In the case of the modelled apartment building, the use of this control concept only makes sense from a certain installed PV power. Because in the case of low PV generation, an independent charge control of the thermal storage tank for the use of high produced power of the PV plant also generates a very high proportion of self-consumption.

A comparative ecological assessment showed that the current CO_2 balance of the system solution is worse than that of a reference variant with full feed-in of the PV surpluses. The reason for this is the significantly lower saving potential of PV electricity when substituting district heating compared to the displacement electricity mix of the grid. It should be noted that the balance does not include any dynamic processes in the event of limitation of renewable energy systems due to grid overloads.

Furthermore, the economic assessment produces a negative balance, as the feed-in compensations is currently still higher than the district heating energy prices. This will change in the future, so that an economical use of the system solution then seems possible.

Regarding to the upstream energy systems, it could be shown that with a simple technical implementation, the self-consumption ratio of the model building can be increased to approx. 73 % and thus the power feed-in can be significantly reduced. This results in a relevant reduction in the load on the grid. For the district heating, the reduction in demand with a constant maximum heating requirement in winter creates new challenges, for example additional excess heat in summer.

6. Acknowledgement

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7. Symbols and abbreviations

dh	district heating
DHW	Domestic hot water
$\Delta\vartheta$	switching hysteresis
M	actuator
MPC	model-based predictive control
m_{i}	mass
PV	photovoltaic
$\varphi_{\text{PV sur}}$	ratio forecast PV surplus
Q_{dh}	thermal energy from district heating
Q_{Sys}	thermal energy demand
T	temperature sensor
τ	time step
$\bar{\vartheta}_{\text{dh R}}$	return temperature district heating
W_{PV}	electrical power – PV generation
$W_{\text{PV sur}}$	electrical power – PV surplus
$W_{\text{PV feed-in}}$	electrical power – PV feed-in

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Data Statement

The datasets generated during the current study are not publicly available but will be available in the final research paper of the project "TEK-EKG: Thermal-electrical Measurement System for Buildings and districts" in the end of 2022.