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OPTIMAL SIZING OF ACTIVE SOLAR ENERGY AND STORAGE SYSTEMS FOR ENERGY PLUS HOUSES

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Abstract

Buildings generating more energy than they require are a promising possibility to increase the share of renewable energies in the energy matrix. The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety funded projects that provide a proof of concept of residential buildings producing energy beyond their own requirements, the so called "Efficiency Houses Plus" (EHP). The present work builds up on data of one of these buildings to propose an optimization model that minimizes the energy provision costs for a building while achieving the EHP standard. The model considers solar energy systems, a heat pump as well as electric and thermal storage systems. The model is used to determinate system configurations able to achieve the EHP standard under seven different scenarios. The results serve to discuss the relevance of each of the considered technologies for EHPs in the near future.

Keywords: *photovoltaics, solar thermal, heat and electric storage systems, energy plus house, net zero energy building, monitoring, MILP*

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1. Introduction

The European Union (EU) has set the goals of a 20% share of renewable energy sources (RES) in the gross final energy consumption and a reduction of 20% of greenhouse gas emissions in comparison to the levels of 1990 by 2020 (Commission of the European communities, 2007). The EU long term aspirations include a decrease in greenhouse gas emissions of at least 80%, which would imply a share of RES of 75% by 2050 in the gross final energy consumption and 97% in electricity consumption (European Commission, 2011). The building sector has one of the highest potentials to contribute to this goals due to the fact that energy requirements for buildings account for 40% of the total energy consumption in the EU (European Commission, 2010, 2003). The largest share of this energy requirements (66%) can be attributed to energy demand for heating and cooling (Institute of Communication and Computer Systems of the National Technical University of Athens, 2008). Retrofitting measures for the existent building stock and high energy standards for new buildings can contribute to reduce these energy requirements considerably. However the strategy of the EU goes beyond that and the directive 2010/31/EU of the European parliament sets the 31st of December 2020 as the deadline when all new buildings shall be Net Zero Energy Buildings (NZEB).

The general idea behind the NZEB is a highly efficient building that produces as much energy as it would require from the grid or fossil sources to cover its demand over a certain period of time (Good et al., 2015). This is, however, a definition that can be interpreted in several ways and therefore, there is no consensus on the NZEB concept. Sources of discrepancy are, among others, the system boundaries and the weighting factors for the different used energy sources. Extensive discussions on this issue can be found in Marszal et al. (2011) and Sartori et al. (2012). One step ahead NZEBs are the so called "Energy plus houses" or "Positive Energy

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Buildings” (Ionescu et al., 2015). The German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety describes the “Efficiency House Plus” (EHP) as a building, which produces energy from renewable sources beyond its final and primary energy needs in a balance period of a calendar year (Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2012). The balance includes the energy need for space conditioning, building operation and equipment (Bockelmann et al., 2015). This definition has been used to fund several projects across Germany. These projects serve to show that technologies are already available, which allow the construction of EHPs. In the present paper hourly data from one of these EHPs are used to calibrate an optimization model that aims at conceiving energy generation systems, which allow buildings to achieve the EHP standard at the minimum possible cost. The model is applied to generate system configurations in scenarios where the system boundaries and assumptions are changed compared to the reference building. These scenarios serve to discuss the relevance of every one of the considered technologies for energy plus houses in the near future.

The paper is structured as follows: In the next section the main characteristics of the studied EHP are presented. Section 3 describes the optimization model and section 4 the case studies. Section 5 is devoted to results. Finally, in the last section of the paper conclusions are drawn.

2. The Schlagmann-BayWa EHP, monitoring concept and data

The investigated building is a family house located in Burghausen, Upper Bavaria, Germany. The building was inhabited by a three-person household during the entire study period. They were allowed to use the house for residential purposes without any restrictions. The house has two storeys, 176 m² of heated living area, a cellar and an external garage. It was built with massive single-shell brick filled with heat-insulating perlite. The energy certificate estimates that the energy demand for heating corresponds to the German Energy Savings Regulation (EnEV) 40 standard. The EHP is equipped with 10.76 kWp of photovoltaics (PV) (4.28 kWp on the main building’s roof that is oriented towards south and has a 44° inclination as well as 6.48 kWp on the roof of the garage oriented towards east and west with half of the capacity in each direction and a 30° inclination). A 10.8 kWh electric storage system, a 51 m² solar thermal system, an electric car and an automatic steering system are also part of the concept. One additional feature of this EHP is a seasonal warm water storage able to store up to 4000 kWh with a volume of 48,000 L. It is dimensioned to cover the energy need for heating and warm water of the house during winter with solar energy harvested during summer.

The EHP was equipped with monitoring and optimal operation systems. All nodes of the energy system were monitored considering also environmental data inside and outside of the building. Data of more than 120 measuring nodes were stored continuously over two operation years (February 1st 2014 to January 31st 2016). The energy production and consumption of PV, solar thermal systems, heat pump, input and output of the storage systems as well as the energy demand for lighting and appliances, room conditioning, warm water, house operation equipment and the electric car were logged. Afterwards data processing, analysis and visualizing were carried out. Monthly amounts of the measured yields and consumptions (see Fig. 1) as well as the hourly averages and sums of the days per month (see Fig. 2) were investigated.

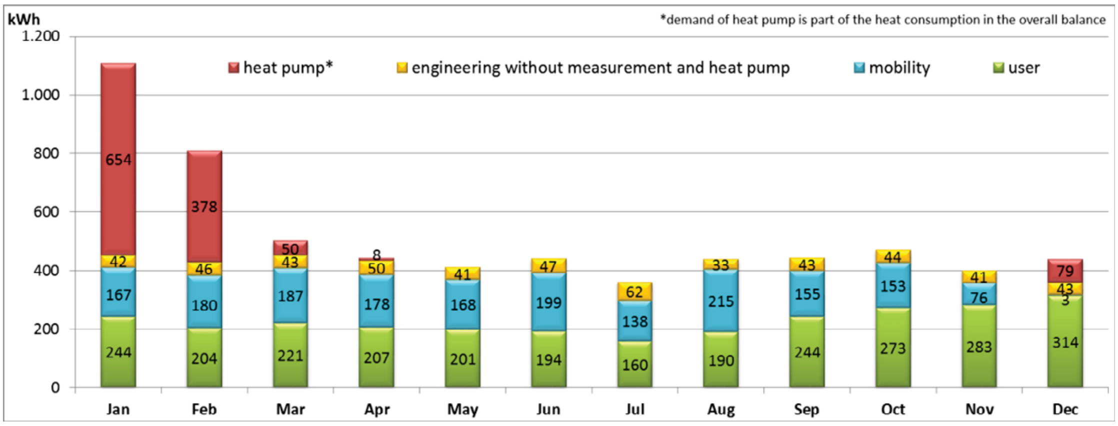

Fig. 1. Electric demand and mobility per month, measured in 2015

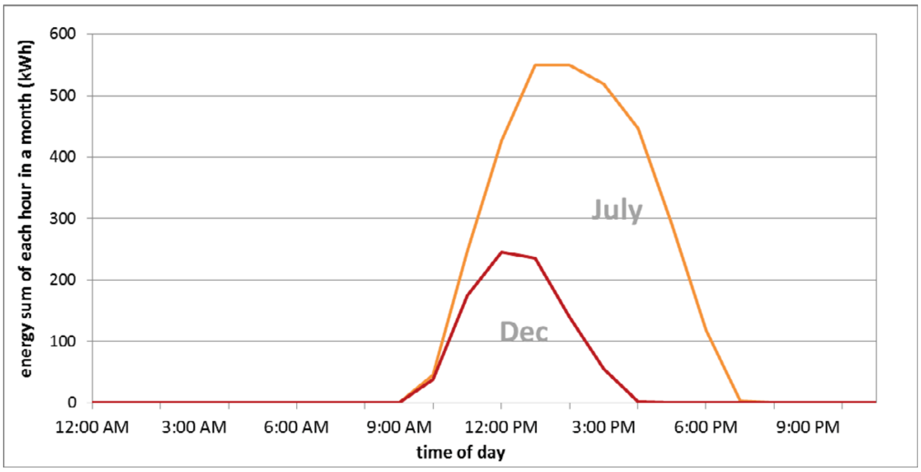

Fig. 2. Energy input into the warm water storage from the solar thermal system. Sum per hour of all days in a month for July and December 2015

The monitoring enables an evaluation of the energy standard and efficiency of technologies, the comparison with the predicted values and the analysis of the temporal development of energy production and consumption. Hourly data of 2015 from the monitoring are the reference for the proposed optimization model, which is described in the next section.

The evaluation of these data provided the evidence that the house of Schlagmann and BayWa fulfill the EHP – standard. On the one hand, the building required in 2015 13,084 kWh for room and hot water heating (incl. heat pump) and 6,464 kWh of electrical energy for the household itself (lighting, cooking and electrical equipment), installation engineering, other heating techniques, battery, other losses and also for the electric car (Fig. 3). On the other hand, the solar system had a yield of 20,675 kWh (solar thermal) and the PV installation generated 10,562 kWh of electric energy (Fig. 3). In total, the energy production exceeded the energy requirements by 11,689 kWh and the balance of primary energy was -14,060 kWh in 2015.

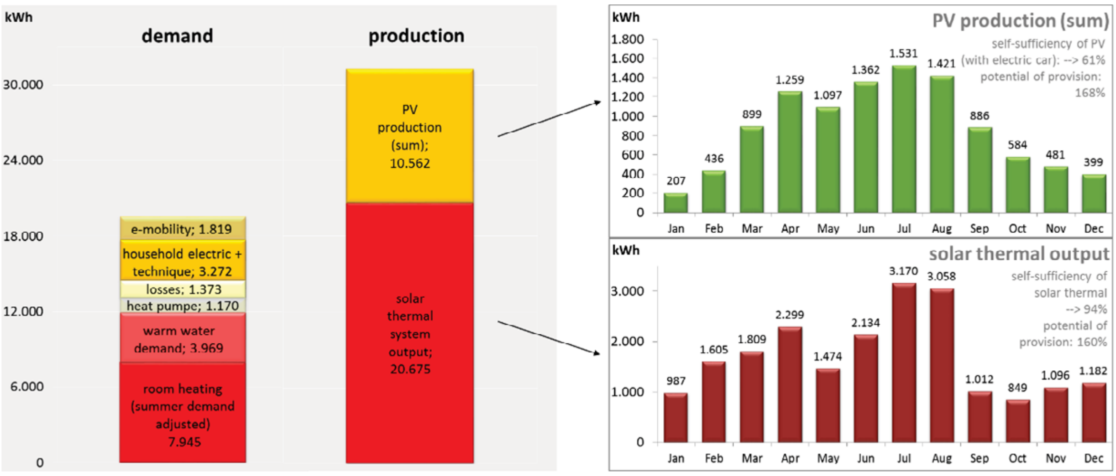

Fig. 3. Overall balance of the monitoring of the EHP of Schlagmann for the year 2015

The data confirm the functional interaction between the warm water system, the heat pump and the input from the solar thermal system. Fig. 4 presents the hourly progress of the heating system over the year 2015. The state of charge (SOC) was accounted on the basis of temperature variations in the warm water storage (sum of the average temperature of the low and the high temperature tanks; every tank has 10 measurement points distributed evenly). Higher solar thermal yields in summer raised the SOC of the warm water storage to a maximum in September and October. Afterwards, the SOC decreased in the winter days until the heat pump was necessary to produce additional heat. The different SOCs at the beginning and end of the year correspond to manual adjustments in the steering system.

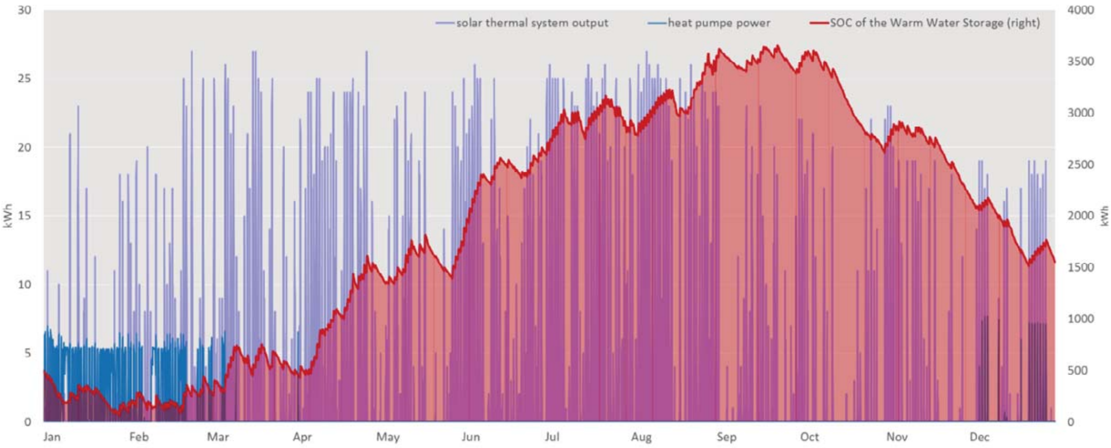

Fig. 4. Results of the monitoring for every hour in 2015 for the State of charge (SOC) of the warm water storage, the usable solar thermal system output and the heat pump output

3. A mixed integer-linear program for minimizing energy provision costs of EHPs

Design optimization of hybrid renewable energy systems for buildings is a research field that has gained significant attention in the last years (Lu et al., 2015a). A multitude of approaches and tools have been developed and some of them, such as the Hybrid Optimization Model for Electric Renewables (HOMER), have been used in dozens of projects all around the world (Erdinc and Uzunoglu, 2012). One of the most common approaches is mathematical programming, where the optimal sizing of hybrid renewable energy systems is reduced to linear, MILP or non-linear optimization problems (Evins, 2013). A MILP is for example the basis of the RED-CAM tool, which has been under development since 2000 and serves to optimize system configurations from a wide range of technologies based on minimum costs or minimum CO_2 emissions (Stadler et al., 2014). The model presented in this paper is also a MILP, but is a tailor-made model since widely used tools such as HOMER or RED-CAM and further tools, reviewed by Lu et al. (2015a), do not address at the same time three characteristics that are important when sizing a system for an EHP: 1) Space constraints for active solar energy generation technologies: The optimal use of space is a critical issue when deciding between technologies that could deliver the same type of energy. Furthermore, the energy input profile of active solar systems depends on geometric and location related characteristics that should be considered (Lang et al., 2015). In an optimal system configuration the right technologies should be installed in the right parts of the building's roof; 2) Use of the full length of data: in order to decrease the computational requirements for finding optimal solutions most of the existent tools rely on typical days or weeks per month to describe energy demand and energy generation yearly profiles. This strategy does not allow to account e.g. for entire weeks of snow coverage of PV systems, which are decisive when dimensioning storage systems. The proposed model uses as input time series of at least one entire year in the highest available temporal resolution. 3) Interdependences in the energy demand of energy generation systems: This is one of the most well-known limitation of HOMER. The tool is unable to account for the electric energy demand of a heat-pump unless this is known apriori and is entered in the model as an input (Lu et al., 2015b). The proposed model accounts for the energy demand profile of every system component that is part of the solution set.

The energy provision costs of the EHP are defined as the sum of the total installation costs, the operation and maintenance costs of the system and the costs of the energy requirements from the grid discounting the earnings of the energy surplus feed into the grid. The objective is to minimize the following problem:

$$\mathrm{Min}((pvCost * \textstyle\sum_a pvSize_a) + (stCost * \sum_a stSize_a) + (esSize * esCost * esReplace) + (hsSize * hsCost) + (hpSize * hpCost) + (opCost * lt) + (lt * eB * \sum_t eGrid_t) - (lt * eS * \sum_t pvSurplus_t)) \qquad \text{(eq. 1)}$$

where $pvSize_a$ is the amount of kWp installed in every roof part and $pvCost$ its corresponding cost per kWp. $stSize_a$ is the size in square meters of the solar thermal system to be installed in every roof part. $stCost$ is the cost per square meter of installed solar thermal system. $esSize, esCost$ and $hsSize, hsCost$ are the size and related cost per unit of the electric storage and heat storage systems. Both $esSize$ and $hsSize$ are given in kWh. For the electric energy storage an additional replacement factor, $esReplace$, is added to account for the short system life expectancy of current storage systems compared with the life time expectancy of components as PV installations. This factor depends on the expected life time of the storage system and lt, which is the expected operation time of the whole system. $hpSize$ is the maximum electrical input of the heat pump in kW and $hpCost$ is the corresponding cost per kW installed capacity. $opCost$ are the yearly maintenance costs of the system. $eGrid_t$ is the amount of electricity that must be consumed from the grid in every period of time in kWh and eB the electricity tariff per kWh. The surplus energy from the PV systems that cannot be used or stored in a certain time step, $pvSurplus_t$, is sold to the grid at a rate eS per kWh.

Several balancing conditions applied. First, the total PV generation per time step is to be divided in three possible uses; PV electricity can be directly used ($ePVUse_t$), it can be stored ($ePVStore_t$) or it can be sold to the grid ($pvSurplus_t$):

$$\sum_a pvSize_a * pvOutput_{t,a} = ePVUse_t + ePVStore_t + pvSurplus_t, \forall t \qquad \text{(eq. 2)}$$

where $pvOutput_{t,a}$ is the output of one kWp PV in t. This depends on weather conditions and the geometric and shadowing conditions of every PV system. The calculation of $pvSurplus_t$ relies on the assumption that all electricity generation surplus can be sold to the grid and no curtailment is required.

Second, the solar thermal systems are assumed to work analogically to the PV systems but the surplus ($stSurplus_t$) cannot be sold to a grid and the energy output cannot be directly used but works depending on the warm water storage system and the heat pump i.e. for energy from the solar thermal systems there are not three but two possible uses:

$$\sum_a stSize_a * stOutput_{t,a} = hSTStore_t + stSurplus_t, \forall t \qquad \text{(eq. 3)}$$

Third, the electric energy supply has to meet the demand, which includes the electricity demand of all appliances in the house ($eDemand_t$), the heat pump ($hpeDemand_t$) and the amount of energy required to operate the heat distribution system ($peDemand_t$):

$$eDemand_t + hpeDemand_t + peDemand_t = ePVUse_t + eStorDischarge_t * eStorDischargeEff + eGrid_t, \forall t \qquad \text{(eq. 4)}$$

The electricity supply includes not only the part of the PV output for direct use and the amount of electricity that must be consumed from the grid but also the output of an electric storage system ($eStorDischarge_t$) decreased by the discharge efficiency of the storage system ($eStorDischargeEff$), which is assumed to be linear.

Fourth, in a similar way the energy demand for heating and warm water ($hDemand_t$) has to be met by the supply. The latest is assumed to be completely delivered by the heat storage system, which also has a discharge efficiency ($hStorDischargeEff$) that is assumed to be linear:

$$hDemand_t = hStorDischarge_t * hStorDischargeEff, \forall t \qquad \text{(eq. 5)}$$

The variables $eStorDischarge_t$ and $hStorDischarge_t$ are bounded by the state of charge of the corresponding storage systems in $t-1$.

Fifth, the state of charge of the electric storage system $eSOC_t$ is calculated with the following equation, taking into account linear charging efficiency $eStorChargeEff$ and energy storing efficiency $eStoringEff$:

$$eSOC_{t+1} = eStoringEff * eSOC_t + eStorChargeEff * ePVStore_{t+1} - eStorDischarge_{t+1}, \forall t \qquad \text{(eq. 6)}$$

The $eSOC_t$ is never negative and the first and last time steps in a year are assumed to be equal. The latest condition ensures the continuous operation of the system during winter days from one year to the next.

Sixth, the state of charge of the heat storage system ($hSOC_t$) is calculated in the same way as $eSOC_t$ with the corresponding storing and charge efficiencies ($hStoringEff$, $hStorChargeEff$), the part of the solar thermal output to be stored, the heat pump output to be stored $hHPStore_t$ and the discharge of the heat storage system $hStorDischarge_t$:

$$hSOC_{t+1} = hStoringEff * hSOC_t + hStorChargeEff * hSTStore_{t+1} + hHPStore_{t+1} - hStorDischarge_{t+1}, \forall t \quad \text{(eq. 7)}$$

Seventh, $hpeDemand_t$ is determined by the coefficient of performance of the heat pump $hpEff$ and the part of $hStorable_t$ that is not directly covered by the energy generation of the solar thermal system $hHPStore_t$:

$$hpeDemand_t * hpEff = hHPStore_t, \forall t \quad \text{(eq. 8)}$$

$$hStorable_t = hHPStore_t + hSTStore_t, \forall t \quad \text{(eq. 9)}$$

The highest $hHPStore_t$ serves to determine the size of the heat pump:

$$hHPStore_t \leq hpEff * hpSize, \forall t \quad \text{(eq. 10)}$$

The storage sizes are defined by the highest state of charge of each system:

$$eSOC_t \leq esSize, \forall t \quad \text{(eq. 11)}$$

$$hSOC_t \leq hsSize, \forall t \quad \text{(eq. 12)}$$

Additional constraints for $ePVStore_t$, $eStorDischarge_t$, $hSTStore_t$ and $hStorDischarge_t$to the capacities of the corresponding storage systems $eCapLimit$ and $hCapLimit$ are also necessary:

$$ePVStore_t \leq eCapLimit, \forall t \quad \text{(eq. 13)}$$

$$eStorDischarge_t \leq eCapLimit, \forall t \quad \text{(eq. 14)}$$

$$hSTStore_t \leq hCapLimit, \forall t \quad \text{(eq. 15)}$$

$$hStorDischarge_t \leq hCapLimit, \forall t \quad \text{(eq. 16)}$$

The size of the PV system in m² is calculated multiplying the required installed capacity in kWp by the amount of square meters necessary to fit one kWp ($AreaPV$) and the solar thermal and PV total systems size is constrained by the available area of every roof part ($roofArea_a$):

$$pvSize_a * AreaPV + stSize_a \leq roofArea_a, \forall a \quad \text{(eq. 17)}$$

Finally, the system configuration should be able to generate sufficient energy to allow the building to achieve the EHP standards. To comply with this, two balance equations are included. One for the final energy balance and one for the primary energy balance of the house, which correspond to the calculation method described in the DIN 18599-1 (Europäisches Komitee für Normung, 2011):

$$\textstyle\sum_t (eDemand_t + hpeDemand_t + peDemand_t + eGrid_t) \leq \sum_t \sum_a pvSize_a * pvOutput_{t,a} \quad \text{(eq. 18)}$$

$$eGridFactor * \textstyle\sum_t (eDemand_t + hpeDemand_t + peDemand_t + eGrid_t) \leq eDisplacementFactor * \sum_t \sum_a pvSize_a * pvOutput_{t,a} \quad \text{(eq. 19)}$$

These equations include the assumption that the only external energy input for the EHP comes from the grid. The last equation corresponds to the primary energy balance where $eGridFactor$ accounts for the energy sources mix of electricity delivered by the grid and $eDisplacementFactor$ is the displacement factor of PV electricity when replacing other energy sources.

4. Scenarios

Seven scenarios with different system restrictions are studied. These scenarios range from the case of a building that represents the current state of the EHP described in Section 2 to the case of a building, which is able to achieve the EHP standard while assuming that there is no energy input from the grid and no feed-in tariff (full auto-sufficient building). These serve to calibrate the model, calculate the limits of auto-sufficiency of domestic buildings and discuss the relevance of every one of the considered technologies for EHPs in the near future. The description of the scenarios is presented in Tab. 1.

Tab. 1. Scenario description

Scenario	Description
Scenario 1 - Current state of the Schlagmann-BayWa EHP	The lower and upper boundaries of the PV, solar thermal, heat pump, and storage systems sizes variables are set to the values of the currently installed systems. The parameter roof area is equal to the real available area of every roof part where a PV or a solar thermal system is installed.
Scenario 2 - minimum system size that would achieve the EHP status under current constraints	Differently to the scenario 1, the lower boundaries of the PV, solar thermal, heat pump, and storage systems sizes are not defined apriori. The objective of this case study is to determine the minimum system sizes that would be necessary to achieve the EHP standard assuming that the maximum installation size of a certain system is the current system size.
Scenario 3 - minimum system size that would achieve the EHP status with flexible sizes	Differently to the scenario 2, the upper boundaries of the PV, solar thermal, heat pump, and storage systems sizes are not defined apriori. The only system size boundary for the PV and solar thermal systems are the roof part sizes.
Scenario 4 - minimum system size that would achieve the EHP status under current constrains without feed-in tariff	This Scenario is equal to scenario 2 except that the feed-in tariff value is set to 0 EUR.
Scenario 5 - minimum system size that would achieve the EHP status with flexible sizes without feed-in tariff	This scenario is equal to scenario 3 except that the feed-in tariff value is set to 0 EUR.
Scenario 6 - EHP standard without electric energy input from the grid	The starting point of this scenario is scenario 3. It is additionally assumed that no electricity energy input from the grid is allowed and that the size of the roofs is three times the current one of the Schlagmann-BayWa EHP. The first additional constraint is equivalent to the assumption that the EHP standard is achieved at every time step.
Scenario 7 – EHP standard without electric energy input from the grid and without feed-in tariff.	In this scenario the impact of no feed-in tariff is studied for the system with the boundaries assumed in scenario 6.

The common parameters for all scenarios include the energy demand for heating, warm water and electricity that have been measured in the house during 2015. The electricity demand includes the residential use and the electric car. The energy generation profiles of the PV and solar thermal systems per unit of installed capacity (kWp and m² respectively) correspond to the hourly time series of measurements from the installations in 2015. $peDemand_t$ ranges from 0.04 kWh when there is no energy demand for heating or warm water to 0.18 when the pumps for the heating system must be activated (This values are based on the measurements of the electricity demand of the corresponding pumps). $hpeDemand_t$ depends on the size of the system to install, the profile of the energy demand for heating and warm water and the output of the solar thermal system. $hpEff$ has been defined as 300% based on the average of the measurements when the only input for the heating system was coming from the heat pump. The efficiency of the storage systems is defined as a round trip efficiency (Solomon et al., 2012), where the charging efficiency is equal to average efficiency of storage systems (75%

for the electric and 85% for the warm water storage systems) and the discharging efficiency is 100%. The hourly self-discharge ratios of the storage systems are set to 0.01%. The final price per kWh of electric energy from the grid is assumed to be 0.28 EUR and the feed-in tariff (in case it is considered in the scenario) is 0.12 EUR. The assumed lifetime of the system is 20 years and $esReplace$ is equal to 2. The installation prices per unit are rounded average prices from multiple vendors presented in Tab. 2. $eGridFactor$ and $eDisplacementFactor$ are taken from the DIN 18559 in its official version of 2012, in that year (when the house EHP was planned) these values where 2.4 and 2.8 respectively.

Tab. 2. System prices per unit (Average from multiple vendors)

System	Price in EUR
PV (kWp)	2100
Solar thermal (m^2)	350
Heat pump (kW)	5000
Warm water storage (kWh)	10
Electric energy storage (kWh)	1000

5. Results

A summary of the results for the seven case studies and the monitoring data of the EHP for 2015 for comparison is presented in Tab. 3. It includes the resulting system sizes, the sum of the results for one year of seven further variables and the minimum energy provision costs for the 20 years lifetime of the system.

The results of scenario 1 show differences to the measured data that have an explanation in the optimal operation under perfect forecast that takes place in the optimization model. While the steering system in the actual EHP operates demand driven and based on current data, the optimization model generates a solution relying on data for the whole year. In the optimization model operation decisions are taken knowing exactly which will be the demand of the building and which is going to be the resources availability for every single time step. As a consequence, the final total output of the PV and solar thermal installations remains equal to the reference building but the internal use of the energy changes. The direct use of PV electric energy is higher while the requirements for energy from the grid and the energy surplus sold to the grid are lower. These differences between the actual EHP and the optimization model show that there is place for improvement in the operation of the energy generation and storage system of the building. Furthermore, despite of its simplicity, the model is able to reproduce the behavior of the warm water storage and the heat pump during the year. As it is presented in Fig. 5, in the scenario 1 the warm water storage stores energy from the solar thermal system in summer in order to meet the energy demand for heating and warm water during the beginning of winter. Consistently, the heat pump is in operation only during the winter months and the first half of spring. The major differences between the model and the actual system are presented at the end of the year (see Fig. 4). These can be explained by the (perfect forecast) information available for the optimization model and the restriction that obligates the model to finish the year at the same level that it starts with.

Scenario 2 shows that less installed capacity would also have been sufficient to achieve the EHP standard. The same PV installed capacity, a heat pump with a third less capacity, considerably smaller solar thermal and warm water storage systems would have been sufficient to produce energy beyond the final and primary energy requirements. Moreover, the electric storage system is not part of the system configuration even though the energy input from the grid is considerably larger than in scenario 1. Due to the considerable system size reduction in scenario 2, the energy provision costs are less than half of the costs of the reference scenario.

When the roof parts can be used without restrictions for every technology (Scenario 3), the solar thermal system is considerably smaller, the available area is covered by a larger PV system and no PV system is required on the roof of the garage. These changes mean an increment in the total energy yield of the PV system, in the PV electric energy direct use, the amount of energy injected into the grid, the energy demand of the heat pump and the energy requirements from the grid. Nonetheless, this system configuration presents lower energy provision costs than the resulting configuration of scenario 2.

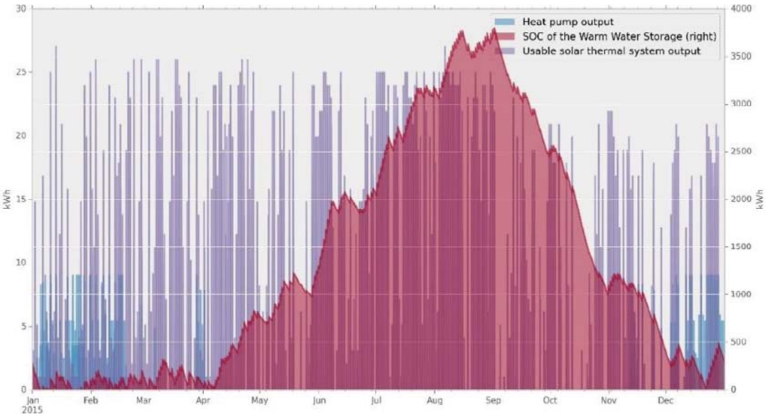

Fig. 5. Results of the scenario 1 for the State of charge (SOC) of the warm water storage, the usable solar thermal system output and the heat pump output for every hour in 2015.

In absence of feed-in tariffs (scenarios 4 and 5) solar thermal systems play an important role covering part of the energy demand for heating and warm water and therefore reducing the electric energy demand of the heat pump. Since surplus electric energy from the PV systems does not generate any income, it is more cost effective to install cheap solar thermal systems to cover part of the energy demand for heating and warm water than to install relatively expensive PV systems to supply the heat pump. This shows that mechanisms for promoting the adoption of renewable energies should be designed while taking into account interactions between technologies. If the interactions are not considered, the final system configurations would not only be more expensive for the system owner but also for the public treasury. It is important to note that even in the absence of feed-in tariffs, the electric energy storage does not appear as part of the solution system configuration.

A totally self-sufficient EHP is unfeasible under the actual system constraints. It would be necessary to have a building with at least three times as much roof space for accommodating active solar energy generation systems (scenarios 6 and 7) to conceive a 100% self-sufficient EHP. Only with PV installations several times larger than in the actual EHP and with an electric energy storage almost eight times larger than the currently installed ones, it would be possible to cover the energy demands of the building during the whole year. The most relevant factor for the large electric storage requirements is a series of consecutive days in winter when there is only little or no PV energy yield (due to snow covering the panels). An example for most part of January is presented in Fig. 6. If the PV yield between 24th and 28th January would be similar to the one of the previous weeks only half of the electric energy storage would be necessary to cover the system's requirements. This situation cannot be observed in optimization tools that rely on average or typical data to represent a whole year of data. Concerning the solar thermal system, this would be only slightly smaller in scenario 6 and a fifth larger in scenario 7 than the one that is currently installed. The warm water storage could be a third of the actual size. Finally, in the absence of feed-in tariffs (scenario 7) the PV system is smaller, the electric energy storage is used more intensely and the solar thermal system is larger than in scenario 6.

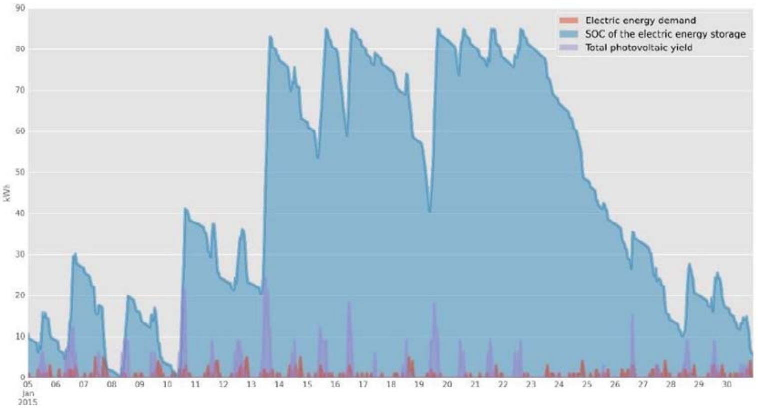

Fig. 6. Results of the scenario 6 for the state of charge (SOC) of the electric energy storage, the total PV yield and the electric energy demand for every hour of the period 05/01/2015-30/01/2015

Tab. 3. Scenario results summary

Variable	Actual EHP	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
Electric energy storage (kWh)	10.8	10.8	0	0	0	0	84	86
PV1 (kWp)	4.28	4.28	4.28	10.35	4.28	6.22	26.9	19.02
PV2 (kWp)	6.48	6.48	3.82	0	2.45	0	19.74	19.74
Heat pump size (kW)	3	3	1	1	1	1	1	1
Solar thermal (m2)	51	51	12.32	5.32	26.91	13.9	47.58	62.89
Warm water storage (kWh)	4000	4000	95	95	107	95	1279	1326
Total PV generation (kWh)	10562.22	10562.22	8631.12	14162.3	7641.54	8505.88	51119.4	40355.34
PV direct use (kWh)	1364	2739	3185.95	3706.04	2714.7	3024.02	3177.4	3513.93
Electric energy to the grid (kWh)	6144	5594.01	5445.17	10455.63	4926.82	5481.86	43125.19	30349.65
Battery output (kWh)	1993	1655.87	0	0	0	0	3546.59	4737.91
Electric energy demand household (kWh)	4590	4590	4590	4590	4590	4590	4590	4590
Electric demand heat pump (kWh)	1176	779.35	3233.04	3881.97	2238.2	3111.64	1328.63	2856.48
Electricity demand heating system (kWh)	809	805.4	805.4	805.4	805.4	805.4	805.4	805.4
Electric energy from Grid (kWh)	3218	1778.85	5442.45	5571.38	4918.98	5482.86	0	0
MILP Solution (EUR)	n.a.	120306	50688.6	41683.07	63158.75	60581.37	205678.06	302528.73

6. Conclusions

State of the art technology can transform a residential building into a power plant. The data of the Schlagman-BayWa EHP show that a single family house can produce energy beyond its own final and primary energy requirements. In fact, to reach the EHP standard considering a yearly balance it would have been sufficient to install a significantly lower capacity, regarding not only the solar thermal, but also the electric and warm water storage systems. In contrast to the first five scenarios, the sixth and seventh scenario, which describe a building without energy input from the grid (equivalent to a building achieving the EHP standard in every time step), are unfeasible considering the available roof areas for installation of PV and solar thermal systems. The proposed MILP can only find a solution for these scenarios when the roof areas are assumed to be three times larger than the current size. The realization of such complete self-sufficiency scenarios would require not only larger energy generation systems, but also electric storage capacities several times higher than the one currently installed in the Schlagmann-BayWa EHP. Self-sufficiency seems to be hardly realizable even for the small demand of a single family house.

The use of the full length of data serves to identify that the main reason for the high electric storage requirements in these scenarios are series of consecutive days where only very little energy can be generated by the PV installations. Furthermore, the modelling showed that even in absence of feed-in tariffs for the PV energy surplus sold to the grid, electric storage systems are only part of the optimal solution when no input from the grid is allowed. It is also only in absence of a feed-in tariff for the surplus PV energy production that the solar thermal systems gain relevancy in the solution system configurations.

Finally, the EHP standard can be achieved in numerous ways, but the economic viability of such buildings requires the selection of the appropriate system configuration, which can be determined using the proposed MILP. It is also important that the design of economic mechanisms to promote certain renewable energy technology takes into account the interactions between technologies, otherwise energy generation systems installed by house owners would be more expensive not only for the owner but also for the public that is paying for these promotion mechanisms.

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8. References

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