Solar power self-consumption after the support period: Will it pay off in a cross-sector perspective?☆

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Abstract

We quantify the cost savings potential of solar power self-consumption by single- and two-family houses with small scale roof-top photovoltaic (PV) systems against the background of recent innovative storage applications in Germany. We analyze different systems where a PV installation is combined with battery storage and/or the technically simplest Power-to-Heat solution (heating rod plus thermal storage). A comparison is made in terms of an households electricity and heating costs under cost-minimizing operation of each system. For this purpose, we carry out comprehensive simulations of site-specific PV production and determine the optimal solar power self-consumption as well as the optimal charging of the hot water thermal storage and the battery system. Results suggest that a significant savings potential can be realized by PV self-consumption. The inclusion of a hot water thermal storage pays off in terms of additional costs savings as well as reductions of GHG emissions.

Keywords: Residential photovoltaic, self-sufficiency, battery system, Power-to-Heat

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1. Introduction

1.1. Motivation

After years of remarkable growth of photovoltaic (PV) systems in Germany, the expansion slows noticeably due to the latest adjustments of the support scheme, the renewable energy act (EEG) (BMWi, 2015). However, a considerable quantity of photovoltaic (PV) capacity – 38.2 GW at the end of 2014 – was built up in recent years fueled by generous financial support instruments of the past. Of this capacity approximately 18.6 % (5.2 GW) are small scale (up to 10 kWp) roof-top systems located on single- and two family houses (SFH) all over Germany (Tab. 1; BMWi (2015)).

Table 1: Photovoltaic capacity in Germany 2014 by size groups

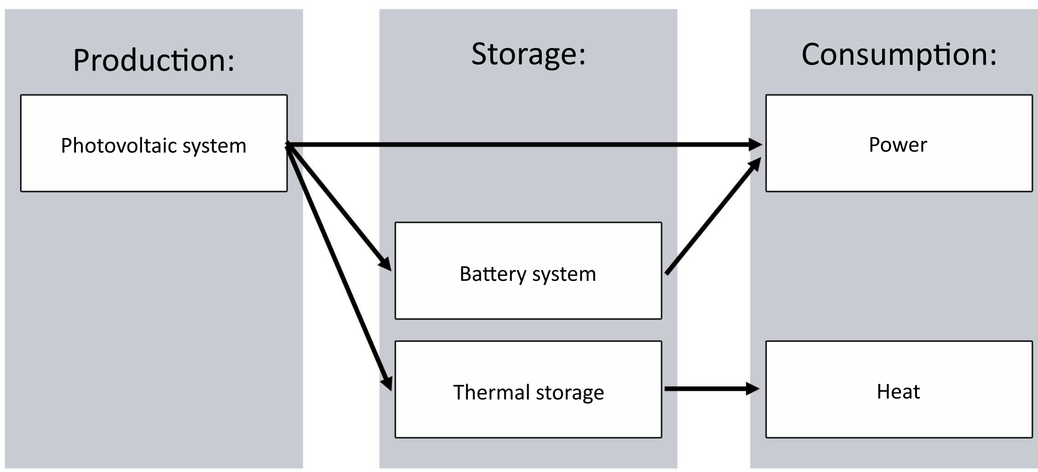
Type	**Up to 0.01 MW**		**>0.01 MW**		**Total**
	MW	Share	MW	Share	MW
Roof-top	5192.8	18.6%	22751.4	81.4%	27944.2
Ground mounted	16.5	0.2%	10275.3	99.8%	10291.8
Total	**5209.3**		**33026.7**		**38236.0**

Source: BMWi (2015)

The remuneration for feeding into the grid ends after a period of 20 years. However, most manufacturers of solar modules provide a technical guarantee of 25 years or even longer (Fraunhofer ISE, 2015). With the end of the support period, the business model for owners of a PV system is changing radically (e.g. Williams et al. (2012); Luthander et al. (2015)). While the goal was previously to maximize feed-in, it is now to maximize self-consumption. This leads to the question: What should an owner of a small-scale PV system do after the end of the support period? Under the assumption that the PV system is operable for five more years, the owner could choose between three possible options: i) she could dismantle or decommission the system, ii) she could keep producing power and sell it directly or iii) she could maximize the benefit of self-consumption. Option i) will only be chosen if the expected revenues of option ii) and iii) are negative or smaller than the scrap value minus the expenses for dismantling the PV system. Option ii) is at least in our opinion very interesting regarding alternative business models for the marketing of electricity. Yet, this option is not the scope of this paper and is left for future research. However, rational households will weigh this option against the cost savings from power self-consumption, which will continue to be sizeable as long as electricity consumer prices in Germany do not plummet dramatically. The research focus of this paper is therefore option iii): the analysis of the potential benefits from self-consumption. However, due to the different patterns of PV production and household consumption, a large part of the electricity must be stored intraday.

At the moment, there are two main storage options for private households: battery systems and hot water thermal storages.
The option iii) is of special interest in the context of Germany's current attempts to decarbonize its private heating market and support renewable energy in residential heating (e.g. Renewable Energy Heat Act). In 2014 the share of the residential sector of total greenhouse gas (GHG) emissions in Germany accounted for 9.45 % (UBA, 2016b). Since space heating and hot water account for 82 % of the final energy consumption in private households, the majority of GHG emissions is caused by heat generation. With 22.5 % (Oil) and 47.9 % (Gas) of the energy consumption for heating purposes, private heat generation in Germany is still heavily dominated by fossil fuels (Destatis, 2016). In addition, due to the currently low oil prices this pattern is not likely to change dramatically in the foreseeable future. In this regard, using energy from the PV system to produce heat could significantly lower the use of fossil fuels and therefore reduce GHG emissions.

Figure 1: Schematic model description



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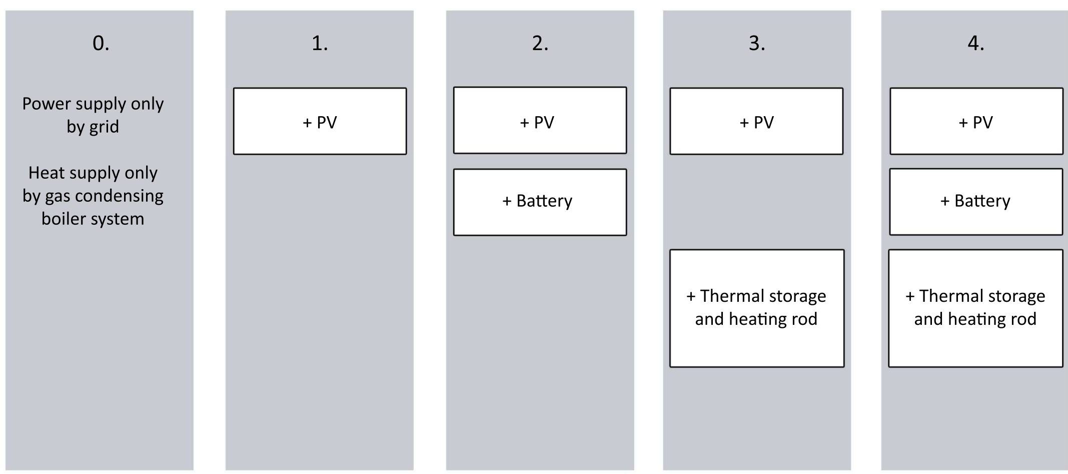
Against this background, we quantify the wider economic potential of solar power self-consumption by single- and two-family houses with small scale roof-top photovoltaic systems against the background of recent innovative Power-to-Heat (PtH) applications in Germany (Fig. 1). We focus on SFH because the majority of the small scale roof-top systems are installed on these types of buildings (BMWi, 2015). A comparison is made in terms of a households electricity and heating costs under cost-minimizing operation of each of four systems (Fig. 2). The first system consists of a PV module and a conventional gas-fired condensing boiler without any storage options. The second system adds battery storage for storing self-produced electricity to the first. The third system includes instead of battery storage a simple Power-to-Heat-module. This PtH-module consists of two elements: a heating rod and a hot water thermal storage tank (herein after: thermal storage). The heating rod is integrated in the thermal storage as a second heat source in addition to the condensing gas boiler. Finally, the fourth system comprises both battery storage and the PtH-module. Comparing energy costs under these four systems among each other as well as with the situation of a fully external provision of electricity and gas provides a comprehensive picture of the microeconomic benefits of PV generation at household level in post-support periods. For this purpose, we carry out comprehensive simulations of site-specific PV production and determine the optimal solar power self-consumption as well as the optimal charging of the hot water thermal storage (hereafter *thermal storage*) and the battery system in hourly resolution.

Figure 2: Schematic description of the four considered system setups



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1.2. Related literature and research context

In recent years a growing research interest concerning the economic potential of PV self-consumption has arisen. This is on the one hand driven by the substantial cost reductions of PV modules and the attainment of grid parity for PV in many countries, which make PV self-consumption more attractive.[1] On the other hand it is due to the declining remunerations of the national support schemes, which reduces attractiveness of in-feed. Luthander et al. (2015) provide a comprehensive literature review of PV self-consumption in buildings. Most of the contributions investigate the use of residential battery systems for an optimized PV self-consumption or the potential of demand side management; only three are concerned with thermal storage applications (Williams et al. (2012); Vrettos et al. (2013); Thygesen and Karlsson (2014)). All of them consider heat pumps as heating source in combination with hot water thermal tanks. The most recent contribution of Lang et al. (2016) also focus solely on electric heating applications. Balcombe et al. (2015) investigate a system setup with a Stirling engine for combined heat and power production with a battery system and a solar PV module in the UK. We add to the debate with a to our knowledge less considered issue. We focus on the status quo by considering already existing PV systems. Furthermore we investigate a scenario which reflects the status quo of the German residential heating sector by investigating the economic benefits of fossil fueled central heating systems (gas condensing boilers). Due to the length of the operating life of those heating technologies (>20 yr.), the residential heating market is still dominated by fossil fuels and a considerable amount of PV roof-top systems is available, it seems interesting to analyze the self-sufficiency potential in the existing stock in a cross-sector perspective.

1.3. Outline of the paper

The remainder of this paper is structured as follows. In Section 2 we present our simulation approach and the data used. First (Section 2.1), average heat load profiles are generated based on a standard bottom-up approach. Second (Section 2.2), the PV output of the roof-top system is simulated on an hourly basis for an average year in Southern Germany. Third (Section 2.3), the derivation of electricity load profiles is explained. In Section 2.4, all three series are used to calculate the cost savings of the different systems. The results are presented in Section 3 and a sensitivity analysis regarding battery size, efficiency and electricity prices is conducted. Section 4 concludes with a discussion.

[1] Grid parity is understood as the situation in which the levelized cost of electricity and thus in the medium run also feed-in tariffs of a newly installed renewable energy source (e.g. PV roof-top system) is less or equal to the domestic electricity price.

2. Data and methodology

2.1. Simulation of the heat load profiles[2]

The energy demand for heating purposes that could potentially be covered by the photovoltaic system was investigated by calculating representative heat load profiles for sample households. In more detail, heat load profiles in hourly resolution over the course of an average year were simulated for a typical single and two family house (SFH) in Southern Germany. To this end, the standard heat load profile method (BGW, 2006) was used to generate the energy demand for space heating (SH) and domestic hot water (DHW) in SFH on an hourly basis. The standard heat load profile method is a common technique used by municipal energy suppliers forecasting gas load curves of non-measured end-users (<1.5 GWh/a) to provide the accurate amount of gas. This engineering tool was developed by the Technical University Munich (Hellwig, 2003) on behalf of the BGW (Federal Association of the German Gas and Water) and VKU (Association of Local Utilities) and allows predicting the temperature-dependent heating energy demand of households with respect to several factors. In this study, we adapt this method described in BDEW (2013) to our purposes by applying it to the considered reference household. To this end, a sigmoid-function is used to calculate the heat load profile based on numerous parameters and specific reference values. The key components affecting the energy demand for SH and DHW are primarily the equipment of the building (thermal insulation status and the used heating system) as well as external factors like the outside temperature, regional climatic parameters like wind conditions and further regional particularities as building and population structure.[3]

To ensure the representative nature of the reference case, we established the following combination of sample building and average weather conditions. For the latter, temperature time series from the Test Reference Year (TRY) database of the German Meteorological Service (DWD) were used. The TRYs represent the characteristic weather and temperature conditions for different regions in Germany over the course of a year. They are developed from long-run measurements of weather conditions and represent the values and variability of the long-time means of respective meteorological regions. The TRYs have the inherent purpose to be used for simulation concerning heating and room air equipment and the thermal performance of buildings (DWD, 2014). In this regard, we used the temperature series of climatic TRY-regions 13, which suitably cover the majority of Southern Germany's land area. Finally, we constructed a theoretical average representation of an individual building with specific energy demand for space heating and hot water per annum. The choice of this reference building requires us to make several assumptions, since one

[2] This section draws heavily on Ehrlich et al. (2015)

[3] For detailed description see Appendix B

of the striking characteristics of the heating market is its diversity and complexity. The number of possible combinations of heating systems and the configuration of the building stock is enormous and many variables need to be taken into consideration.

To begin with, we focus on single-family and two-family houses only and do not consider multi-family houses in our analysis, since SFH make up about 82.6 % of the national housing stock (Destatis, 2014) and the majority of the small scale photovoltaic roof-top systems are installed on these building types (BMWi, 2015). Moreover, we assume the sample SFH to have a thermal insulation status of a refurbished building according to the Heat Insulation Ordinance (WSchVO95) with a condensing gas boiler system. We think of this combination as an adequate description of an average SFH since natural gas is by far the most important energy carrier for SH and DHW in Germany and the assumed insulation standard represents a fair average of the energy efficiency of the German housing inventory. The specific final energy use for heating and hot water per m^2 living area for such combination is assumed to be 134 kWh/m^2a (Adolf et al., 2013). Furthermore, the living space of the sample SFH in our analysis is assumed to match the national average of SFH with 141 m^2 (Destatis, 2014). Combining these two values, the end-energy use for the reference SFH for space heating and hot water per annum applied in this study was 18.894 kWh.

2.2. Simulation of residential photovoltaic production

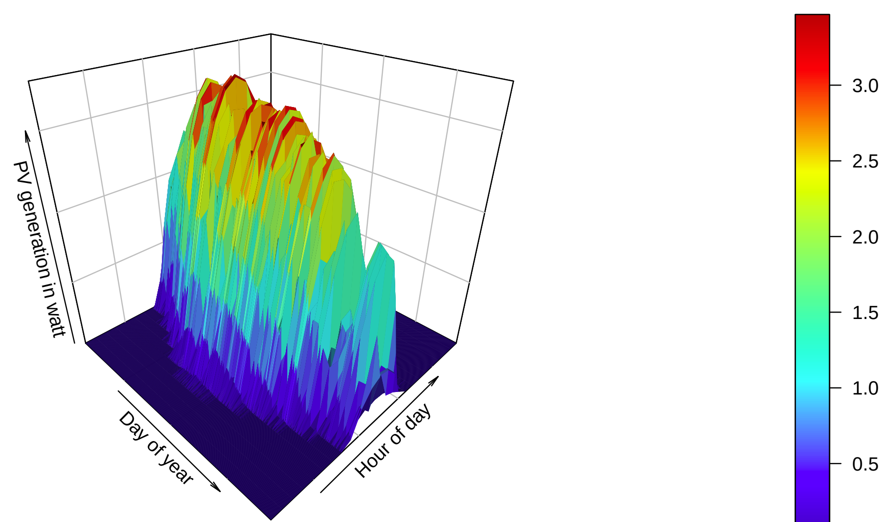
The output of a solar module is mainly driven by three parameters: the solar irradiance on the tilted surface, the ambient temperature and technical characteristics of the used solar panel (Hellman et al., 2014). We model the equation for hourly PV power production in line with established methods (e.g. Lang et al., 2016; Duffie and Beckman, 2013; Hellman et al., 2014). The output P_t^{PV} of the PV system at hour t is computed as:

$$P_t^{PV} = G_t(\beta, \phi, \delta_t, \gamma, \omega_n) \times A \times \eta_t(\eta_r, \kappa_{TC}, G_t) \times PR \quad (1)$$

The function G_t represents solar irradiation on the PV module, A is the parameter for the area-size of the modules, the function η_t represents the relative efficiency and PR the performance ratio of the system. Parameters of the functions G_t and η_t are explained in formal detail in Appendix A1. However, the basic mechanisms and parameters used in the simulation are explained shortly in a less formal manner in the following paragraph.

The solar irradiation on the tilted surface depends on location, azimuth and declination of the modules. Due to the feed-in tariffs in Germany, most systems have a production-maximizing southern orientation and a declination between 30°– 40°(Zipp, 2015; Fraunhofer ISE, 2015). Since we consider already installed systems, we assume a southern orientation (azimuth = 0) and an average declination of 35°. For solar irradiance and ambient temperature, we again make use of the time series from the TRY database. The horizontal and diffuse irradiation data is calculated by the DWD, the ambient temperatures are measured at the corresponding weather station (Muehldorf). For the technical specifications (e.g. temperature coefficient) of the solar panel, we use average values for a crystalline PV modules which we have found in recent literature on PV power modelling (e.g. Hellman et al., 2014; Lorenz et al., 2011; Skoplaki and Palyvos, 2009; Mattei et al., 2006). We assume a nominal module efficiency of 15.3 %, which is corrected for temperature effects (Eq. A.7/A.8 in Appendix A). Typical values for the performance ratio (PR) lie between 0.8 – 0.9. Since we do not consider newly installed PV modules, we use a conservative PR of 0.7, taking degradation effects into account. In Figure 3 the simulated production profile is depicted. One can see the daily and seasonal pattern. In sum, 4517 kWh are generated over the course of a year.

Figure 3: PV production



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2.3. Electricity load profile

To simulate a household's consumption pattern of electricity, researchers can draw on artificial load profiles. In practice, such load profiles are used by network operators for predicting the load caused by small customers without registered measurement devices. In Germany, the German Association of Energy and Water Industries (BDEW) publishes standard load profiles for 12 different groups of these customers, including one representing the consumption pattern of an average household. Precisely, the information given takes the form of tables with performance values for each 15-minute interval within a day. In case of the household profile, different tables for work days, Saturdays and Sundays/public holidays are provided. Moreover, seasonal variation is reflected by differentiating between summer, winter and a transition period. We apply these data to construct a load profile for a representative household in 2014. We do this by distributing the known average annual electricity consumption of a German household with three or more persons in 2014 (5.283 MW) over all 15-minute intervals of the year, accounting for off-days according to the calendar. Afterwards, the obtained 15-minute load estimates are added up to hourly values, in order to match the resolution of the simulated generation patterns.

2.4. Cost simulation

Our aim is to analyze the cost savings from electricity self-consumption under each of the four energy systems described above. This is done by simulating electricity and heating expenses at an hourly level for each of the systems plus for a reference household without electricity self-generation. In doing so, we assume a cost-minimizing operation of each system, as should be realistic for economically rational households. As a consequence, optimal system operation will strongly hinge on the evolution of consumer prices of electricity and fossil heating sources. Current market conditions in Germany reveal a significant discrepancy. In 2014, the annual average consumer price of electricity amounted to 29.78 Ct/kWh (Destatis, 2016) and thus remained close to an all-time high. During the same time period, effective gas prices per kWh were observed to lie at an average of 6.80 Ct/kWh (Destatis, 2016) and declined afterwards. Even with recovering fossil fuel prices in the future, it is highly unlikely that the price gap between the two energy forms will narrow considerably. Hence, imposing a strict priority of direct self-consumption of electricity compared to an indirect self-use for heating purposes via the PtH-module is no controversial assumption: total cost savings will simply be higher. Precisely, in absence of any superior information on future price patterns, we conduct our simulations based on the annual average prices of electricity and gas in 2014.

Further design options concern the technical side. Adding batteries to the PV module can be expected to raise electricity cost savings: by creating storage opportunities, the adverse impact of the limited conformity of generation and consumption patterns over time can partly be neutralized. The degree of this effect is crucially determined by storage capacity as well as discharge efficiency of the battery system. In principle, by combining several battery cells to one system, storage capacities of considerable magnitude could be created. However, costs of larger systems are still prohibitively high from the perspective of single households (McKenna et al., 2013). In this study, we therefore only consider battery storages up to 5 kWh. As a base case value, we choose 3 kWh, which was found to be most cost-efficient by Balcombe et al. (2015). In reality, discharge efficiency is a time-variant measure, changing slightly with ambient temperature, operating voltage and state-of-charge. Trying to reproduce these complex details in our simulation would add little to our understanding of the economic implications. Instead, we follow parts of the literature by treating discharge efficiency as a fixed parameter defined as the ratio of usable electricity output to electricity input (Castillo-Cagigal et al., 2011; Chen et al., 2012; Purvins et al., 2013). As a parameter value for our base case simulations, we impose an efficiency level of 80 % as proposed by Balcombe et al. (2015). This will later be varied as part of our sensitivity analysis.

Capacity considerations are also relevant for the Power-to-Heat module. The amount of electricity-generated heat available to the household over time both depends on the performance capacity of the heating rod and the storage capacity of the thermal storage. For the former, a value of 6 kW is implemented, which is within the typical range of sizes currently sold on the market. For the latter, a volume of 500 l is chosen, which is sufficiently large for single-family and two-family houses. A further technical restriction is a constraint to the quantity of heat stored at each instant, which is defined by the upper and the lower temperature limits of the thermal storage. For these limits, experience-based values of 35° C and 85° C were applied. Furthermore, the hourly level of standing losses of heat energy stored within the thermal storage is accounted for by applying the approximation proposed by the norm DIN EN 304. Finally, the efficiency of energy conversion through PtH has to be specified. As the heating rod is simply plugged into the thermal storage, efficiency can be assumed to approach 100 %. In our simulations, we apply a value of 99 %. Having defined the economic and technical settings, we can formulate the cost equations resulting from the premise of cost-minimizing operation. As explained above, this premise will imply a usage priority of self-generated PV electricity for the purpose of direct consumption. Under System 1 (no storage opportunities), equations for electricity (C^E) and heating (C^H) costs summed up over the hours of our simulation year are simply defined as:

$$C_1^E = p^E \times \sum_{t=1}^{8760} max.\{Q_t^E - P_t^{PV}; 0\} \tag{2}$$

$$C_1^H = p^H \times \sum_{t=1}^{8760} Q_t^H \tag{3}$$

where Q^E (Q^H) marks the (exogenous) consumption quantities of electricity (heat) and p^E (p^H) denotes the corresponding consumer price on the market. With this system, savings potentials compared to the reference of fully external provision are thus restricted by the amount of PV electricity that can be instantly consumed. Under System 2, the existence of battery storage enhances savings opportunities, but only with respect to electricity costs:

$$C_2^E = p^E \times \sum_{t=1}^{8760} max.\{Q_t^E - P_t^{PV} - \nu \times B_{t-1}^{PV}; 0\} \tag{4}$$

$$C_2^H = C_1^H \tag{5}$$

where B_{t-1}^{PV} denotes the batterys state-of-charge at the end of the preceding hour and denotes the discharge efficiency. Under System 3, opportunities to save heating costs are created by the PtH-module, where the accumulated amount of heat in the thermal storage represents a constraint:

$$C_3^E = C_1^E \tag{6}$$

$$C_3^H = p^H \times \sum_{t=1}^{8760} max.\{Q_t^H - \widetilde{Q_{3,t}^H}; 0\} \tag{7}$$

where $\widetilde{Q_{3,t}^H}$stands for the maximum amount of heat that can be drawn from the thermal storage in hour t under System 3 (i.e. the amount causing the storage temperature to drop to its minimal level of 35° C). A precise formula for $\widetilde{Q_t^H}$ is derived in Appendix C. Most importantly, it positively depends on recent levels of electricity generation and negatively on recent levels of electricity consumption. Under the full System 4, the household is in the position to make use of two kinds of energy storages for cutting its energy expenses. Given the priority of electricity consumption, only the amount of generated PV electricity that exceeds the capacity of battery storage will be directed to the PtH-module. Hence, electricity expenses will be the same as under System 2. In general:

$$C_4^E = C_2^E \tag{8}$$

$$C_4^H = p^H \times \sum_{t=1}^{8760} max.\{Q_t^H - \widetilde{Q_{4,t}^H}; 0\} \tag{9}$$

where $\widetilde{Q_{4,t}^H}$ as the maximum amount of heat extractable from the thermal storage will tend to be lower than under System 3. Finally, for each system, model dynamics are described by the evolution of two state variables over time: state-of-charge of the PV battery and temperature within the thermal storage. The corresponding dynamic equations are given in Appendix C.

3. Results

3.1. Base case

Base case simulations were performed based on the set of parameter values mentioned above. Table 2 lists the outcome in terms of annual electricity and heating costs in our simulation year. As explained, the Reference is here simply energy costs of a household without own generation capacities. They are simply computed as annual consumption times assumed consumer price. The first comparison that can be made is between the Reference and System 1 (PV module without storage facilities). As heat provision is not affected, savings are limited to expenses for electricity.

Under the given setup and current consumer prices, annual savings would amount to about 620 Euros. This is quite a considerable amount, given that no further fixed costs will accrue in case of already installed solar modules. A further comparison with System 2 then tells us something about the returns of investments into battery storage (with 3 kWh capacity in the base case). Again, in absence of technical means to transform electricity into heat, heating costs are not influenced. Moreover, as expected, the storage option causes a further reduction in electricity expenses. The ability to store limited amounts of self-generated electricity during the day allows for a better exploitation of PV electricity for the purpose of self-consumption. Additional savings compared to System 1 are simulated to lie in a range of about 200 Euros per annum. These costs need to be weighed against the one-time investment costs of battery storage. Currently, costs of battery capacity are in a magnitude of 1300 to 2000 Euro/kWh in Germany (Stenzel et al., 2015). All in all, PV module owners with battery storage could expect to save about 840 Euros in electricity costs over the course of the simulation year.

Table 2: Simulated energy costs under the different systems for the base case scenario

System	**Electricity costs in Euro/year**	**Heating costs in Euro/year**	**Total costs in Euro/year**	**Heat related GHG reduction kg/year**
Reference	1573.20	1284.72	2857.92	-
System 1 (PV)	944.09	1284.72	2228.81	-
System 2 (+ Bat.)	732.13	1284.72	2016.85	-
System 3 (+ Therm.)	944.09	1157.82	2101.91	463.11
System 4 (+ Bat. + Therm.)	732.13	1200.79	1932.92	294.08

Source: Own calculations

The additional potential of electricity usage for heating purposes is revealed by the simulations for Systems 3 and 4. In absence of battery storage (System 3), annual savings in heating costs through the PtH-application are estimated to be about 130 Euro. Again, these values have to be seen in relation to expected investment needs. For households already possessing a thermal storage tank as part of their heating system, investments will confine to the acquisition of an electric heater. Currently, heaters with a performance capacity of 6 kW are available at prices of about 800 Euro (including installation costs) (Bernhard and Fieger, 2011). For households without thermal storage capacities, the need to buy a storage tank will raise investment costs even more. Finally, a comparison to the most comprehensive System 4 with its twofold storage options reveals the trade-off in cost efficiency between electricity and heating. While the addition of battery storage reduces electricity costs compared to System 3, heating costs are slightly higher: less PV electricity is available for PtH-purposes, as more of it can be used in a direct manner. Nevertheless, total costs are the lowest under this setup. Compared to the operation of a PV module alone (System

Table 3: Level of self-sufficiency, share of self-used PV generation and share of feed-in.*

System	**Self-sufficiency Power in %**	**Self-sufficiency Heat in %**	**Used PV gen. in %**	**Grid feed-in in % of PV gen.**
System 1 (PV)	39.99	-	46.76	53.24
System 2 (+ Bat.)	53.46	-	62.52	36.87
System 3 (+ Therm.)	39.99	12.20	97.77	1.40
System 4 (+ Bat. + Therm.)	53.46	7.74	94.91	0.02

* PV generation = 4517 kWh/a, power demand = 5283 kWh/a, heat demand = 18.894 kWh/a

Source: Own calculations

1), savings in energy costs add up to more than 295 Euros per annum. Again, this sum needs to be put in perspective by the investment expenses associated with the creation of storage capacities.

Table 3 provides metrics for self-sufficiency, used PV production and unused PV production of the different system setups. Self-sufficiency indicates the share of residential power/heat demand which can be met by PV production over the course of the year (column 1 and 2). It therefore includes also stored PV generation. Column 3 shows the share of PV production which could actually be used on-site over the course of a year. It therefore also includes conversion losses. Column 4 shows the part of the annual PV production which could not be used on-site and must be fed into the grid.[4] The level of power self-sufficiency only varies with the availability of a battery system. 40% of the power demand could be met directly (System 1 and 3). With the battery system this share could be raised by 13 percentage points. Regarding the level of heat self-sufficiency a maximum is reached in System 3. More than 12 % of the annual heat demand could be met by the PV system and the PtH-module. The lower share for System 4 (7.7 %) is due to the priority use of PV generation for charging the battery. System 4's lower share of used PV production is caused by the lower efficiency of the battery. The unused PV production lies between half of the annual production (System 1) and nearly zero (System 4).

3.2. Environmental merits

Apart from sole monetary savings, the setup in Systems 3 and 4 enables us to calculate the potential reduction of GHG emissions due to substitution of gas with PV electricity for heating purposes. Assuming an emission factor of 201 grams CO_2 per kWh of gas (according to (UBA, 2016a) leads to a reduction of GHG emissions per kWh used in the PtH-system of that very same

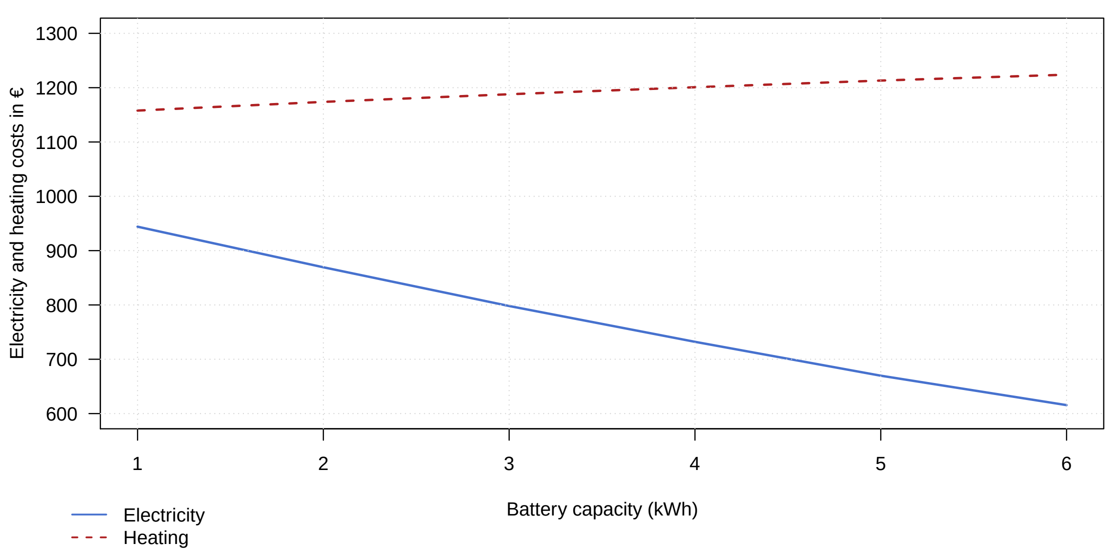
[4]We do not consider any costs or remunerations regarding grid in-feed, since this is not the scope of our analysis.

amount, since the PV electricity is completely renewable without any GHG emissions. Hence, in System 3 the GHG emission savings account for about 0.46 tons while in System 4 0.29 tons of GHG emissions would be avoided.

3.3. *Sensitivity analysis*

Given the high level of technical and economic detail involved in our model specification, a sensitivity analysis is essential for understanding the dependence of simulation results on the scenario design. In principle, such an analysis could address any technical feature of the household's system of energy provision. However, as the perspective of this paper is on future savings potentials for owners of representative PV systems in Southern Germany, we limit our subsequent discussion to the specification of additional storage options and future economic conditions. One potentially crucial parameter in this regard is the capacity of battery storage. A higher capacity allows for more significant reductions of electricity expenses, as consumption becomes less reliant on current weather conditions. However, as mentioned above, large battery capacities are currently assessed to be prohibitively expensive right now and likely also in the nearer future from the viewpoint of an average household. We therefore restrict the parameter variation to a reasonable range of up to 5 kWh.

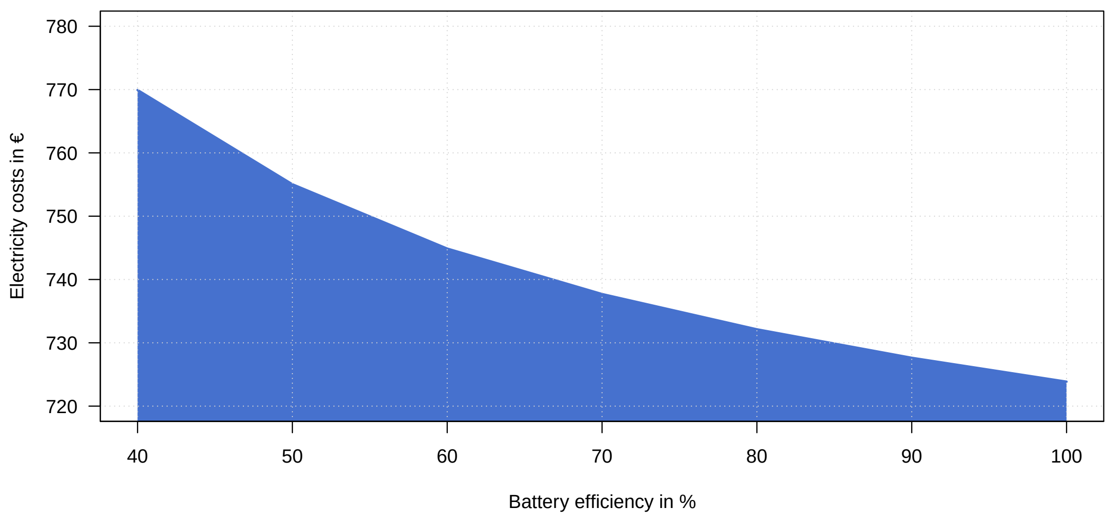
Figure 4: Electricity and heating costs for different battery capacities



Source: own depiction

Figure 4 plots the households energy expenses across this spectrum for the full System 4 (as should be clear by now, results for electricity costs will be equivalent to those of System 2). It documents that electricity costs in particular show some degree of sensitivity towards the evolution of capacity levels. For instance, employing battery capacities of 5 kWh instead of 3 kWh is predicted to lower electricity costs by more than 100 Euros. At the same time, heating costs would increase slightly. In all, it remains doubtful whether the savings potential of such a capacity increase could amortize the acquisition within a reasonable amount of time.

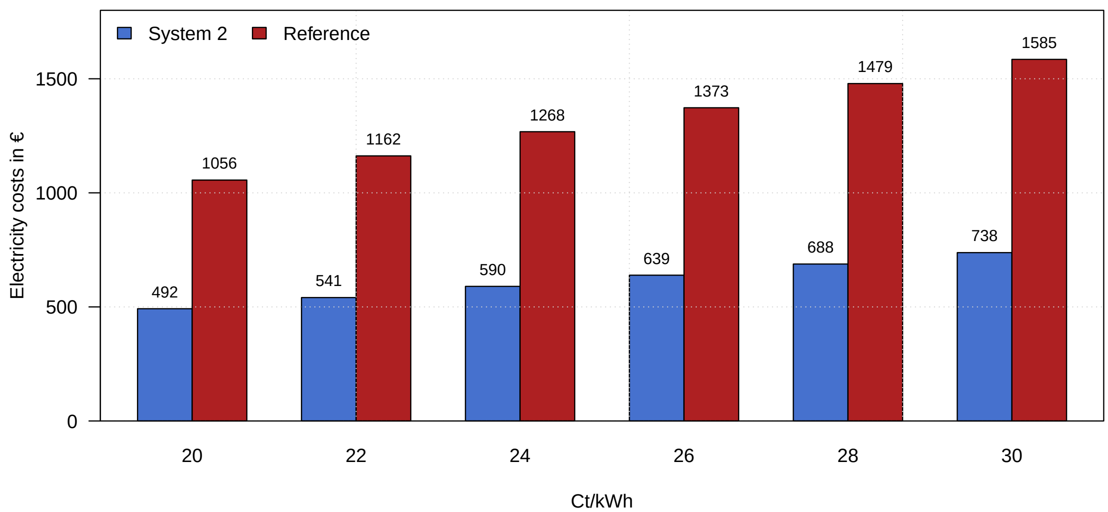
Figure 5: Electricity costs for different battery efficiency levels



Source: own depiction

Another critical aspect is the battery's discharge efficiency. As explained, we model the efficiency by a parameter defining the input-output-ratio of the battery, which was according to a literature suggestion set at 80 %. Figure 5 displays the variation of electricity costs over different efficiency levels for a 3 kWh storage (Systems 2 and 4), where the range corresponds to the proposition of Balcombe et al. (2015). It demonstrates that the assumption of a half as high battery efficiency would imply a reduction in annual savings of about 36 Euros, a comparatively small difference. Finally, we assess the sensitivity of expenses towards future consumer prices of electricity. This is a rather straightforward task. As long as electricity prices per kWh continue to exceed fossil fuel prices, there is no change in the usage rational: the use of self-generated electricity for direct consumption will have priority over PtH-conversion. Under all conceivable scenarios, it is highly unlikely that this price spread will vanish in the foreseeable future. Therefore, an isolated sensitivity check merely consists of a simple up- and downsizing of cost levels, which is executed here for a reasonable price range of 20 to 30 Ct/kWh. Figure 6 shows the corresponding variation in electricity costs for the reference household and for a household with PV module and 3 kWh battery storage (System 2). As obvious, the relative cost discrepancies of the two systems remains unchanged. In absolute terms, even at a future price level of merely 20 Ct/kWh, the annual cost savings of a PV owner with battery storage would amount to more than 500 Euros compared to a conventional consumer household.

Figure 6: Electricity costs for different consumer prices of electricity



Source: own depiction

4. Discussion

The purpose of this paper was to assess the cost savings potential of solar power self-consumption of single- and two-family houses in Southern Germany after the support period. We focused on a cross-sector perspective and therefore took heat demand (SH and DHW) into account. In the reference case, the heat demand is satisfied by the gas condensing boiler and electricity consumption by the grid. In this case, the annual costs amounted to 2860 Euros. The comparison of the four system setups (Fig. 2) indicate that the biggest (gross) cost savings potential could be achieved with a battery system and a thermal storage: about 920 Euro/year. However, the benefit of using

solar self-production without any storage applications is in a magnitude of 620 Euro/year. This shows that the bulk of the savings potential is driven by the correlation of PV production and electricity demand. Through the use of the PV system for self-consumption the annual electricity bill could be reduced significantly (-40%). The difference between the use of a battery system (about 840 Euro/year) and the PtH module (about 750 Euro/year) is of little importance in terms of cost savings. Nevertheless, against the backdrop of relative high battery prices per kWh, it seems more reasonable to choose the PtH option rather than the battery.
However, one must bear in mind that results are strongly influenced by our derivation method of load profiles for heat and electricity. Since the load profiles are mainly driven by socio-economic properties of the household (presence of children/unemployment), this holds for the individual savings potential as well. This relationship might be of interest for further research.

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Appendix A. Simulation of of heat demand

Symbols:

Index

$n = 1, ...N$: Days of the year ($N = 365$)

Parameters

A, B, C, D : Specific regional parameters (simgmoid-coefficients)

Exogneous variables

$\bar{T}_n$: Average temperature for day n at the respective location [$^\circ C$]

$\tilde{T}_n$: Respective temperature for day n as the geometric average outside temperature of days $n-1, n-2$ and $n-3$ [$^\circ C$]

Endogneous variables

Q_D = heat load at day D

Q_N = heat load per year (in kWh)

$h(T_{D_i})$ = sigmoid function for day D

Equations:

$$Q_D = h(T_D)\left[\frac{Q_N}{\sum_i^N h(T_{D_i})}\right] \quad \text{with} \quad h(T_D) = \left[\frac{A}{1+\left(\frac{B}{T-40}\right)^C} + D'\right] \tag{A.1}$$

$$T = \frac{T_t + 0.5T_{t-1} + 0.25T_{t-2} + 0.125T_{t-3}}{1 + 0.5 + 0.25 + 0.125} \tag{A.2}$$

Q_D is the target value and denotes the predicted energy consumption on day d. The sigmoid coefficients A, B, C and D are specific regional parameters representing the building structures and regional climatic characteristics of the German federal states with differentiation in wind-layers (see table B.1). In this study the coefficients for a normal wind-layer are used (BGW, 2006). T denotes the temperature applied to the specific day. In order to take the thermal storage capacity of buildings into account, the geometric series of the average outside temperature of days d, $d-1$, $d-2$ and $d-3$ is calculated. Finally, Q_N denotes the customer value (kWh). In practice this value would be the total amount of energy of the previous period for the specific household. Since this data is not available, we constructed an assumption based energy consumption average described in Section 2.1 The time series for the daily average outside temperature were taken from the Test Reference Year (TRY) database of the German Meteorological Service (DWD): region 13 - Swabian Franconian Alpine foreland (weather station: Mühldorf/Inn).

Table A.1: Parameters of the sigmoid function

Federal State	Q_N	A	B	C	D'
Bavaria	18 894	3.0217	-37.1823	5.6477	0.0950

Source: BGW (2006)

Appendix B. Simulation of photovoltaic production

Symbols:

Index

$t = 1, ...T$: Hours of the year ($T = 8760$)

$n = 1, ...N$: Days of the year ($N = 365$)

Parameters

ϕ : Latitude of the weather station / PV system

γ : Azimuth of the PV system

β : Slope of PV panel

ρ : Ground albedo (0.2)

A : Total panel area

PR : Performance ratio (0.7)

κ_{TC} : Temperature coefficient of the solar module (-0.4%/° C)

T_{NOCT} : Nominal operating cell temperature (25° C)

T_{STC} : Standard test condition temperature of the solar module (46° C)

η_r : Reference solar module efficiency (15.3%)

Exogenous variables

ω_n : Hour angle at solar noon at day n

G_t^g : Total radiation on horizontal surface in$t$

G_t^b : Beam radiation on horizontal surface in t

G_t^d : Diffuse radiation on horizontal surface in t

T_t^a : Ambient temperature in t

Endogenous variables

P_t^{PV} : Generated electricity by the PV module in t [kWh]

G_t : Total radiation on tilted surface in t

R_n^b : Geometric factor at day n

ψ_n : Angle of incidence at day n

ψ_n^Z : Zenith angle at day n

δ_n : Declination at day n

η_t : Solar module efficiency in t

T_t^C : Cell temperature in t

Equations:

$$G_t = R_n^b \times G_t^b + (0.5 \times (1 + \cos\beta \times G_t^d) + \rho \times G_t^g \tag{B.1}$$

$$G_t^g = G_t^b + G_t^d \tag{B.2}$$

$$\cos(\psi_n) = \sin(\delta_n) \times (\sin(\phi) \times \cos(\beta) - \cos(\phi) \times \sin(\beta) \times \cos(\gamma)) + \cos(\omega_n) \times \cos(\delta_n) \times (\cos(\phi) \times \cos(\beta) + \sin(\phi) \times \sin(\beta) \times \cos(\gamma)) + \cos(\delta_n) \times \sin(\beta) \times \sin(\gamma) \times \sin(\omega_n) \tag{B.3}$$

$$\cos(\psi_n^Z) = \cos(\phi) \times \cos(\delta_n) \times \cos(\omega_n) + \sin(\phi) \times \sin(\delta_n) \tag{B.4}$$

$$R_t^b = \frac{\cos(\psi_t)}{\cos(\psi_t^Z)} \tag{B.5}$$

$$\delta_n = -23.45 \times \cos(2 \times \frac{\pi}{365.25} \times (n + 10)) \tag{B.6}$$

$$\eta_t = \eta_r \times (1 + \kappa_T C \times (T_t^c - T_{STC}) \tag{B.7}$$

$$T_t^c = T_t^a + (T_{NOCT} - 20°C) \times \frac{G_t}{800\, W/m^2} \tag{B.8}$$

Appendix C. Cost simulation

Symbols:

Index

$t = 1, ...T$: Hours of the year ($T = 8760$)

Natural constant

c : Specific heat capacity of water (4182 $joule/[kg \cdot °C]$)

Parameters

C : Capacity of the battery storage [kW]

η : Efficiency of heating rod

m : Capacity of thermal storage [kg]

$T^{s,\, min}$: Minimum temperature within the thermal storage [$°C$]

$T^{s,\, max}$: Maximum temperature within the thermal storage [$°C$]

$\bar{S}$: Capacity of heating rod [kW]

p^g : Consumer price of gas [Euro/kWh]

p^e : Consumer price of electricity [Euro/kWh]

Exogenous variables

P_t^{PV} : Generated electricity by the PV module in t [kWh]

Q_t^E : Electricity consumption in t [kWh]

Q_t^H : Heat consumption in t [kWh]

Endogenous variables

B_t : State-of-charge of the battery at the end of t [kW]

T_t^s : Temperature within the thermal storage at the end of t [$°C$]

PtH_t : Heat energy [kWh] generated through PtH in t

E_t : Standing losses of heat energy [kWh] stored within the thermal storage during t

Equations of motion:

$$B_t = B_{t-1} + P_t^{PV} - Q_t^E \tag{C.1}$$

$$T_t^s = T_{t-1}^s + \Delta T_{t-1,t}^s \tag{C.2}$$

$$\Delta T_{t-1,t}^s = \frac{3\,600\,000 \frac{J}{kWh}}{c \times m} \times (PtH_t - Q_t^E - E_t) \tag{C.3}$$

$$PtH_t = max.\{B_{t-1} + P_t^{PV} - Q_t^E - C; 0\} \tag{C.4}$$

$$E_t = \frac{0.08532 \; \frac{kWh}{C^\circ} \times T_{t-1} - 2.11937 \; kWh}{24} \tag{C.5}$$

Side conditions:

$$0 \leq B_t \leq C, \; T^{s,\,min} \leq T_t^s \leq T^{s,\,max}$$

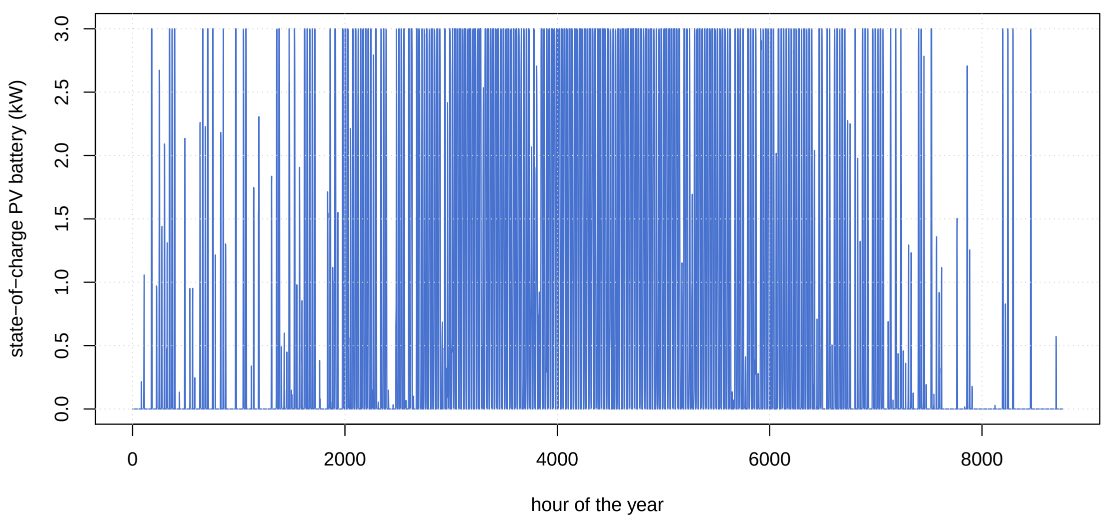
Derivation of the maximum amount of heat energy extractable from the thermal storage $\widetilde{Q_t^H}$:

Making use of (C.3):

$$T^{s,\,min} - T_{t-1}^s = \frac{3\,600\,000 \frac{J}{kWh}}{c \times m} \times (PtH_t - Q_t^E - E_t)$$

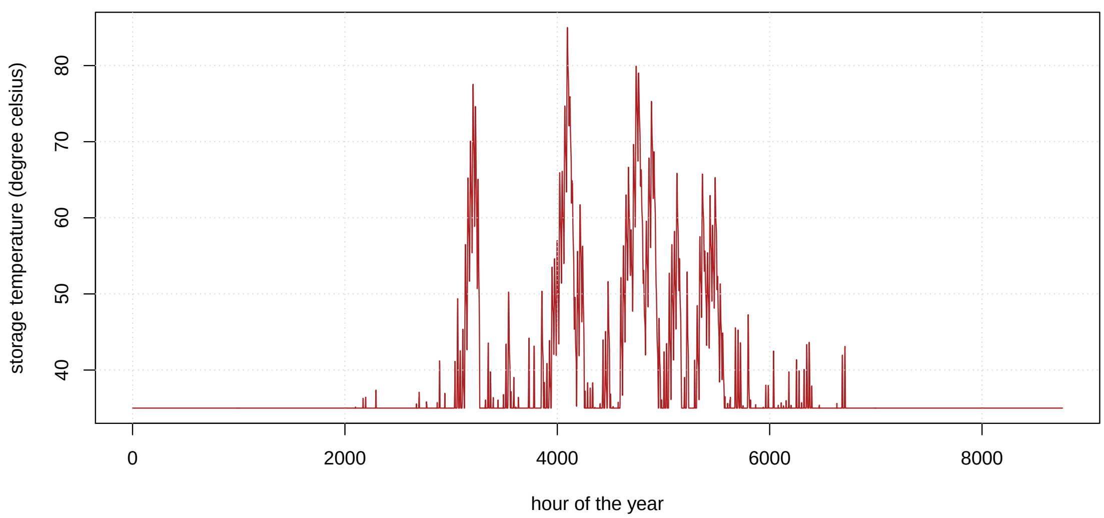
$$\widetilde{Q_t^H} = \frac{c \times m}{3\,600\,000 \frac{J}{kWh}} \times (T_{t-1}^s - T^{s,\,min}) + PtH_t - E_t$$

Figure C.1: Time profile of PV battery charge (System 4)



Source: own depiction

Figure C.2: Time profile of heat storage temperature (System 4)



Source: own depiction