MSc Program
Renewable Energy Systems

Potential variable cost reductions through optimized dispatch of heat pump with thermal storage systems

A Master's Thesis submitted for the degree of
"Master of Science"

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Affidavit

I, **Ulrich Tschiesche**, hereby declare

1. that I am the sole author of the present Master Thesis, "Potential variable cost reductions through optimized dispatch of heat pump with thermal storage systems", 55 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

Flexible controlled heat pumps in combination with thermal storages are expected to play a key role in near future energy systems exhibiting larger shares of renewable energies. In such systems, surplus energy from windfarms or PV will be stored and used later at times of higher energy demands and prices. For energy consumers, this will lead to cost savings while supporting the further expansion of renewable energies. In this work, these relevant cost savings are quantified using a linear programming approach. Furthermore, is this approach applied to different energy users, electricity tariffs and heat demands. As a result, it is shown that the potential variable cost savings with respect to heat users and electricity tariffs vary from 0.9 to 2.7 €/MWh, and the potential load shift from 3 to 6 hours.

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1. Introduction

Following the “Paris Climate Agreement” of 2015 the target of international climate policy was to limit global warming by 2°C. To achieve this target industrialized countries are encouraged to largely stop the use of fossil fuels by the middle of this century.

The EU has set up a climate and energy policy framework for 2030. It requests that by 2030 the EU`s greenhouse gas emissions be reduced by at least 40 % as compared to 1990. At the same time, a share of renewable energy in the total energy consumption of 27 % and an increase in energy efficiency of 27 % must be achieved. For Austria, the greenhouse gas emission reduction target of 36 % by 2030 and compared to 2005 is proposed in the new draft “Effort Sharing Regulation”. To keep the costs for climate change mitigation measures at a tolerable level, investments should focus on technologies which support future developments and enable the phasing out of fossil fuels (Umweltbundesamt, 2017).

According to the Austrian report on climate protection 2017 the main sources of greenhouse gas emissions (excluding the emissions trading system) in 2015 were the sectors transport (44.7 %), agriculture (16.3 %), buildings (16.1 %) as well as energy and industry (12.6 %).

EU commission analysis predict that 90 % of the emissions in the building sector can be reduced until 2050 (Umweltbundesamt, 2017). Currently the Austrian building sector still relies on fossil fuels like oil or gas for heating purposes to a large extent. Whereas the contribution of renewable energy technologies like solar thermal or heat pumps, which can also be used to substitute fossil fuels (Agora, 2017), is rather small. In 2015 the share of energy provided by solar thermal and heat pumps was only about 4 % of the total energy consumption in the building sector.

The high future potential of those technologies is also reflected in the large increase of new installed heat pumps in the recent years. From the year 2000 to 2015 the amount of new installed heat pump capacities increased from about 25 MW_{th} per year to more than 200 MW_{th} per year (Umweltbundesamt, 2017). For Austria, future model predictions estimate an absolute increase in operating heat pumps in the range of 260.000 to 620.000 pieces by the year 2030 (Hartl et al, 2016).

In addition to the positive effects of emission reduction by compensation of fossil fuels flexible operating heat pumps are also essential to integrate fluctuating renewable energies efficiently in the long run. Flexible operating heat pumps and thermal storage systems can be used for operational strategies which allow the integration of electricity production from renewable energy sources (Fischer et al, 2014; Molitor et al, 2011; Papaefthymiou et al, 2012). Therefore, the flexibility of such systems can also help to reduce peak loads (Agora, 2017).

Several recent studies deal with demand side management (DSM) in connection with heat humps and thermal storage systems, variable electricity prices and system cost savings due to different operation schemes.

Molitor et al (2011) analyzed the load shifting potential of heat pump control in single family households, exposed to time-varying electricity prices using a detailed physically based simulation model. The conclusion of this study is that by applying currently available tariff schemes potential cost savings for the end consumer are small but with the application of time-varying tariff schemes financial benefits are increasing.

In his work Papaefthymiou et al (2012) present a methodology for the quantification of the flexibility offered by the thermal storage of building stock equipped with heat pumps, to power systems with significant penetration of wind power. Also, in this study the potential of heat pumps as a flexibility option show a significant impact of operational constraints. Furthermore, it was found that this DSM option is a valuable alternative to conventional storage plants.

Other studies evaluated a range of operational strategies for capacity controlled heat pumps connected to a thermal storage in German multifamily houses (Fischer et al, 2014) or the flexibility of a heat pump pool when the Smart-Grid-Ready interface is used for direct load control (Fischer et al, 2016).

In this study, a straightforward linear optimization model was developed. The model optimizes the operational costs of a combined heat pump and thermal storage system under certain constraints. Data on electricity prices and heat load profiles were used as model input.

The main research questions in this study are:

1. What are the potential cost savings for different heat users which can be obtained from the operation of a combined flexible heat pump control and storage system?

and

2. How would an increased PV integration in the Austrian power supply system influence the operational cost savings resulting from a combined flexible heat pump control and storage system?

In addition to the previously mentioned research this work also contributes to the current research by analyzing the cost effects of a flexible heat pump and thermal storage system for different heat users and electricity prices influenced by larger shares of PV.

2. Materials and methods

2.1 Data background information

In this study, publicly accessible data like historic electricity spot market prices was used along with data from other sources such as heat load profiles and modelled electricity prices used as input data for the optimization model. The following chapter illustrates the major backgrounds in terms of access and properties of this model input data.

2.1.1. Electricity prices

Like other commodities electricity is traded in markets where wholesale prices are driven by supply and demand interactions. Beside the so called over-the-counter (OTC) market there are also formalized markets such as the Austrian EXAA, German EEX or French EPEX power exchanges (E-Control, 2017).

Data on electricity prices is accessible online. Historic electricity spot market prices for example can be downloaded from the homepage of the "European Energy Exchange AG" (www.eex.com).

In this study, a time series of EEX spot market prices on an hourly basis ranging from 2003 to 2014 was used for simulations. Due to comparison reasons and computational limitations, the optimization model was conducted only for the year 2012. In 2012 the spot market prices range from 0 to almost 180 €/MWh (Figure 1).

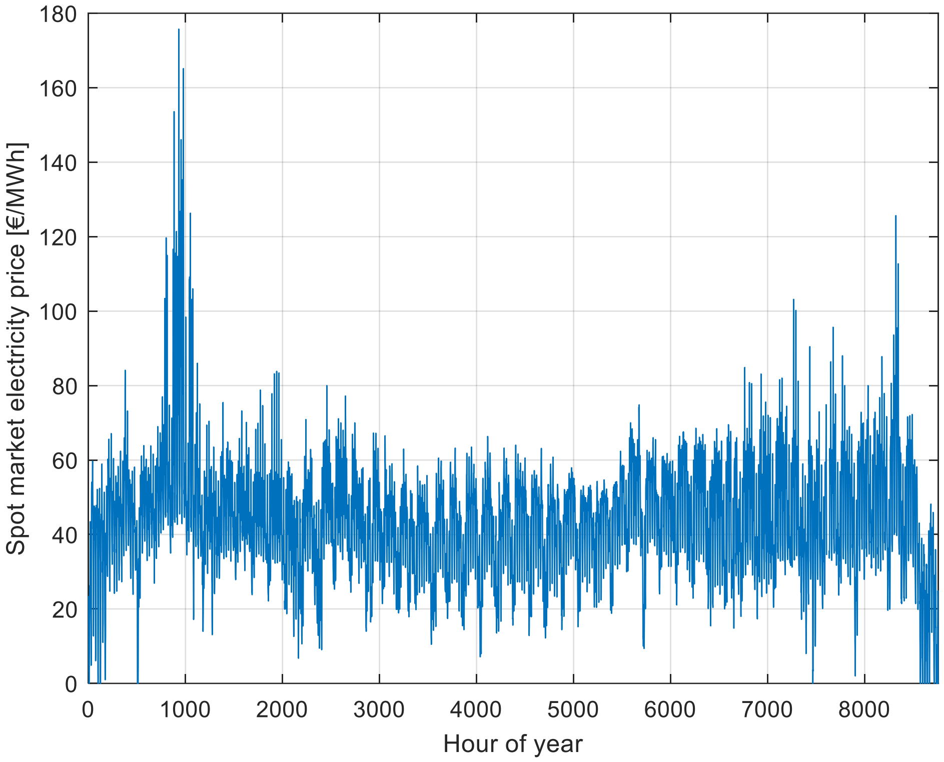

Figure 1: Hourly EEX spot market electricity prices of the year 2012 (Source: own graph)

The previously mentioned wholesale prices are the basis for a supplier's energy price estimation. Usually, consumer prices include additional system charges, taxes, levies and surcharges. For example, electricity consumers in Austria must pay the electricity levy, the green power support payments, the community levy and VAT (E-Control, 2017). Therefore, a basic charge of 50 €/MWh was added to the hourly spot market prices representing these additional costs (Figure 2). The average or mean value of this hypothetical variable electricity retail tariff is 93.2 €/MWh.

At this point, it must be emphasized that the variable electricity tariffs used in the simulations of this study are purely hypothetical tariffs which do not exist today.

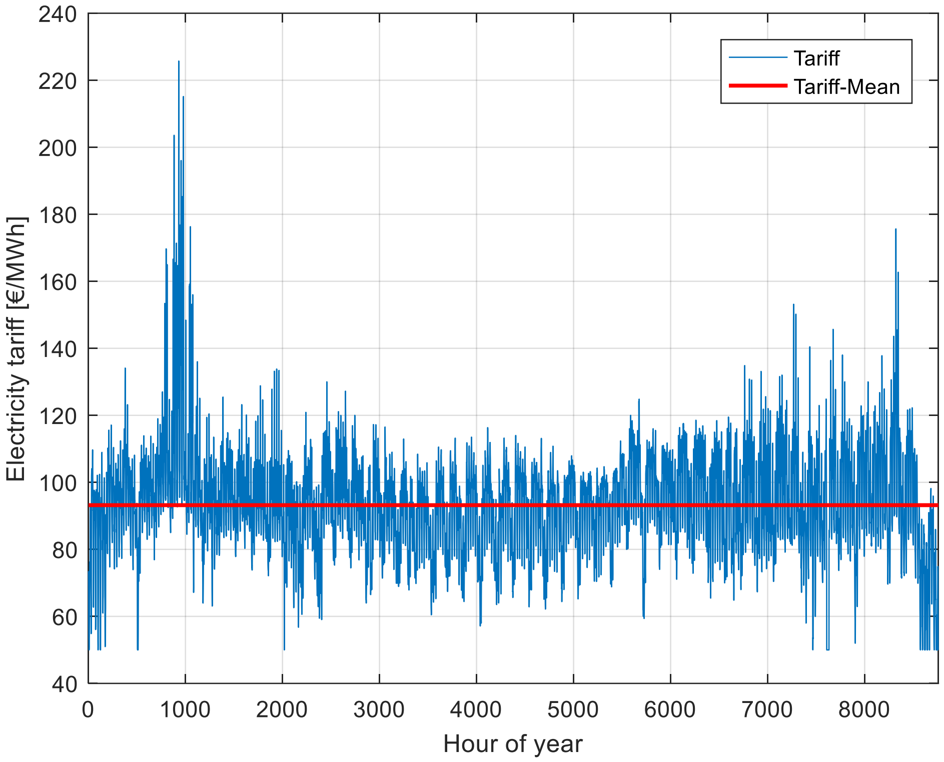

Figure 2: Hypothetical variable electricity retail tariff of the year 2012 (Source: own graph)

2.1.2. Heat load

The basic methodology for the calculation of heating and cooling energy needs is shown in Figure 3. According to this methodology the energy demand on an hourly basis for heating is directly connected with outdoor temperatures and user profiles.

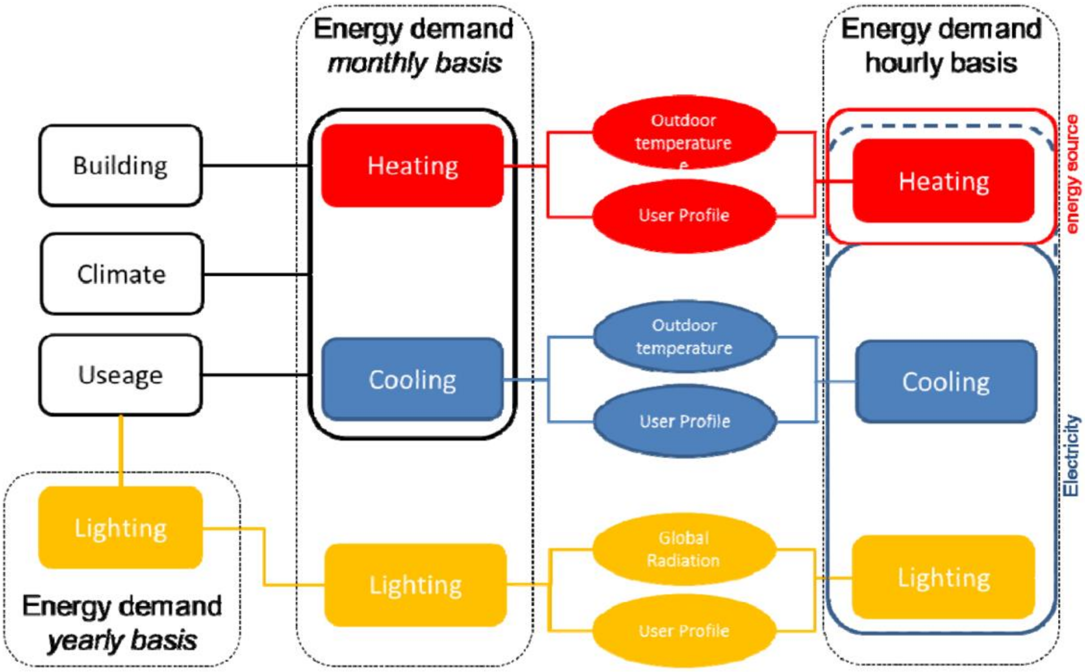

Figure 3: System diagram for the calculation of heating and cooling energy needs (Source: Kranzl et al (2014), p.16)

Today two common solutions for the estimation of heat load profiles for certain time periods exist. The use of “standard load profiles” is already a well-established, old and less accurate solution. Whereas the importance of “synthetic load profiles” increased in recent years and are now applied in many research projects (Fischer et al, 2016).

In this study, synthetic load profiles derived in the research project PRESENCE[1] have been applied. Within this model a weight is determined for every hour, with the temperature difference between the outdoor temperature and the heating threshold temperature. Subsequently the energy demand of heating and cooling was estimated on an hourly basis by multiplying the computed weights for each hour with the monthly energy demand (Kranzl et al, 2014).

By following the above-mentioned procedure annual heat load profiles for different user categories have been calculated by multiplying the weights for each hour of the year by the assumed annual heat demands. Further details on the user categories and corresponding annual heat demands under consideration can be found in Table 1.

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[1] http://www.eeg.tuwien.ac.at/eeg.tuwien.ac.at_pages/research/downloads/PR_356_B068675_PRESENCE_FinalPublishableReport_submitted__neueVorlage_rev1.pdf

For comparability reasons, the optimization model was conducted using the synthetic heat load profiles of only one location, the city of Vienna, Austria, and a constant annual heat demand of 50 MWh per year for all user categories. Furthermore, the same optimization model was conducted with a range of variable annual heat demands corresponding to certain user categories.

Table 1: Synthetic heat load profiles and annual heat demands for different user categories in Vienna (Source: own data)

Number	Data name (German)	User category name (English translation)	Annual heat demand [MWh/a]	
			Constant	Variable
1	EFH_NEU	Single-family house	50	10
2	MFH_NEU	Multi-family house	50	50
3	Handel	Retail	50	60
4	Banken	Banking	50	200
5	Beherbergung	Lodging	50	150
6	Baeckerei	Bakery	50	100
7	Waescherei	Laundry	50	100
8	Dienstleistung	Services	50	200
9	Gastst_tte	Guesthouse	50	50
10	Gewerbe	Manufacturing	50	300

Figure 4 shows the annual heat load profile of a single-family household having an annual heat demand of 50 MWh. In this user category, the highest heat loads naturally occur during winter season and can reach a maximum of 23.1 kW. During the summer season, the lowest estimated heat loads are about 0.9 kW, due to demand for hot water.

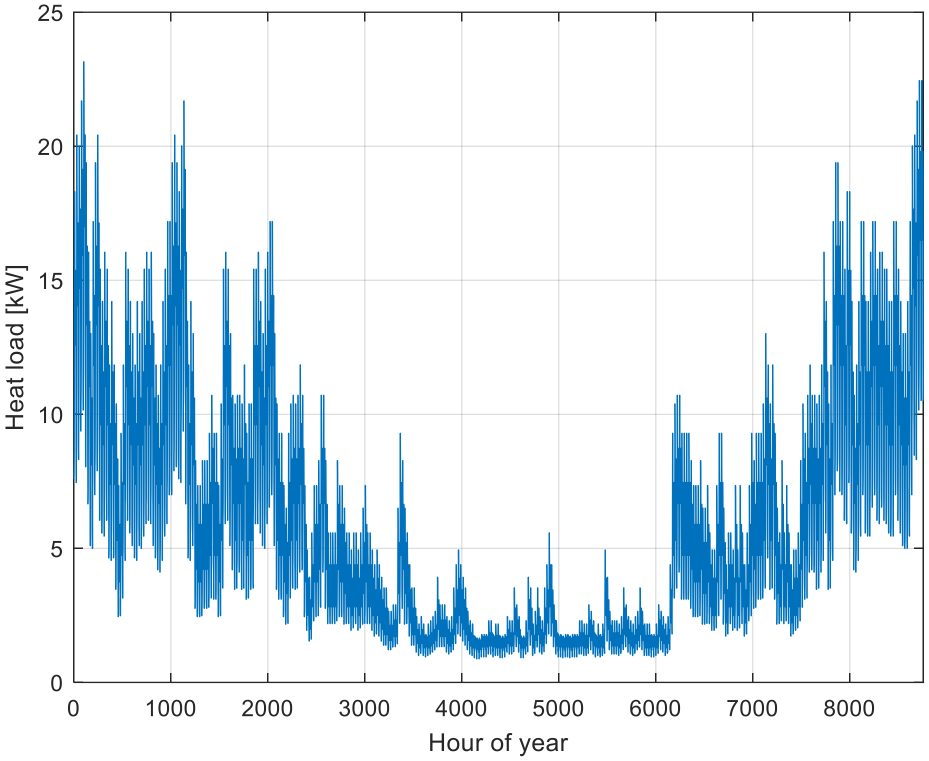

Figure 4: Annual synthetic heat load profile for a single-family house in Vienna (Source: own graph)

Furthermore, heat load duration curves for all user categories have been derived from the earlier estimated heat load profiles (see Figure 5). The area below the heat duration curve equals the annual heat demand, which in this case is assumed to be constant for all user categories.

By comparing the different user categories, it was found that user category “Retail” has the largest differences in maximum and minimum heat loads. While the peak heat load in this category is 31.6 kW the lowest heat load is only 0.07 kW. While user category “Bakery” has the smallest differences in maximum, 12.5 kW, and minimum, 1.6 kW, heat loads. Moreover, the heat load duration curves of other user categories are located in between the categories “Retail” and “Bakery”. This means that e.g. “Lodging” has smaller deviations in its heat load profile than “Retail” but larger deviations than “Bakery”.

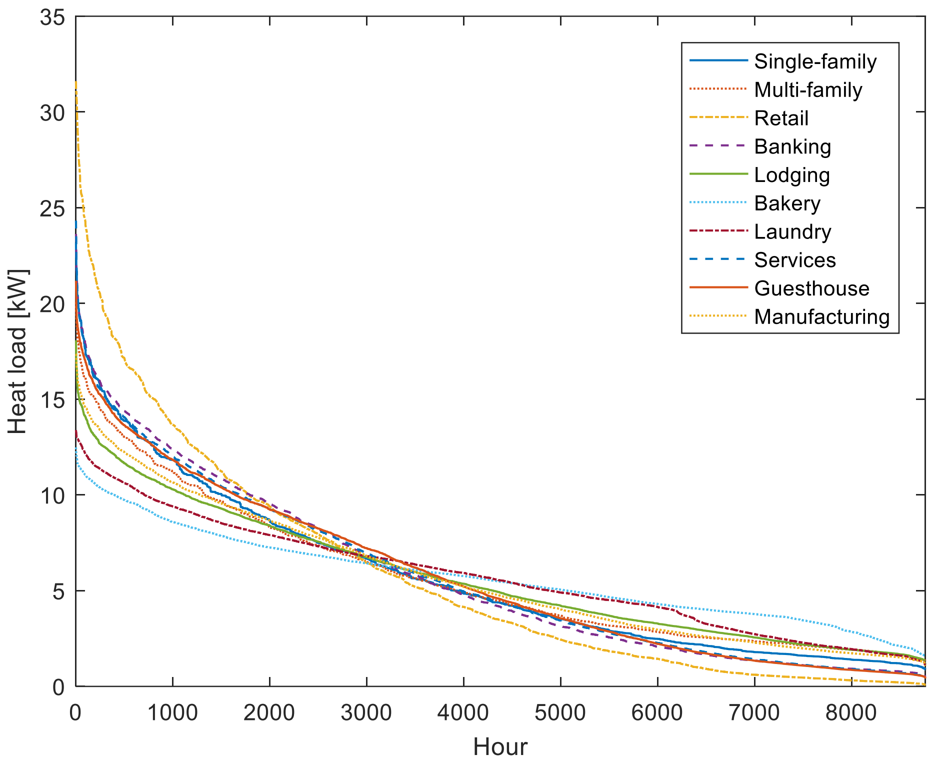

Figure 5: Heat load duration curves of synthetic heat load profiles for different user categories in Vienna (Source: own graph)

2.1.3. Electricity prices for different PV penetration levels

With an increasing share of energy provision from renewable energy sources like solar or wind energy the conventional electricity price pattern is likely to change over time. Especially at times of high wind feed-in and/or high solar irradiation spot market prices are expected to decrease. In recent years, even negative spot market prices developed at times of large energy feed-in coming from German off-shore wind farms at times of strong local winds.

Furthermore, increasing PV penetration levels can lead to lower electricity prices where spot market prices used to be high (Hartner, 2016).

In this study, modelled electricity prices developed for different PV penetration levels have been used. These modelled prices have been calculated in previous studies by Permoser (2016) and Hartner (2017). First, a linear dispatch model was used for the derivation of electricity spot market prices for the year 2012. Based on the calibrated model, the installed PV capacity was raised to certain amounts and the corresponding spot market prices have been calculated (Permoser, 2016).

Like the spot market prices in Chapter 2.1.1. a basic charge of 50 €/MWh was added to the modelled electricity prices. A comparison of the hypothetical historic and modelled electricity tariffs (PV share 0 %) can be seen in Figure 6. The correlation coefficient of modelled and historic prices is 0.77 (Hartner, 2017).

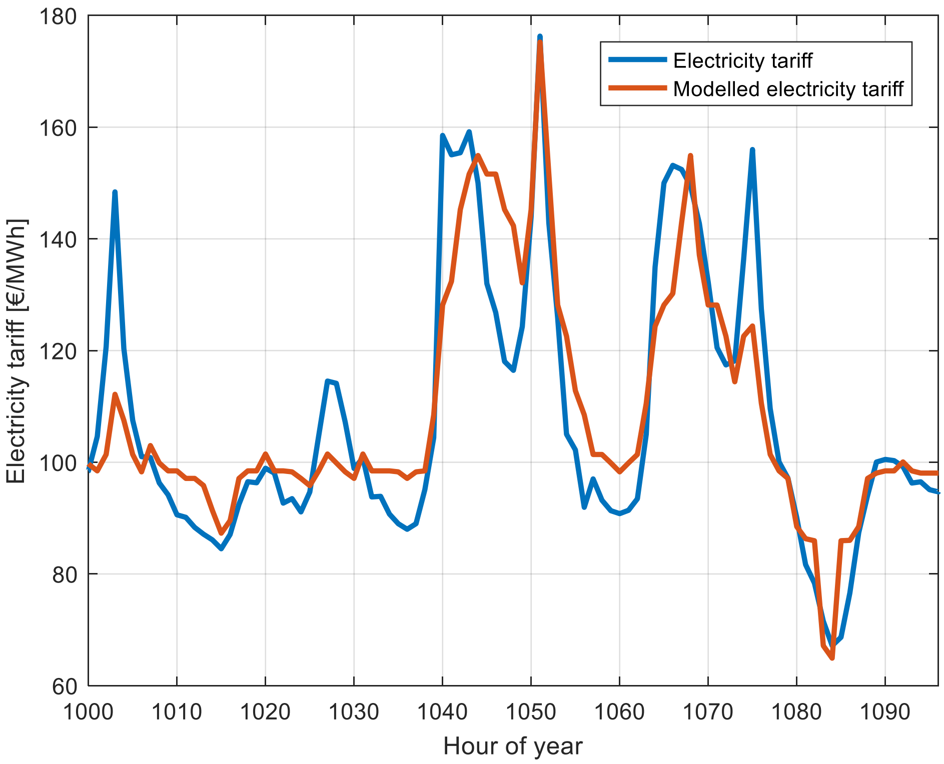

Figure 6: Hypothetical historic and modelled electricity retail tariffs (PV share 0%) (Source: own graph)

The effect of increased electricity feed in from PV installations on electricity prices is shown in Figure 7 for winter season and in Figure 8 for summer season. At noon when electricity tariffs are usually high, larger shares of PV would lead to significantly lower electricity tariffs. This effect increases with increasing installed PV capacities and is also depending on weather conditions and the corresponding irradiation levels.

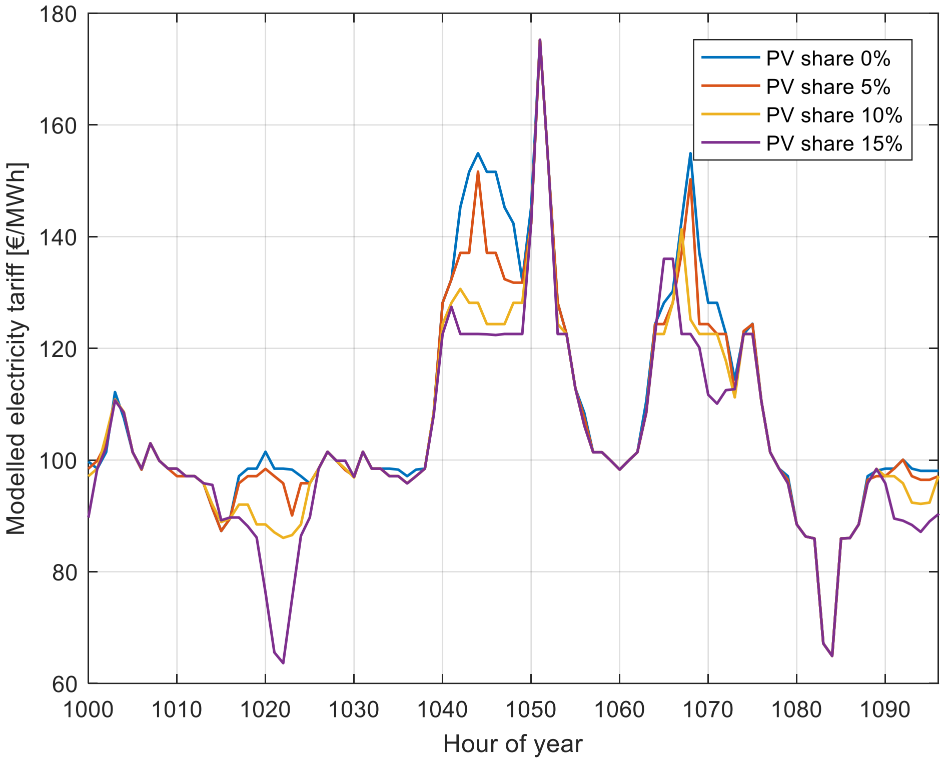

Figure 7: Hypothetical modelled hourly electricity retail tariffs for different PV penetration levels (Winter season - mid of February) (Source: own graph)

By comparing the figures for the winter and summer seasons it can be seen that the effect of reducing the noon peaks of electricity tariffs by increasing PV penetration is much larger during the summer season. According to Figure 8 the electricity tariffs in summer even fall until the hypothetical basic charge of 50 €/MWh is reached. This means that the corresponding spot market prices would be zero or even negative.

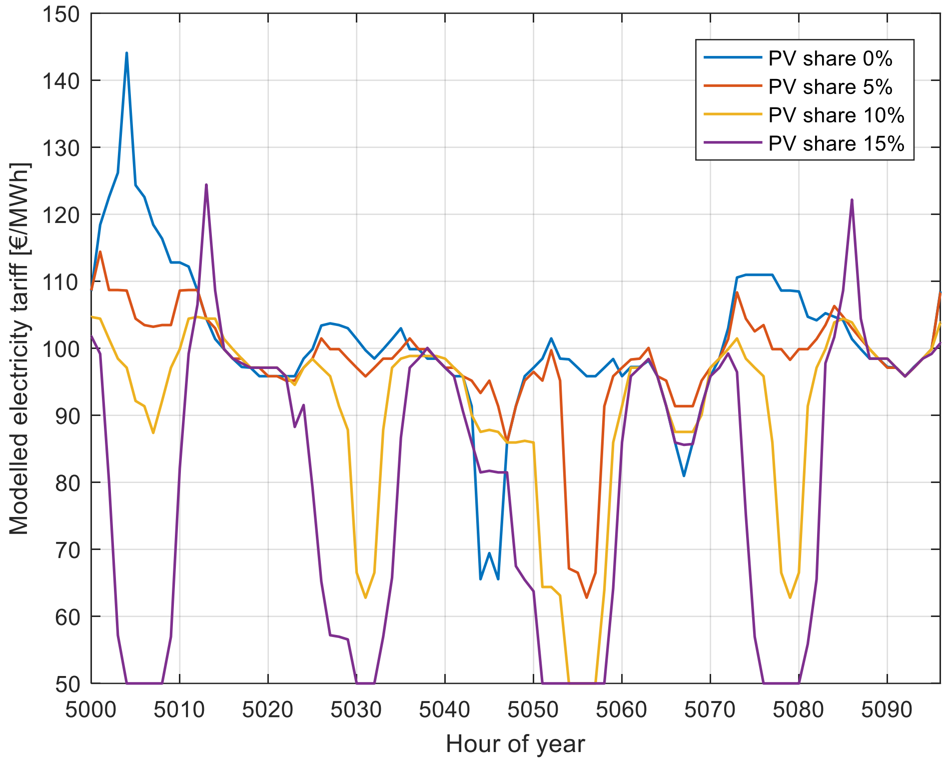

Figure 8: Hypothetical modelled hourly electricity retail tariffs for different PV penetration levels (Summer season - end of July) (Source: own graph)

2.2. Model description

Based on the linear programming approach an optimization model was developed using the above described input data and the software tool MATLAB[2] in combination with YALMIP[3] and a solver provided by GUROBI[4].

2.2.1. Linear programming

In this study, the optimization problem was solved using a linear programming approach. Basically, in linear programming (or optimization) a linear objective function is minimized or maximized while satisfying a set of linear equality and/or inequality constraints (Bazaraa et al, 2010).

At first an objective function is formulated. Subsequently decision variables and

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[2] https://de.mathworks.com/products/matlab.html
[3] https://yalmip.github.io/
[4] http://www.gurobi.com/index

constraints (linear and/or bound constraints) are defined. Variables stratifying all the constraints are called feasible points and a set of all feasible points yield the feasible region. A geometric solution of an optimization problem is shown in Figure 9. In this example, the problem consists of only two variables. The *objective function* must be moved in parallel to the point at which the objective is minimized.

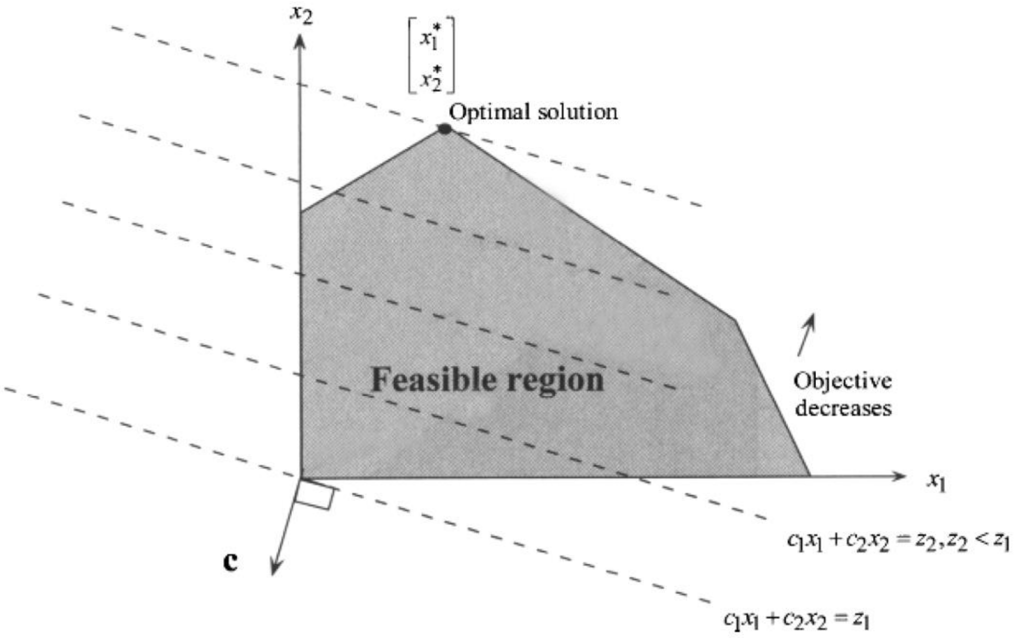

Figure 9: Geometric solution of a linear programming problem (Source: Bazaraa M. S. et al (2010), p. 19)

For more complex problems consisting of more than two variables other computational methods are widely used today (see Chapter 2.4.).

2.2.2. Optimization problem formulation

The formulation of the heat pump and storage operation optimization problem follows the above described methodology of linear programming. The defined objective is minimizing the total operational costs of a heat pump driven heating system for a certain period (see Equation 1).

Objective function:

$$Min \sum_{t=1}^{T} C_{hp,t} \cdot P_{hp,t} \tag{1}$$

The operational costs at time t are calculated by multiplying variable fuel costs the heat pump $C_{hp,t}$ by the operational power of the heat pump $P_{hp,t}$. The costs for operating the heat pump are derived from the electricity prices $p_{el,t}$ divided by the heat pump's coefficient of performance COP_{hp} (see Equation 2). Due to simplification issues a constant COP_{hp} of 3 was applied in all conducted calculations.

$$C_{hp,t} = \frac{p_{el,t}}{COP_{hp}} \tag{2}$$

Heat pump and storage operation constraints:

As next step, several linear and bound constraints on the operation of the heat pump and storage are formulated.

The first linear constraint defines that coincident loading of the storage with heat and directly heating of the building is possible. Therefore $P_{hp,t}$ is the sum of the thermal energy for loading the storage $x_{hps,t}$ and the thermal energy for directly heating $x_{hpd,t}$ (see Equation 3).

$$P_{hp,t} = x_{hps,t} + x_{hpd,t} \tag{3}$$

Furthermore, the sum of the thermal energy for directly heating $x_{hpd,t}$ and the thermal energy for unloading the storage $x_{st,t}$ is limited by the demanded heat load d_t (see Equation 4).

$$x_{st,t} + x_{hpd,t} \geq d_t \tag{4}$$

The sum of $x_{hps,t}$ and $x_{hpd,t}$ is in the range between 0 and the maximum capacity of the heat pump HP_{max} (see Equation 5).

$$0 \leq x_{hps,t} + x_{hpd,t} \leq HP_{max} \tag{5}$$

Subsequently, constraints characterizing and limiting the operation of the storage are set. By applying a linear storage balance equation, the state of charge of the storage at time t plus 1 (SOC_{t+1}) is calculated.

The state of charge SOC_{t+1} is the state of charge of the previous time step SOC_t plus the additionally needed thermal energy for loading the storage $x_{hps,t}$ minus the thermal energy deduced from the storage (unloading) $x_{st,t}$ and minus 2 % thermal energy losses ($SOC_{t-1} \cdot 0.02$) per hour (see Equation 6).

$$SOC_{t+1} = SOC_t + x_{hps,t} - x_{st,t} - SOC_t \cdot 0.02 \tag{6}$$

The constraints regarding the operation of the storage express, that thermal energy for loading the storage $x_{hps,t}$ must be in the range of 0 and the maximum loading capacity of the heat pump cap_{hp}. Likewise, the thermal energy unloading the storage $x_{st,t}$ must be in the range of 0 and the maximum unloading capacity of the storage cap_{st} (see Equation 7 and Equation 8).

$$0 \leq x_{hps,t} \leq cap_{hp} \tag{7}$$

$$0 \leq x_{st,t} \leq cap_{st} \tag{8}$$

The storages' state of charge SOC_t is always in the range of 0 and the maximum state of charge SOC_{max} (see Equation 9).

$$0 \leq SOC_t \leq SOC_{max} \tag{9}$$

2.3. Model settings

Some of the defined model parameters have already been discussed in the previous chapters. An additional assumption request that the storage cannot be loaded and/or unloaded at maximum capacity of the heat pump. Therefore, the maximum loading level (cap_{hp}) and unloading level (cap_{st}) of the storage is set to 95 % of the maximum capacity of the heat pump.

To make sure that the heat pump is capable to supply heat throughout the considered period the maximum capacity of the heat pump HP_{max} was assumed to be 110 % of the maximum heat demand.

For the calculation of SOC_{max} the maximum heat load within the considered period was multiplied by factors defining possible scenarios ranging from 0 to 10. In further consequence, the optimization model was conducted for each storage size scenario, user category and PV penetration level. The calculated model outputs were later used to draw conclusions about a reasonable storage size, either with or without "flexible control" (smart metering) and for different PV penetration levels.

2.4. Software

The linear optimization model described in the previous chapters was solved using various software tools. The developed model was set up and calculated using MATLAB scripts which can be applied for solving linear optimization problems.

In recent years, a wide range of software for solving optimization problems is available. Many of those so-called solvers are free and easily accessible on the Internet (Löfberg, 2004). The MATLAB toolbox YALMIP was used for the simple development of the optimization problem. In several previous works YALMIP proved to be a powerful tool for optimization algorithm development in MATLAB (Löfberg, 2004).

Besides linear programming, YALMIP also supports standard problem classes like quadratic programming or second order cone programming and advanced problem classes like robust optimization or multiparametric programming. For increased solving abilities of these problems, around 20 external solvers are interfaced with YALMIP (Löfberg, 2004).

In this study, the external solver GUROBI was used for the linear programming optimization task. GUROBI solver is a commercial solver for mixed-integer conic programs and is free available for academia (Löfberg, 2017).

Used software and versions:

- MATLAB R2016b
- YALMIP toolbox R20160930
- GUROBI optimizer 7.0.2

3. Results

This chapter explains the results derived from the applied optimization modeling and scenarios. Estimates for the model variables, demonstrating the underlying principles of an optimized heat pump and storage operation, are presented. Furthermore, the annual and specific costs in relation to different storage capacities are presented for all user categories and PV penetration levels. Finally, savings from cost reduction, due to the optimized operation of a flexible heat pump and thermal storage system, are presented for all analyzed scenarios.

3.1. Optimized storage and heat pump operation for different user categories

The basic functioning of the simulated heat pump and thermal storage system with the relevant model variables are presented in Figure 10 for the winter, and in Figure 11 for the summer seasons. These illustrations give an overview of parameters like heat load or electricity tariff and the dynamic interactions between different variables.

Per hour, the required heat load is provided by direct heat from the heat pump or by unloading the storage or by both simultaneously (see Figure 10a). Consequently, the storage's state of charge increases when loading the storage and decreases when unloading the storage (see Figure 10b). The assumed heat pump can provide direct heat or load the storage (see Figure 10c). The prevailing dynamic electricity tariff fluctuations are shown in Figure 10d.

As mentioned earlier, the overall goal of the optimization conducted here is to find the minimum total operational costs. Therefore, the variables are combined such that at times of high electricity prices the storage is unloading. At the same time SOC decreases and the power of the heat pump is kept as low as possible. Whereas at times of low electricity tariffs the heat pump provides direct heat supply and is loading the storage.

For example, in Figure 10 the electricity tariff rises from 90 €/MWh in hour 1037 to 160 €/MWh in hour 1040. The system then reacts to the price increase with a short delay.

From hour 1040 to hour 1044 the tariff stays high and therefore the generation of the heat pump (Generation HP) is zero. Within the same time the storage is unloading. From hour 1040 to hour 1044 the heat demand is fully provided by unloading the storage. At hour 1046 the storage is almost empty and the heat pump starts again providing direct heat and loads the storage.

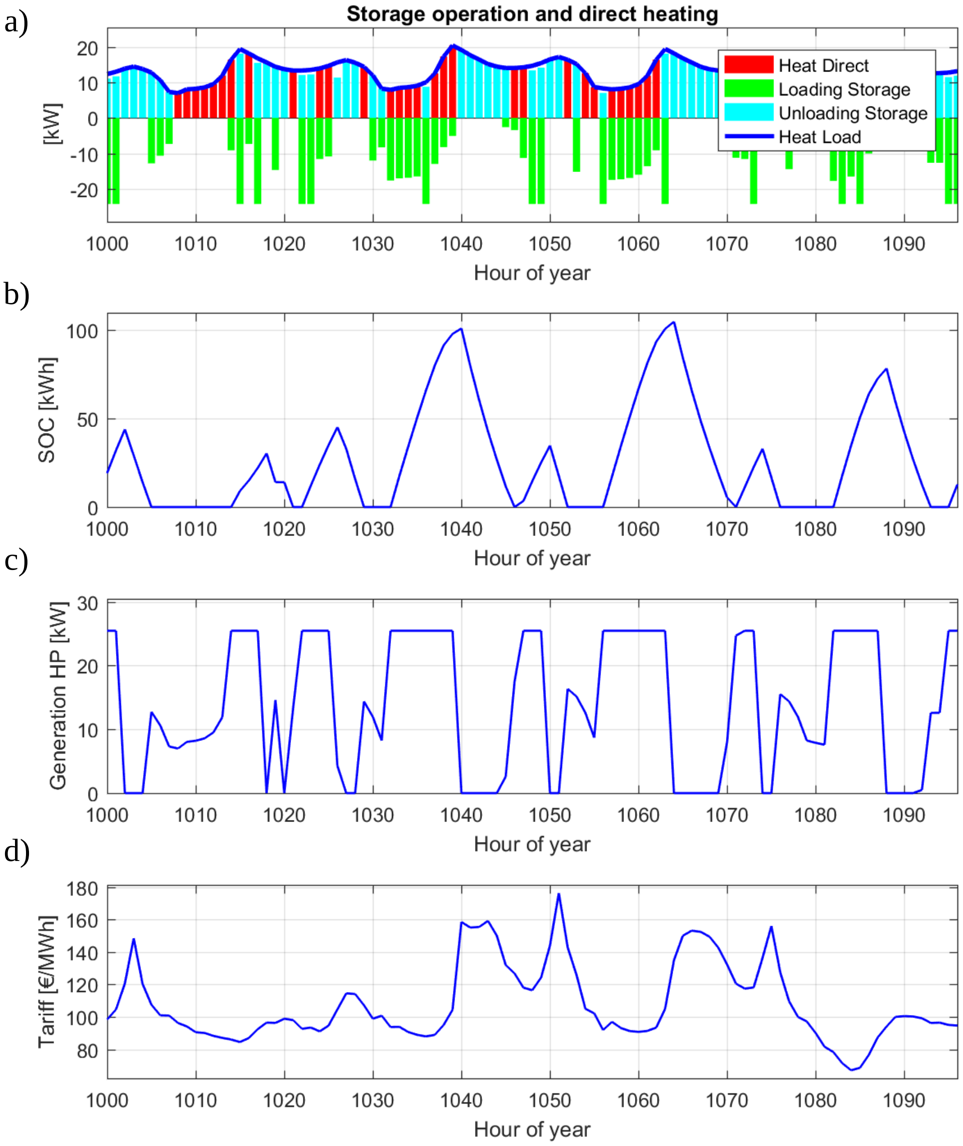

Figure 10: Time series of the derived optimization model variables and parameters for a heat load profile of a single-family household (Winter season - mid of February) (Source: own graph)

Since the heat demand for user “Single-family” is lower during the summer than during winter seasons, also the corresponding heat loads, the storage`s state of charge and the heat generation of the heat pump are lower (see Figure 11).

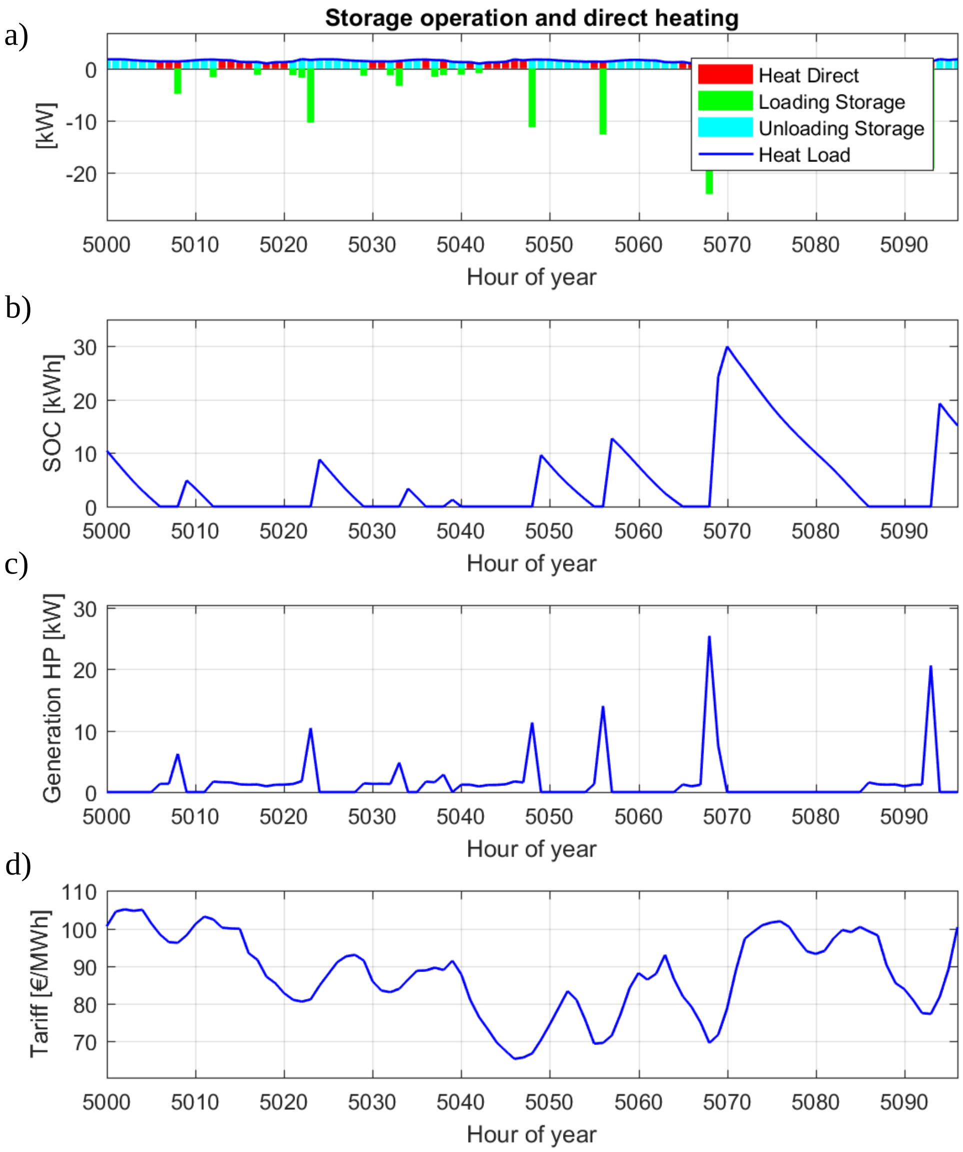

Figure 11: Time series of the derived optimization model variables and parameters for a heat load profile of a single-family household (Summer season - end of July) (Source: own graph)

In order to evaluate which user category would benefit most from having a flexible control system for an optimized heat pump and storage operation, the optimization model was conducted for each user category and different storage capacities.

Generally it was found that a flexible control system, which is capable to optimize the operation according to a dynamic electricity price scheme, can bring cost reductions in the range of 3.9 % to 6.3 %.

In all user categories, the total annual costs decreases with increasing storage capacity. At first, the cost reduction appears to be almost linear; it then decreases further, until a certain storage capacity threshold is reached, where additionall capacities cannot provide any additional flexibilty to the system.

After reaching this threshold additional storage capacities do not yield any further cost reductions. No more heat is available which would then be stored by additional storage capacities. The storage would become overdimensioned.

The potentially highest annual costs are estimated for single-family and multi-family households. In case there is no flexible control system and storage available (SOC_{max} equals 0) the annual cost for a single-family household would be about 1570 €. These annual costs decrease until SOC_{max} is about 100 kWh. After this is reached no further decreases in costs could be expected from an increased SOC_{max}. The annual costs remain constant at about 1480 € (see Figure 12).

Furthermore all other user categories' annual costs at the point where SOC_{max} equals 0 range below single- and multi-family households. The lowest annual costs at this SOC_{max} level of 1510 € are calculated for user category "Laundry". In this category, the SOC_{max} threshold where no further cost reduction can be expected, lies at about 50 kWh.

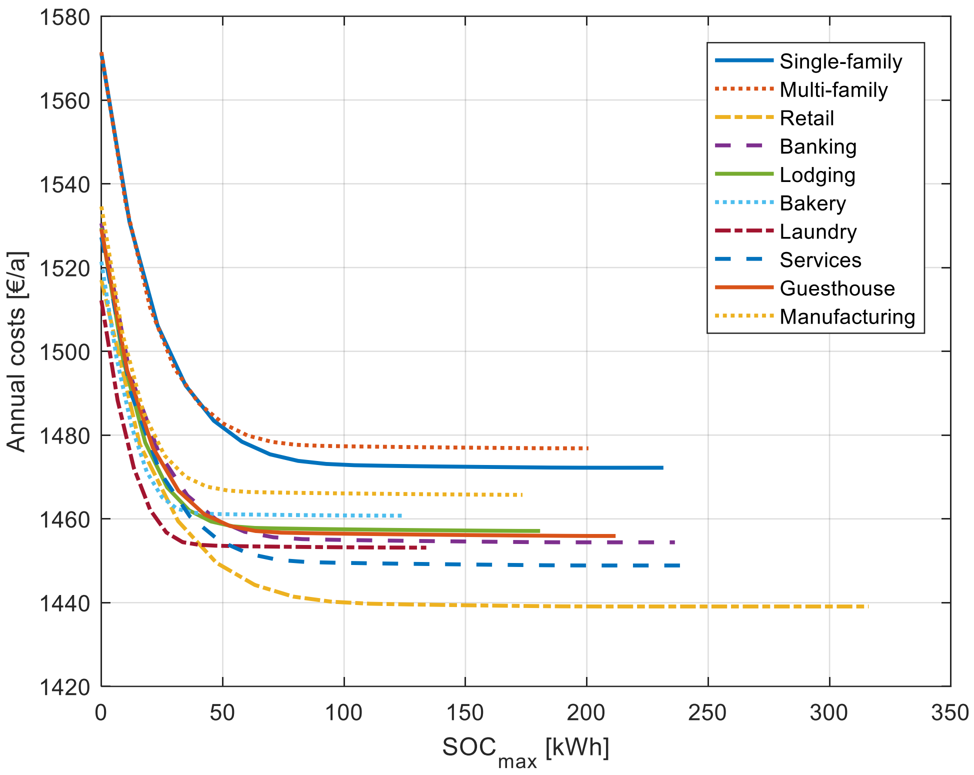

Figure 12: Annual costs and SOC$_{max}$ levels for different user categories (Source: own graph)

One explanation for the varying annual costs of the different user categories is found in the different heat load profiles and the coincidental overlapping of heat loads and electricity tariffs. In Figure 13 the correlation of heat loads and electricity tariffs are depicted for user categories “Single-family” and “Laundry”. For both user categories, no significant correlations can be observed.

The highest potential for cost reductions, which will be discusses in more detail in Chapter 3.3., can be expected for user categories with strong overlaps of high heat loads and high electricity tariffs.

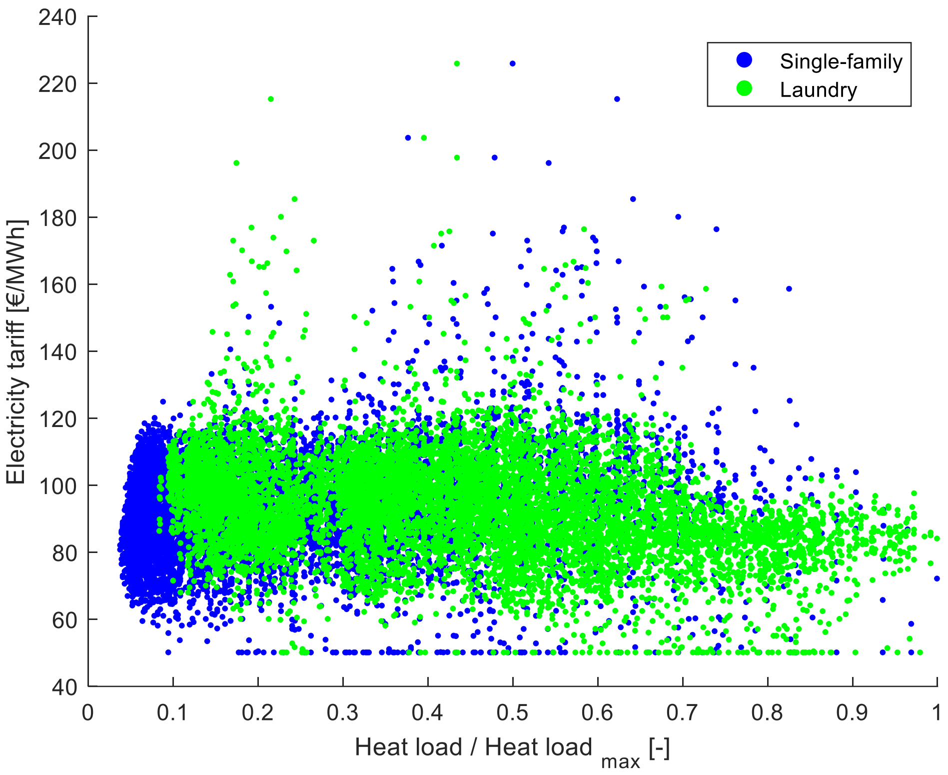

Figure 13: Correlation of electricity tariff and heat load for user category "Single-family" and "Laundry" (Source: own graph)

The specific costs are defined as the annual variable costs divided by the annual heat demand. Therefore, specific costs are very useful when comparing user categories with different load profiles and different annual heat loads.

The maximum time it takes to fully unload the thermal storage can be calculated by dividing the maximum state of charge (SOC_{max}) by the maximum unloading capacity of the thermal storage. For the simulations, the maximum unloading capacity of the storage is assumed to be the same as the maximum capacity of the heat pump (HP_{max}). Since the SOC_{max} / HP_{max} – ratio is equal for all user categories this ratio is very useful for specific cost comparisons. Generally, the specific cost versus SOC_{max} / HP_{max} – ratio relationships are very similar to the distributions in Figure 12.

According to Figure 14, the highest specific costs are estimated for the user categories "Single-family" and "Multi-family". In the "Single-family" case, the specific costs range from about 31.7 €/MWh where SOC_{max} / HP_{max} = 0, to a minimum of 29.7 €/MWh.

For the user category "Laundry" the specific costs range from about 30.3 €/MWh where SOC_{max} / HP_{max} = 0, to a minimum of 29.2 €/MWh. Hence the possible cost reduction is about 45 % less for "Laundry" than for "Single-family" while having the same annual heat demand.

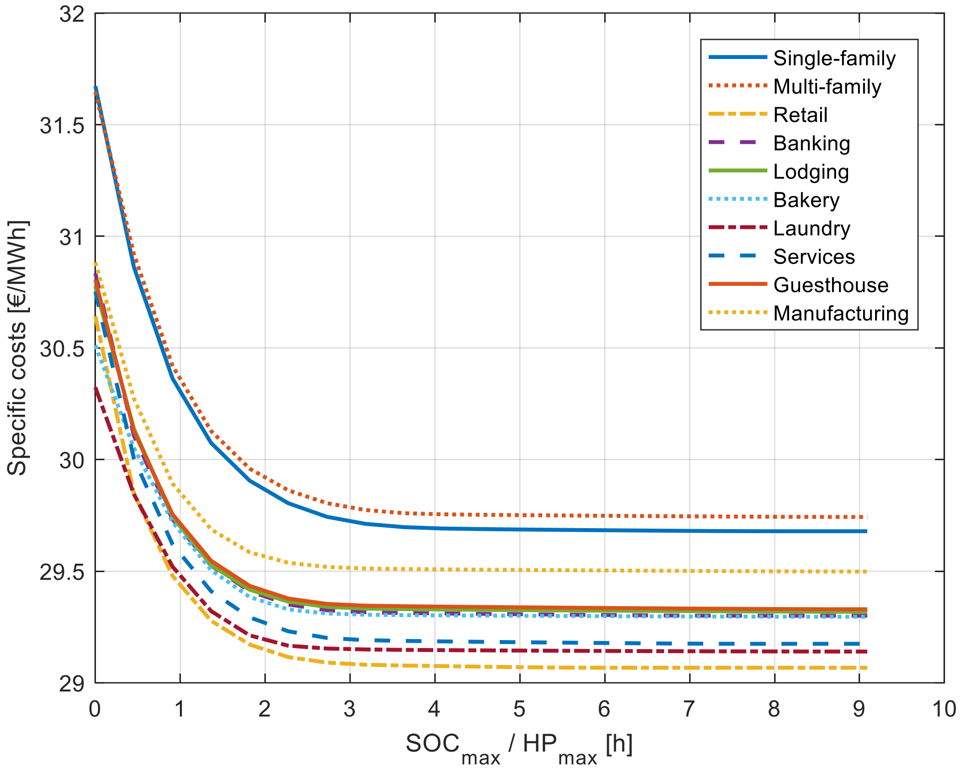

Figure 14: Specific costs and SOC_{max} / HP_{max} - ratios for different user categories (Source: own graph)

3.2. Optimized storage and heat pump operation for different user categories and PV penetration levels

Besides different user categories the optimization model was applied using hypothetical modelled electricity tariffs for certain PV penetration levels (see Chapter 2.1.3.). From the derived results, it is possible to analyze the influence of increasing shares of PV in the power supply system on cost reductions through the flexible operation of heat pumps and thermal storage control systems. In this chapter, the annual and specific costs as well as the cost savings for several PV penetration levels and user categories are quantified and presented. The potential cost reductions range from 2.3 % to 9.0 %.

In Figure 15 the optimization model results for a single-family house are shown, with an annual heat demand of 50 MWh with respect to different storage capacity (SOC_{max}) scenarios and for the PV penetration levels of 0 %, 5 %, 10 % and 15 %.

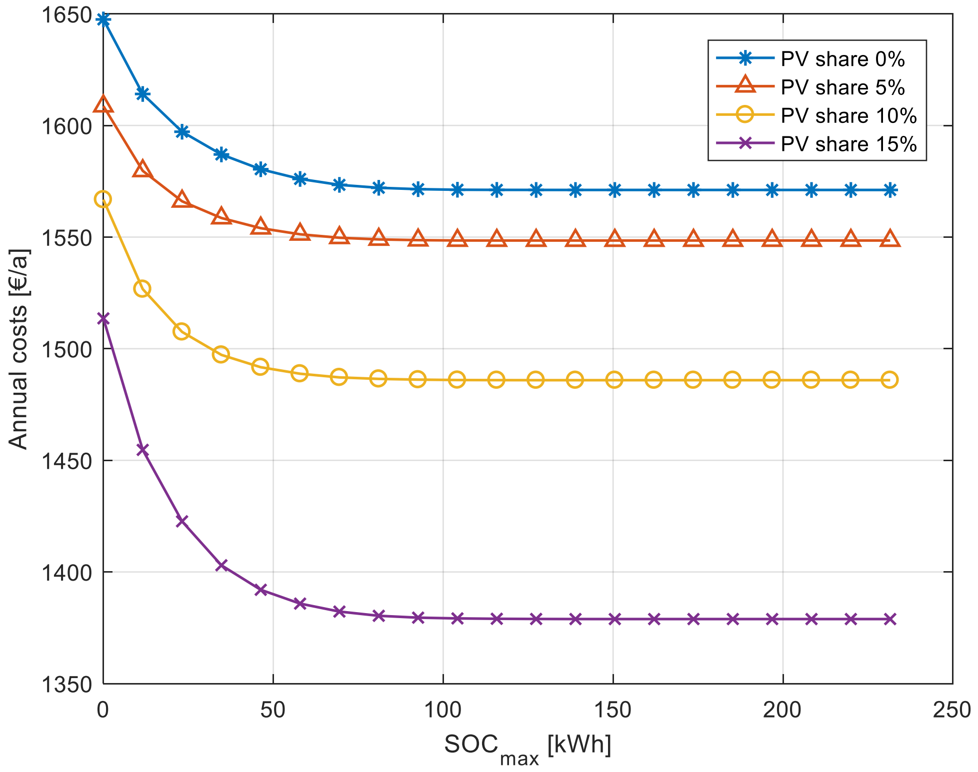

Figure 15: Annual costs and SOC_{max} levels for a single-family household and different PV penetration levels (Source: own graph)

As can be seen, for all conducted scenarios, the annual costs decrease with higher shares of PV in the power supply system. Furthermore, the cost difference for different PV shares at $SOC_{max} = 0$ is up to about 28 % lower than in the case of larger SOC_{max} levels. In case of PV shares of 10 % and 15 % this effect expands until the threshold storage capacity is reached. This effect, though, cannot be observed for a PV share of 0 % and 5 %. Here, the difference in annual costs is almost constant for all storage capacity scenarios.

According to the optimization model output the annual costs for a single-family house at $SOC_{max} = 0$ with an annual heat demand of 50 MWh are about 1650 €. For the same SOC_{max} level the annual costs for the case PV share is 15 % are only about 1510 €. Hence, an increase from 0 to 15 % PV penetration level would lead to a potential annual cost reduction of about 140 € even when there is no flexible heat pump control system and storage. The cost reduction results from a generally lower price level because of increasing PV feed-in into the system.

In all four PV share cases, the threshold for the annual costs is reached at a storage capacity of about 100 kWh. At this SOC_{max} level the annual costs for the heat pump and storage operation are about 1575 € for PV share 0 % and about 1380 € for PV share 15 %. The potential cost reduction is therefore almost 200 €. Compared to the previous case the cost reductions are achieved due to the combination of different tariff pattern effects for different PV penetration levels and the optimized operation of the heat pump and the thermal storage.

For the user category "Single-family" the specific costs in relation to SOC_{max} / HP_{max} - ratios and for different PV penetration levels are shown in Figure 16.

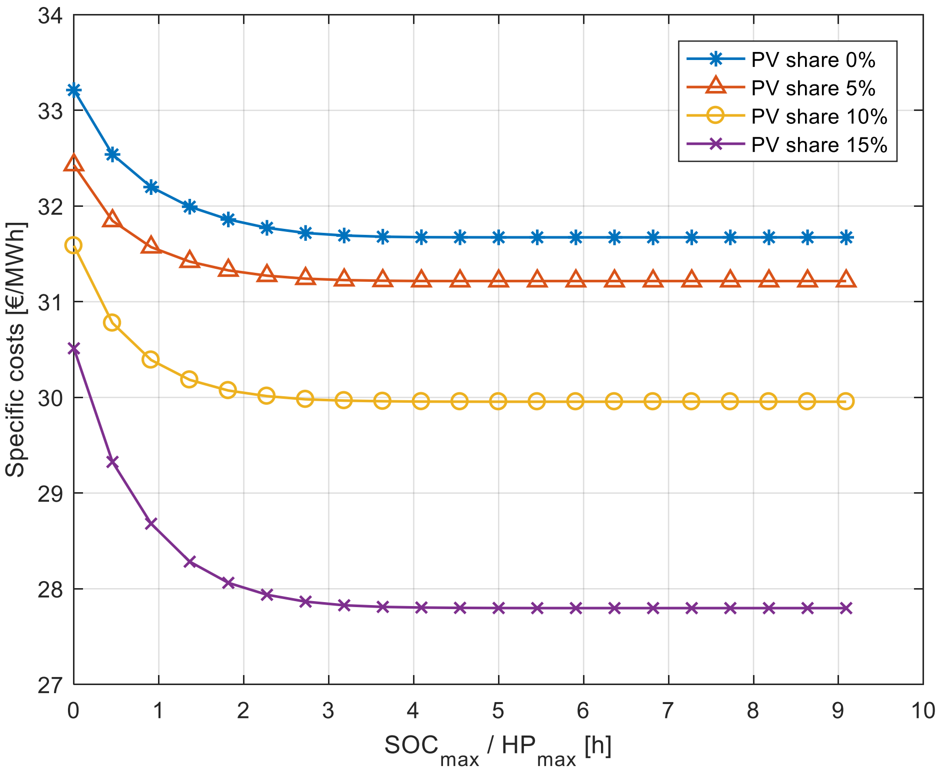

Figure 16: Specific costs and SOC_{max} / HP_{max} - ratios for a single-family household and different PV penetration levels (Source: own graph)

Analogical to the annual costs the specific costs decrease with increasing PV penetration levels and increasing SOC_{max} / HP_{max} - ratios. At SOC_{max} / HP_{max} = 0 the specific costs for PV share 0 % are 33.2 €/MWh and decrease to 30.5 €/MWh for a

PV share of 15 %. At SOC_{max} / HP_{max} = 4 hours the specific costs for a PV share of 0 % are 31.7 €/MWh and decrease to 27.8 €/MWh for PV share 15 %.

As mentioned earlier user category "Single-family" has the strongest overlapping in high loads and high electricity tariffs. For comparison, also the model outcomes for the user category "Bakery", which has a similar heat load duration curve as the user category "Laundry", are presented in following figures.

For "Bakery" the annual costs at SOC_{max} = 0 are about 1620 € for a PV share of 0 %. With increasing PV penetration levels, the annual costs at this SOC_{max} level decrease to about 1465 € for a PV share of 15 % (see Figure 17).

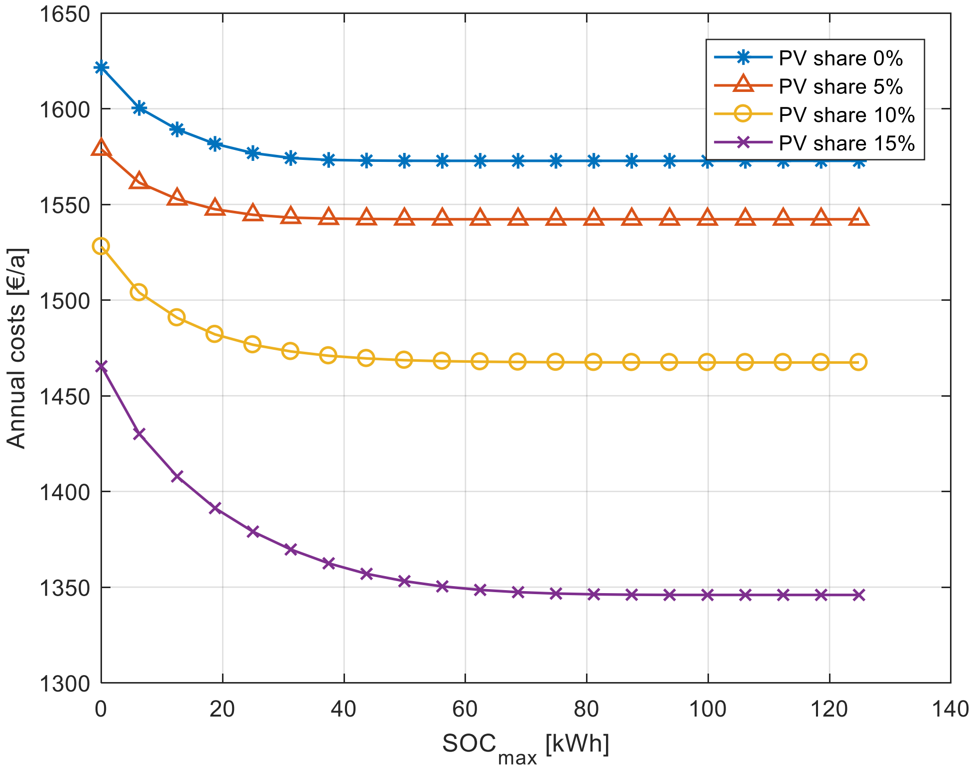

Figure 17: Annual costs and SOC_{max} levels for user category "Bakery" and different PV penetration levels (Source: own graph)

In comparison to the user category "Single-family" the thresholds where higher SOC_{max} levels does not lead to any lower annual costs appear different for the user category "Bakery". While for the user category "Single-family" the SOC_{max} threshold for all PV share scenarios is about 100 kWh the SOC_{max} threshold for user category "Bakery" is about 50 kWh for PV share 0 % and 100 kWh for PV share 15 %.

The specific costs at SOC_{max} / HP_{max} = 0 are 32.6 €/MWh for a PV share of 0 % and decrease to 29.4 €/MWh for a PV share of 15 % (see Figure 18). No more cost reductions were achieved after more than about 3 hours SOC_{max} / HP_{max} – ratio for a PV share of 0 %. The specific costs at this point are about 31.6 €/MWh. The SOC_{max} / HP_{max} - ratio threshold for a PV share of 15 % is about 6 hours. Here the specific costs are about 27.0 €/MWh.

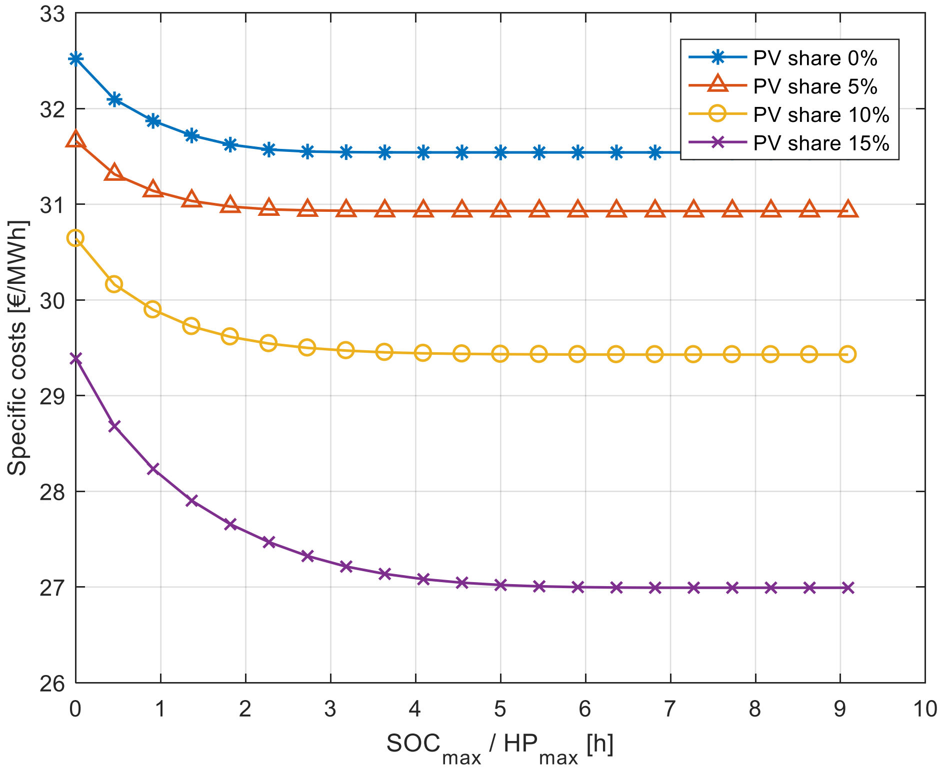

Figure 18: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Bakery” and different PV penetration levels (Source: own graph)

3.3. Potential cost savings based on constant and variable heat demands for different user categories and PV penetration levels

The maximum cost reductions or savings which can be expected from having a flexible heat pump control system and thermal storage installed are calculated as difference in annual costs at SOC_{max} = 0 or specific costs at SOC_{max} / HP_{max} = 0 and the corresponding costs at maximum SOC_{max} or maximum SOC_{max} / HP_{max}. As mentioned earlier, in most cases no significant further cost reduction can be achieved after reaching a certain storage capacity threshold.

For all user categories, the optimization model's estimated maximum cost savings for hypothetical historic and all modelled PV penetration level electricity tariff patterns are summarized in Table 2. It can be seen that there are significant fluctuations in the cost savings depending on user category and tariff pattern.

Table 2: Maximum annual cost savings [€/a] and specific cost savings [€/MWh] for hypothetical historic electricity tariffs and modelled PV share electricity tariffs for all user categories with a heat demand of 50 MWh/a (Source: own calculation)

Electricity tariff pattern:	Hypoth. tariff		PV share 0%		PV share 5%		PV share 10%		PV share 15%	
Cost savings:	Ann.	Spe.	Ann.	Spe.	Ann.	Spe.	Ann.	Spe.	Ann.	Spe.
Single-family	98.9	1.99	76.4	1.54	60.2	1.21	80.9	1.63	134.7	2.72
Multi-family	94.6	1.91	73.8	1.49	57.5	1.16	79.6	1.60	135.5	2.73
Retail	77.9	1.57	61.2	1.24	48.4	0.98	62.1	1.25	106.7	2.16
Banking	76.2	1.53	61.1	1.23	46.8	0.94	64.3	1.30	113.4	2.28
Lodging	72.3	1.46	59.4	1.20	44.3	0.89	66.5	1.34	125.1	2.52
Bakery	60.7	1.22	48.8	0.98	36.5	0.73	60.6	1.21	119.5	2.40
Laundry	59.0	1.18	47.4	0.95	36.2	0.73	61.0	1.22	119.3	2.39
Services	78.4	1.58	63.1	1.27	48.5	0.98	66.6	1.34	117.0	2.36
Guesthouse	73.2	1.48	58.0	1.17	44.6	0.90	62.2	1.25	110.4	2.22
Manufacturing	68.9	1.39	55.9	1.13	41.8	0.84	62.8	1.26	118.3	2.38

In case of the hypothetical electricity tariff pattern with whole sale electricity prices of the year 2012 on top of a constant tariff of 50 €/MWh the highest cost savings can be expected for the user category “Single-family”. Considering an annual heat demand of 50 MWh the annual cost savings are almost 99 € and the specific cost savings are almost 2 €/MWh or 6.3 %. For the same tariff pattern, the lowest savings can be expected for user category “Laundry”. In this user category, the annual cost savings are 59 € and the specific cost savings are 1.2 €/MWh or 3.9 %.

The cost savings for all user categories and modelled prices at a PV share of 0 % are lower than for the historic electricity tariff pattern. In case of the user category “Single-family” the expected annual cost savings are about 22.5 € less for the modelled electricity tariffs than for the historic electricity tariffs. This difference in savings can be explained with the deviations between historic and modelled hourly electricity tariffs. However, applying modelled electricity tariff patterns for different

PV penetration levels is a good start for studying its' effects on savings which can be expected from a combined flexible heat pump control and storage system at higher PV penetration levels.

One interesting outcome of the optimization model is that the savings for tariff patterns at a PV share of 5 % are less than for a PV share of 0 % while the savings for a PV share of 10 % and 15 % are more than for a PV share of 0 %.

For the user category "Single-family" the annual cost savings decrease from about 76 € at a PV share of 0 % down to about 60 € at a PV share of 5 %. At a PV share of 10 % the savings rise to about 81 € and at a PV share of 15 % increase to about 135 € which is about 76 % more than the savings at a PV share of 0 %.

Furthermore, depending on the hypothetical modelled electricity tariff pattern for different PV shares the order of estimated cost savings differs for some user categories. For example, the highest savings in the tariffs at a PV share of 0 %, 5 % and 10 % appear for the user category "Single-family", but at a PV share of 15 % the highest savings show up for the user category "Multi-family". On the other hand, the lowest savings appear for the user category "Laundry" at a PV share of 0 % and 5 %, but at a PV share of 10 % the lowest savings are evaluated for the user category "Bakery", and at a PV share of 15 % for the user category "Retail" (see Table 3).

Table 3: Maximum cost savings [%] for hypothetical historic electricity tariffs and modelled PV share electricity tariffs for all user categories (Source: own calculation)

	Cost savings [%]				
Electricity tariff pattern:	Hypoth. Tariff	PV share 0%	PV share 5%	PV share 10%	PV share 15%
Single-family	6.3	4.6	3.7	5.2	8.9
Multi-family	6.0	4.5	3.6	5.1	9.0
Retail	5.1	3.8	3.1	4.0	7.1
Banking	5.0	3.8	3.0	4.2	7.6
Lodging	4.7	3.7	2.8	4.3	8.4
Bakery	4.0	3.0	2.3	4.0	8.2
Laundry	3.9	2.9	2.3	4.0	8.2
Services	5.1	3.9	3.1	4.3	7.8
Guesthouse	4.8	3.6	2.8	4.0	7.4
Manufacturing	4.5	3.4	2.6	4.1	7.9

To obtain more adequate solutions on the possible cost savings for specific heat users more appropriate variable heat demands have been applied in an additional optimization model calculation. According to Table 1 (see Chapter 2.1.2.), for the additional simulations the applied variable heat demands range from 10 MWh/a for user category “Single-family”, and up to 300 MWh/a for user category “Manufacturing”. In Table 4 the calculated annual and specific cost savings are shown for different user categories with variable heat demands.

Table 4: Maximum annual cost savings [€/a] and specific cost savings [€/MWh] for hypothetical historic electricity tariffs and modelled PV share electricity tariffs for all user categories with variable heat demand (Source: own calculation)

Electricity tariff pattern:	Hypoth. tariff		PV share 0%		PV share 5%		PV share 10%		PV share 15%	
Cost savings:	Ann.	Spe.	Ann.	Spe.	Ann.	Spe.	Ann.	Spe.	Ann.	Spe.
Single-family	19.8	1.99	15.3	1.54	12.0	1.21	16.2	1.63	26.9	2.72
Multi-family	94.6	1.91	73.8	1.49	57.5	1.16	79.6	1.60	135.5	2.73
Retail	93.5	1.57	73.4	1.24	58.1	0.98	74.5	1.25	128.1	2.16
Banking	304.6	1.53	244.4	1.23	187.4	0.94	257.3	1.30	453.7	2.28
Lodging	217.0	1.46	178.2	1.20	132.9	0.89	199.4	1.34	375.4	2.52
Bakery	121.3	1.22	97.6	0.98	73.1	0.73	121.2	1.21	239.0	2.40
Laundry	118.0	1.18	94.7	0.95	72.4	0.73	122.0	1.22	238.6	2.39
Services	313.4	1.58	252.5	1.27	193.9	0.98	266.4	1.34	468.2	2.36
Guesthouse	73.2	1.48	58.0	1.17	44.6	0.90	62.2	1.25	110.4	2.22
Manufacturing	413.2	1.39	335.6	1.13	251.1	0.84	376.6	1.26	709.6	2.38

Depending on the underlying annual heat demands the ranking of the different user categories’ cost savings is different than in the case of constant heat demands.

For the hypothetical historic tariff pattern, the highest annual cost savings of about 413 € were estimated for user category “Manufacturing” with a heat demand of 300 MWh/a. For the same tariff pattern, the lowest annual cost savings of about 20 € were calculated for user category “Single-family” with an annual heat demand of 10 MWh. In case of variable heat demands the calculated specific cost savings are equal for all user categories and electricity tariff patterns compared to the corresponding outcomes of calculations with constant heat demands.

4. Discussion

This study is a theoretical analysis with the aim to demonstrate the potential cost reductions which can be achieved from the combination of a heat pump and thermal storage with a flexible control system or smart device. The applied optimization model is more a conceptional than a detailed physical model. Simplified assumptions on certain model parameters, electricity tariffs or heat demands include a certain degree of uncertainty and limitations of their application. Nevertheless, the derived results are suitable to discuss the issues of flexibility regarding thermal storage size and potential cost savings for different heat users as well as increased PV penetration levels.

4.1. Flexibility and thermal storage size

To see whether the results on thermal storage size and related variable cost savings are reasonable, the potential storage volume must be calculated. Considering a given maximum thermal storage temperature of 65 °C and maximum flow temperature of 40 °C the heat energy provided by a 1000-liter thermal storage water-tank would be 29 kWh. This simplified sample calculation would fit to a single-family household having a heat pump and floor heating system for heating and hot water supply. Given the annual heat demand of the single-family household is 10 MWh the calculated SOC_{max} threshold where no more cost reductions can be achieved would be about 25 kWh. In this hypothetical case, the applied storage size or SOC_{max} – level could be a realistic estimate. For the other user categories, deeper investigations on this topic will require detailed specific information on the installed heating systems and thermal storages.

For certain user categories, a larger thermal storage would lead to higher cost reductions whereas for other user categories no further cost reductions can be achieved. For example, the SOC_{max} / HP_{max} ratio threshold for user category “Single-family” is about 4 hours but for user category “Laundry” or “Bakery” only about 3.

Furthermore, the load shifting potential varies not only between the different user categories it also varies depending on the electricity tariffs resulting from higher PV penetration levels. In the case of user “Single-family” the SOC_{max} / HP_{max} ratio threshold is about 4 hours for all PV penetration levels. But for user category "Bakery" the SOC_{max} / HP_{max} ratio threshold at PV share 0 % is about 3 hours and increases to about 5.5 hours at PV share 15 %. Therefore, for some user categories changing electricity tariffs due to increased PV penetration can lead to additional cost savings and larger load shifting potentials with larger thermal storages. For example, the difference in specific cost savings between "Single-family" and "Laundry" is much higher for electricity tariff PV share 0 % than for tariff PV share 15 %.

In this study, the SOC_{max}- and SOC_{max} / HP_{max} ratio thresholds indicate the points where no further cost reductions can be expected from increasing the storage size. The SOC_{max} / HP_{max} ratio threshold is also an estimate for the maximum load shifting potential of a system.

4.2. Profitability and cost coverage

To evaluate the cost coverage of an investment in a thermal storage and/or flexible control system or smart device, correct assumptions on the annual heat demand is essential. Generally, it was found that higher heat demands lead to higher annual cost savings while the specific cost savings do not change.

If the investment costs for a smart device are about 200 to 500 €, the calculated annuities for 10 years duration and 5 % interest rate would be about 26 to 65 € per year. The calculated potential annual cost savings for user "Single-family" with 10 MWh annual heat demand are about 20 € and for user "Multi-family" with 50 MWh annual heat demand about 95 € (see Table 4). In this example case, it is not profitable for user "Single-family to invest in a smart device. Whereas for user "Multi-family" it could be so, if there were no additional investment costs for a thermal storage tank.

The investment costs for a thermal storage water tank range from 0.5 €/kWh to 7 €/kWh (Frauenhofer, 2013)[5]. The calculated potential annual cost savings for user "Services" with 200 MWh annual heat demand are about 313 €, and the calculated

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[5] https://www.umsicht-suro.fraunhofer.de/content/dam/umsicht-suro/de/documents/studien/studie_speicher_energiewende.pdf

SOC_{max} threshold is about 400 kWh. Considering the investment costs of 7 €/kWh, the resulting total investment costs are 2.800 € and the derived annuity of the investment (5 % interest rate, 10 years duration) is 363 €. In this simplified case, the investment in a smart device and a thermal storage tank might not be profitable. However, if there is already a thermal storage present it could be profitable to invest in a smart device.

According to the above-mentioned examples the investments profitability highly depends on the investment costs for the smart device and the thermal storage tank. In some cases, the investment in a smart device could only be profitable if there is already a storage available. To evaluate if such investments are profitable, more detailed up-to-date information on the investment costs for smart devices and thermal storages are essential.

Furthermore, it was found that for some user categories the annual cost savings increase with increasing PV penetration levels. In such cases also the resulting investment’s profitability or cost coverage could increase.

For consumers, these theoretical assumptions concerning profitability are very limited and can only be applied if their electricity supplier also supports a time variable electricity tariff like a basic charge on top of wholesale market prices. These kinds of variable electricity tariffs used in the simulations of this study are purely hypothetical tariffs and do not exist now.

5. Conclusion

In this work, a linear programming approach and optimization model for flexible controlled heat pump and thermal storage systems was used to analyze the potential cost savings for different heat users. It is shown that some heat user categories like “Single-family” or “Multi-family” have larger cost saving potentials than others, as for example the “Laundry” or “Bakery” categories. For the first applied hypothetical variable electricity tariff, the calculated cost savings can be up to 6.3 % of the total operational costs.

Furthermore, it was demonstrated that the cost saving potentials increase with increasing PV penetration in the energy supply system. In this second case, the cost saving potential for some heat users can be up to 9 %.

These findings have been discussed in terms of flexibility, reasonable thermal storage size and cost coverage.

In terms of cost coverage, it was found that the investments profitability highly depends on the investment costs for the smart device and the thermal storage. For some users, the investment in a smart device could only be profitable if there is already a thermal storage present. Here, only basic assumptions have been applied on the costs of smart devices.

Load shifting potentials were calculated for the different user categories. It was found that some user categories display larger load shifting potentials than others. For some users, the load shifting potential could also increase with increasing PV penetration levels.

In this study, a threshold for SOC_{max}- and the SOC_{max} / HP_{max} ratio was introduced. These thresholds indicate the limits for a reasonable storage size and the load shifting potentials for the different user categories. Since the thresholds presented in this study are only rough estimates, further research should focus on the detailed thresholds’ calculation.

Future research on these topics should also focus on the application of realistic energy tariff patterns provided by an energy supplier, and a deeper analysis of capital and investment costs, as well as the profitability of the different heat supply system`s components.

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List of abbreviations

DSM	Demand Side Management

Indices:

t	Index for hourly time steps [1…8760]

Parameters:

$C_{hp,t}$	Variable fuel costs of the heat pump [€/MWh]
$p_{el,t}$	Price of electricity [€/MWh]
COP_{hp}	Coefficient of performance of the heat pump [-]
$SOC_{t-1} \cdot 0.02$	Thermal energy losses (2%) [kWh]
cap_{hp}	Max. loading capacity thermal storage [kW]
cap_{st}	Max. unloading capacity thermal storage [kW]
SOC_{max}	Maximum state of charge thermal storage [kWh]
d_t	Heat load [kW]
HP_{max}	Maximum capacity of the heat pump [kW]

Variables:

$P_{hp,t}$	Generation heat pump [kW]
$x_{hps,t}$	Thermal energy heat pump [kW] (loading storage)
$x_{st,t}$	Thermal energy storage [kW] (unloading storage)
$x_{hpd,t}$	Thermal energy heat pump [kW] (direct heating)
SOC_t	State of charge thermal storage [kWh]

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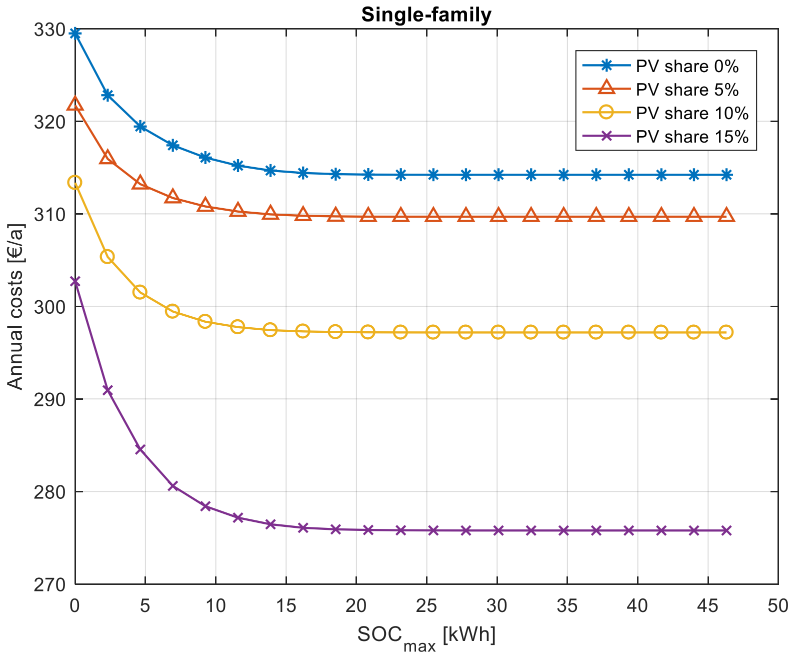
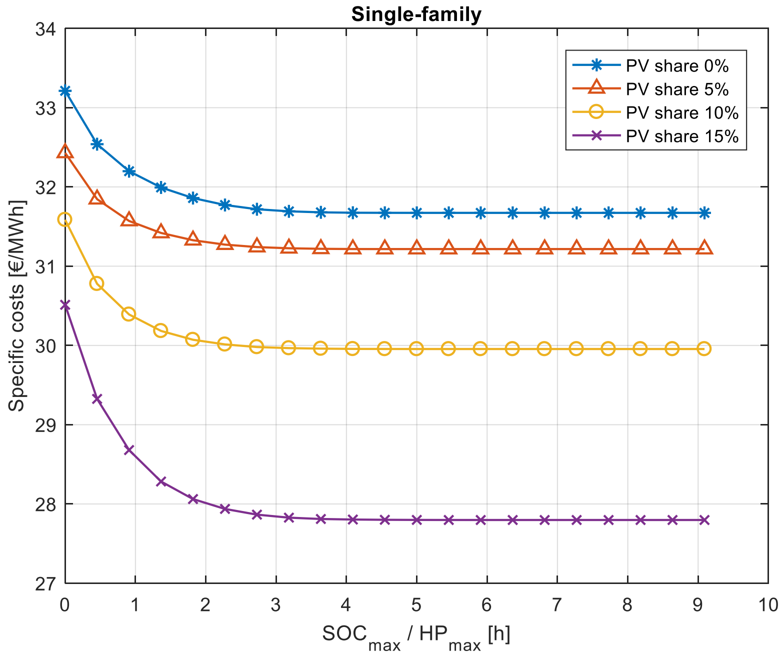
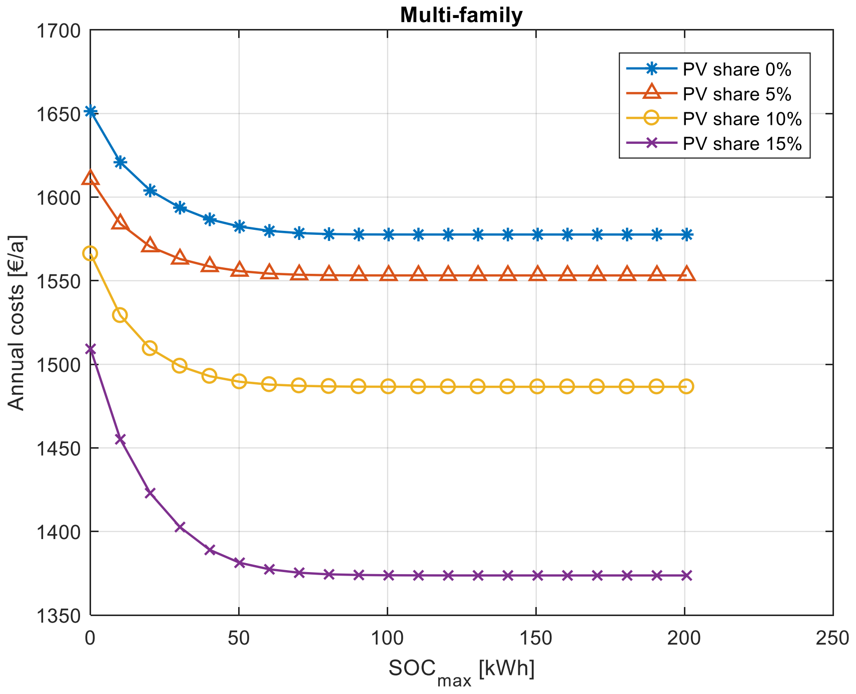
Appendixes



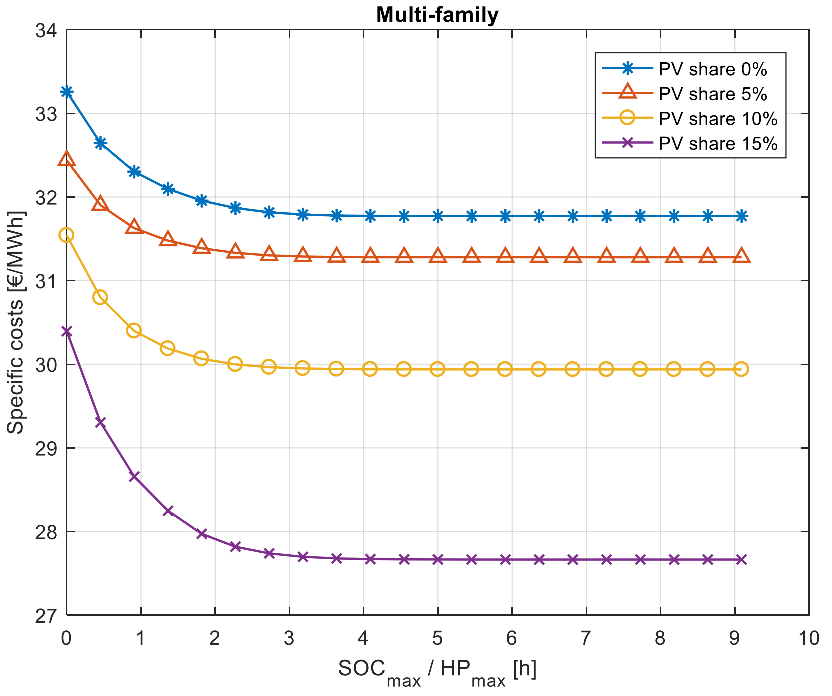
Appendix 1: Annual costs and SOC$_{max}$ levels for user category "Single-family" with an annual heat demand of 10 MWh and different PV penetration levels (Source: own graph)



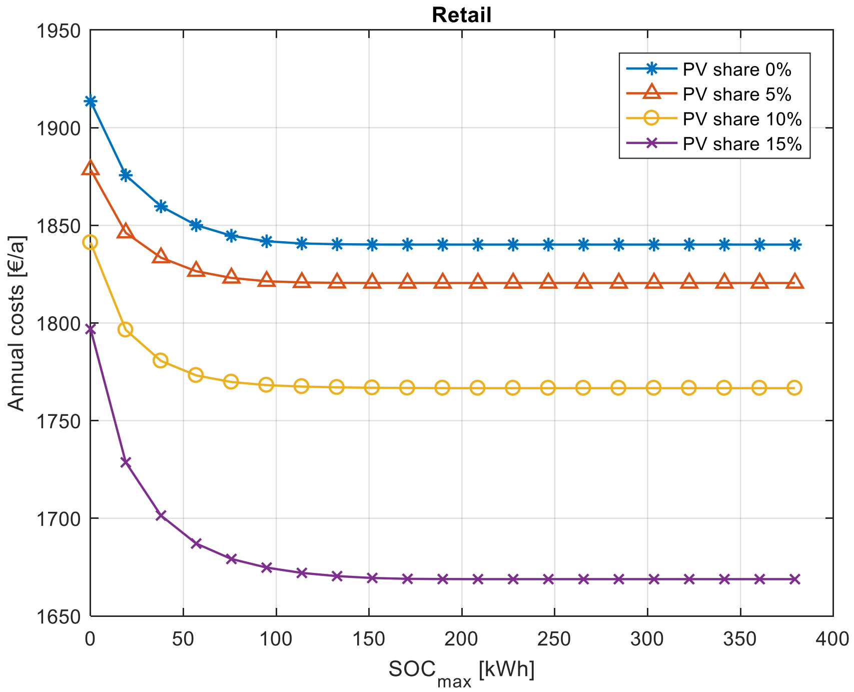
Appendix 2: Specific costs and SOC$_{max}$ / HP$_{max}$ - ratios for user category "Single-family" and different PV penetration levels (Source: own graph)



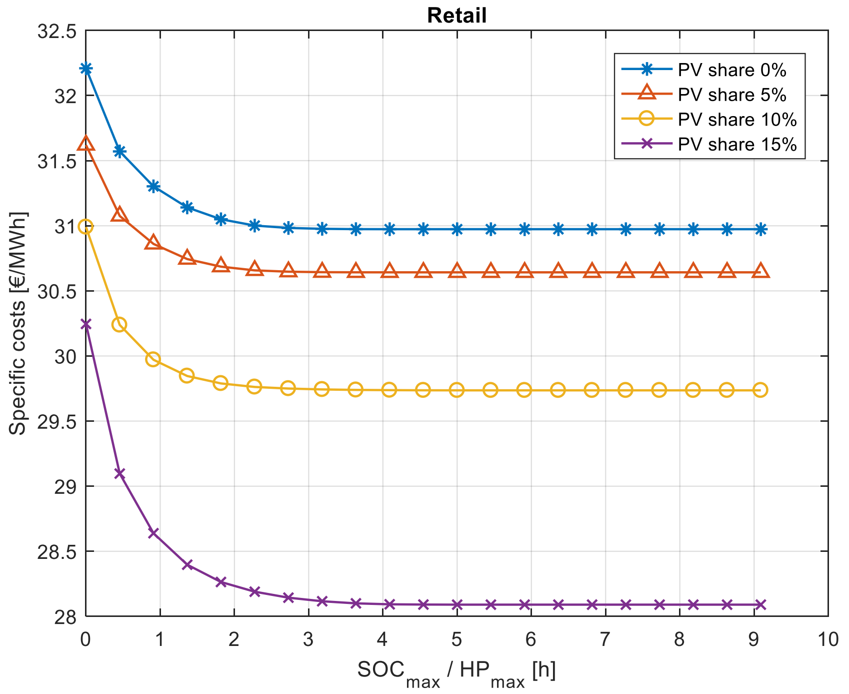
Appendix 3: Annual costs and SOC_{max} levels for user category “Multi-family” with an annual heat demand of 50 MWh and different PV penetration levels (Source: own graph)



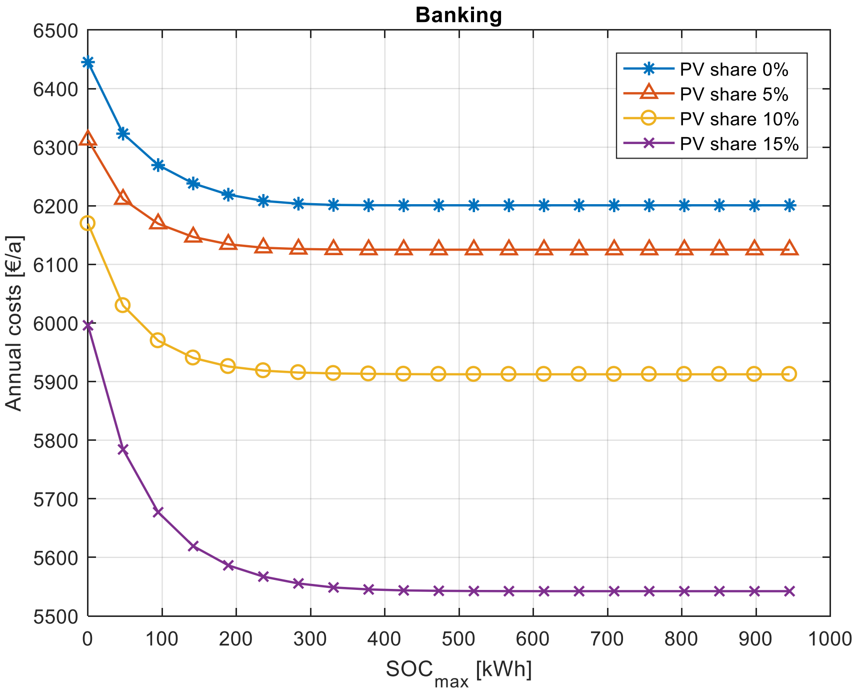
Appendix 4: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Multi-family” and different PV penetration levels (Source: own graph)



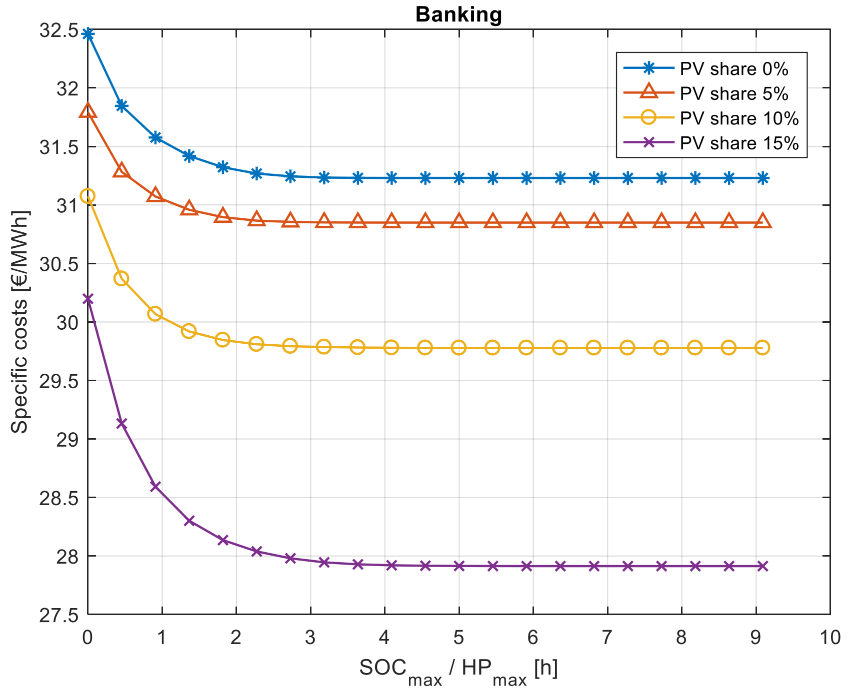
Appendix 5: Annual costs and SOC_{max} levels for user category “Retail” with an annual heat demand of 60 MWh and different PV penetration levels (Source: own graph)



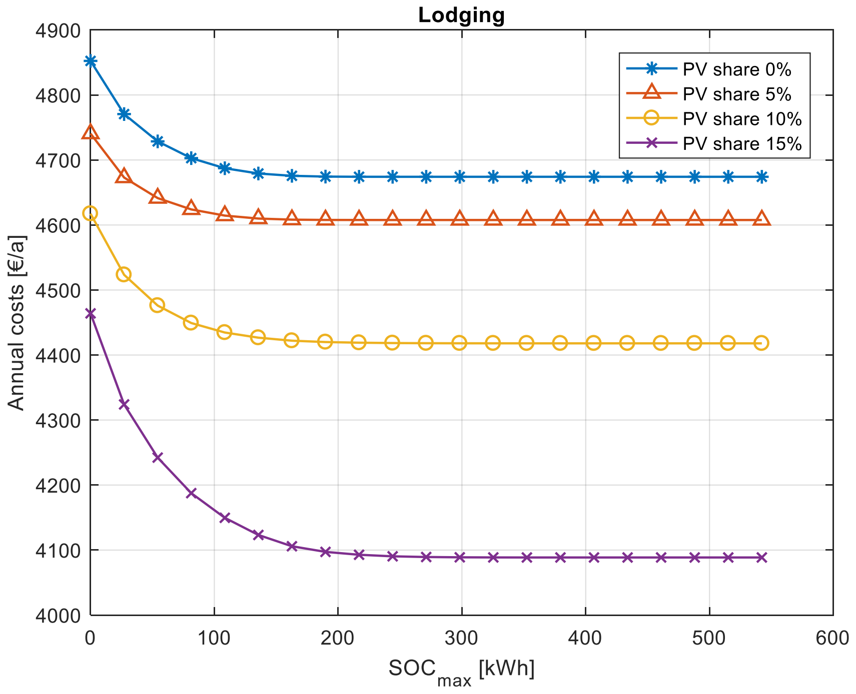
Appendix 6: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Retail” and different PV penetration levels (Source: own graph)



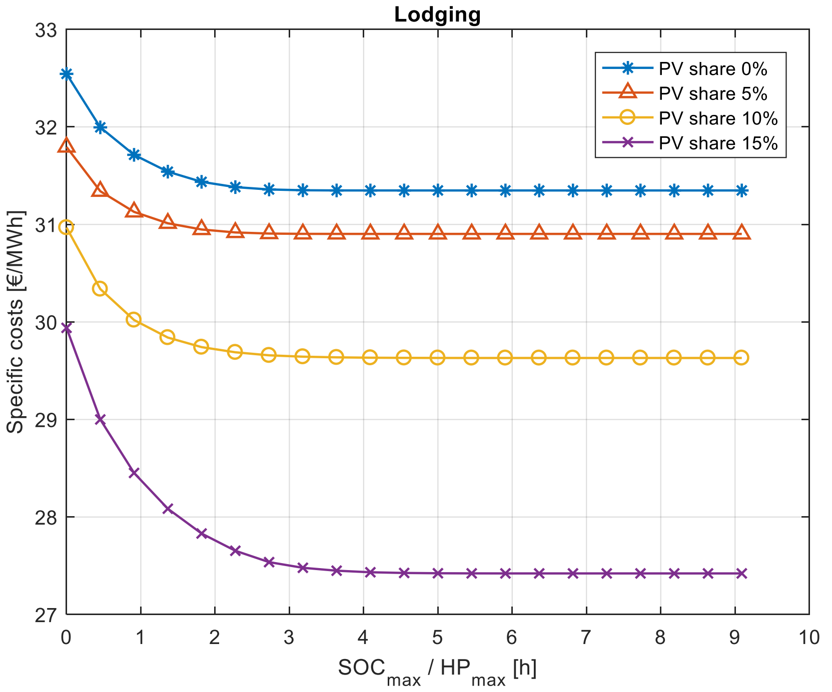
Appendix 7: Annual costs and SOC_{max} levels for user category “Banking” with an annual heat demand of 200 MWh and different PV penetration levels (Source: own graph)



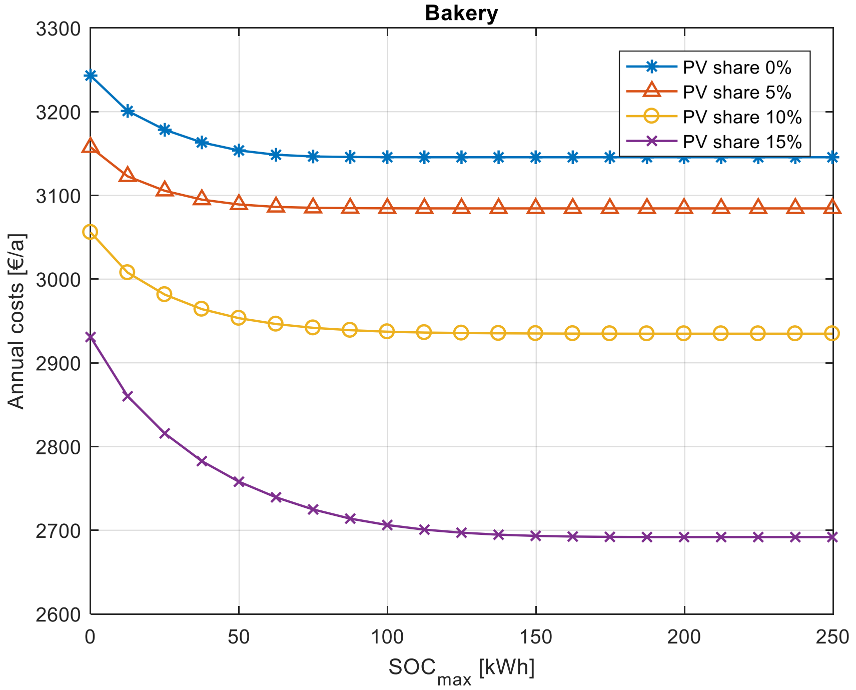
Appendix 8: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Banking” and different PV penetration levels (Source: own graph)



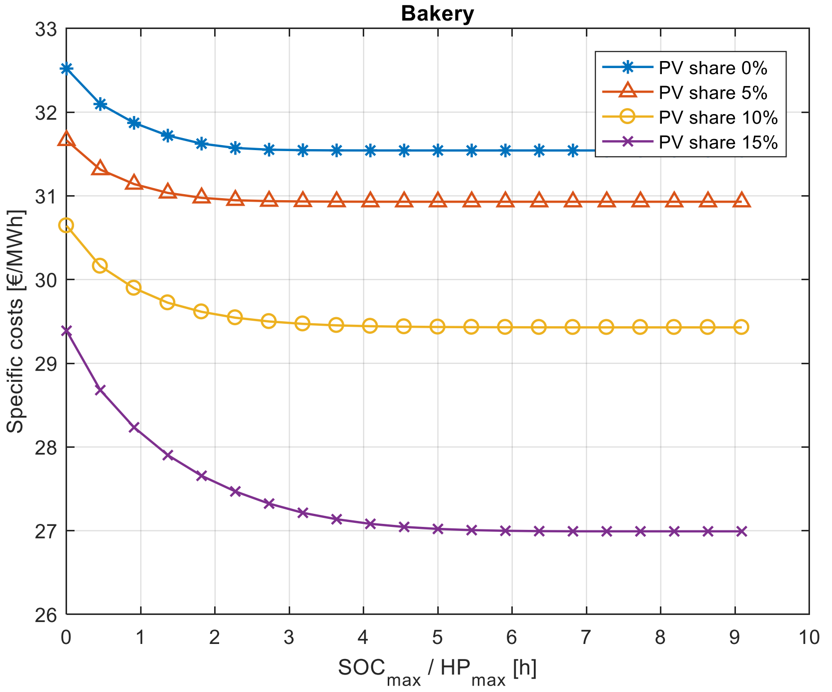
Appendix 9: Annual costs and SOC$_{max}$ levels for user category "Lodging" with an annual heat demand of 150 MWh and different PV penetration levels (Source: own graph)



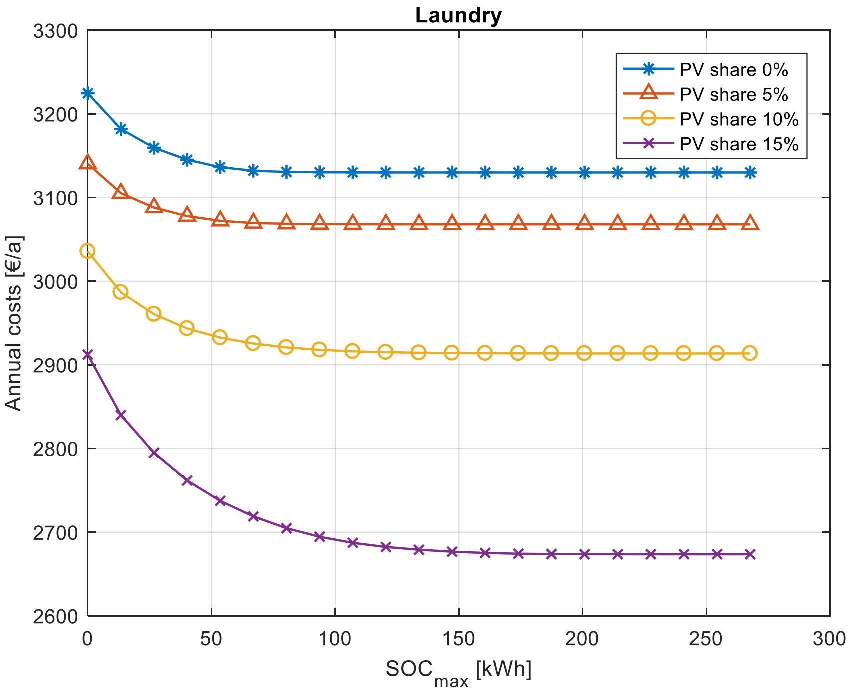
Appendix 10: Specific costs and SOC$_{max}$ / HP$_{max}$ - ratios for user category "Lodging" and different PV penetration levels (Source: own graph)



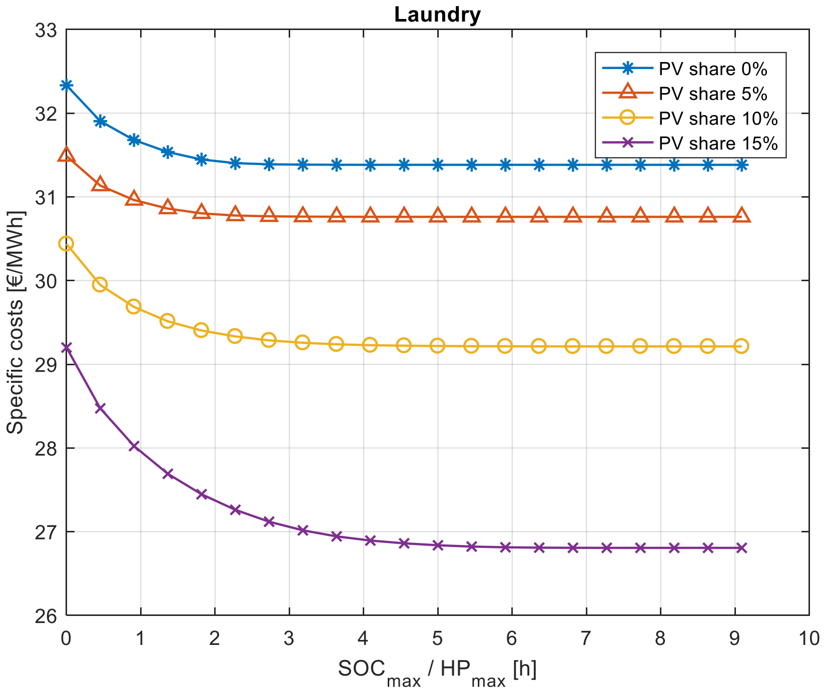
Appendix 11: Annual costs and SOC$_{max}$ levels for user category “Bakery” with an annual heat demand of 100 MWh and different PV penetration levels (Source: own graph)



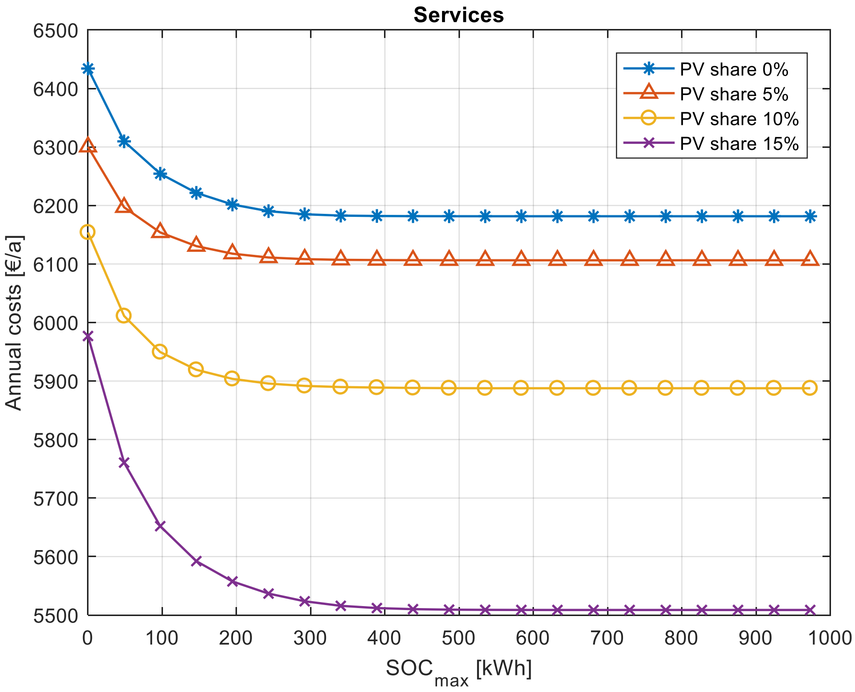
Appendix 12: Specific costs and SOC$_{max}$ / HP$_{max}$ - ratios for user category “Bakery” and different PV penetration levels (Source: own graph)



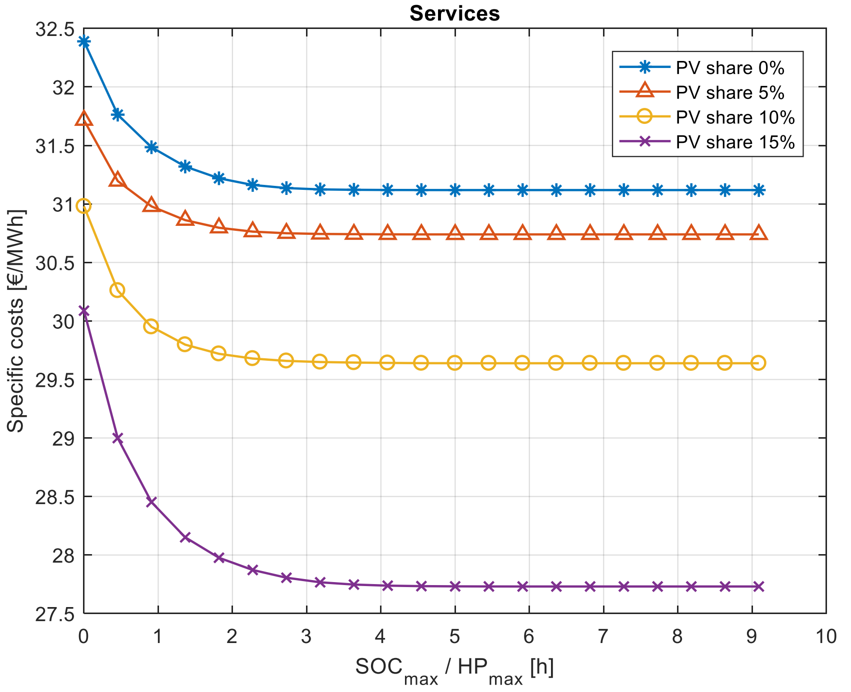
Appendix 13: Annual costs and SOC_{max} levels for user category “Laundry” with an annual heat demand of 100 MWh and different PV penetration levels (Source: own graph)



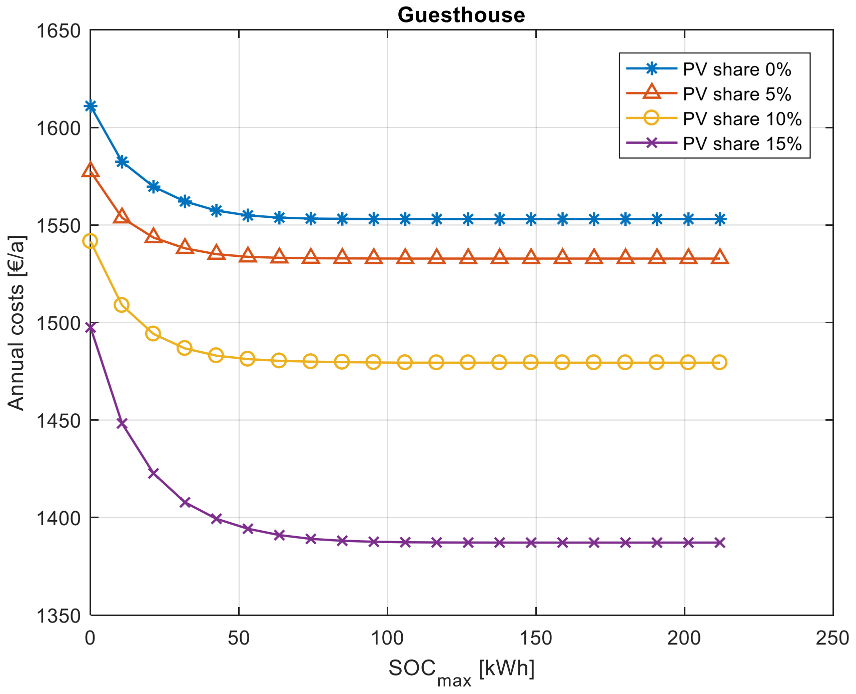
Appendix 14: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Laundry” and different PV penetration levels (Source: own graph)



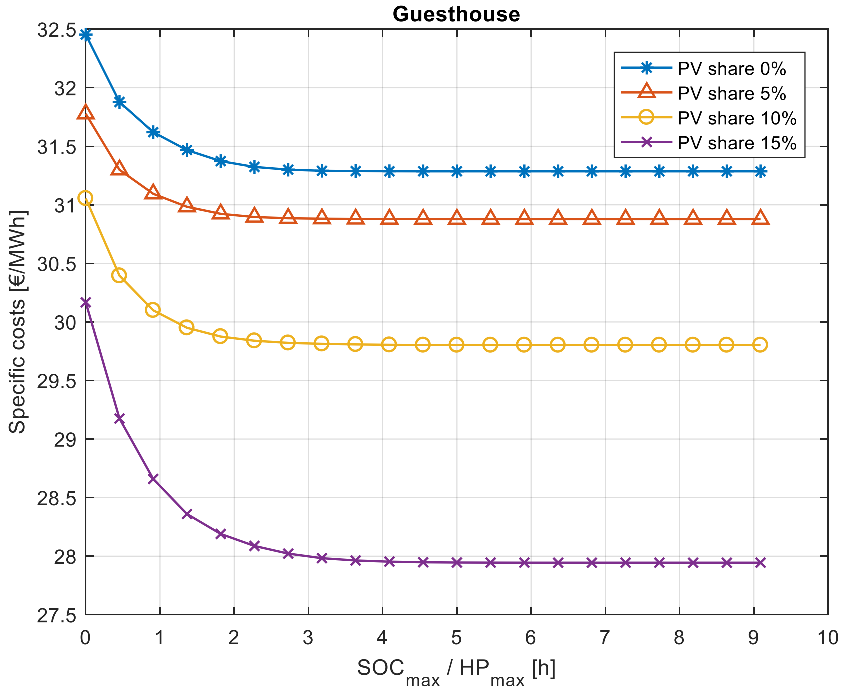
Appendix 15: Annual costs and SOC_{max} levels for user category “Services” with an annual heat demand of 200 MWh and different PV penetration levels (Source: own graph)



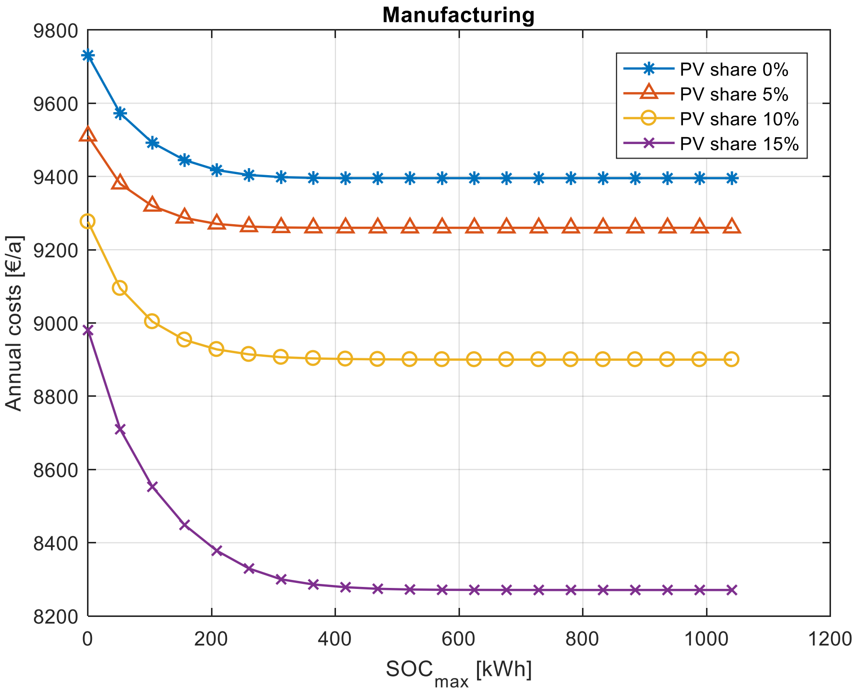
Appendix 16: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Services” and different PV penetration levels (Source: own graph)



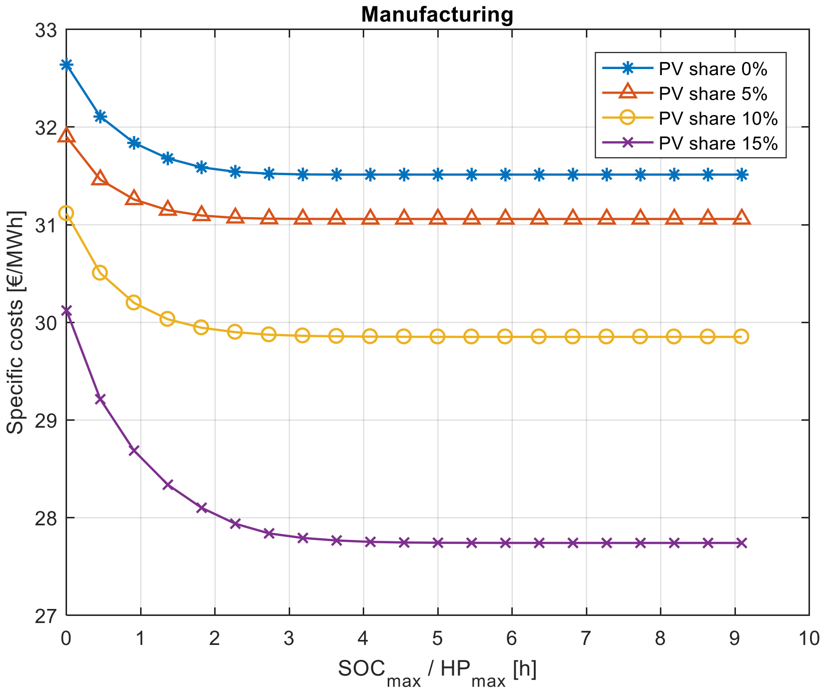
Appendix 17: Annual costs and SOC_{max} levels for user category “Guesthouse” with an annual heat demand of 50 MWh and different PV penetration levels (Source: own graph)



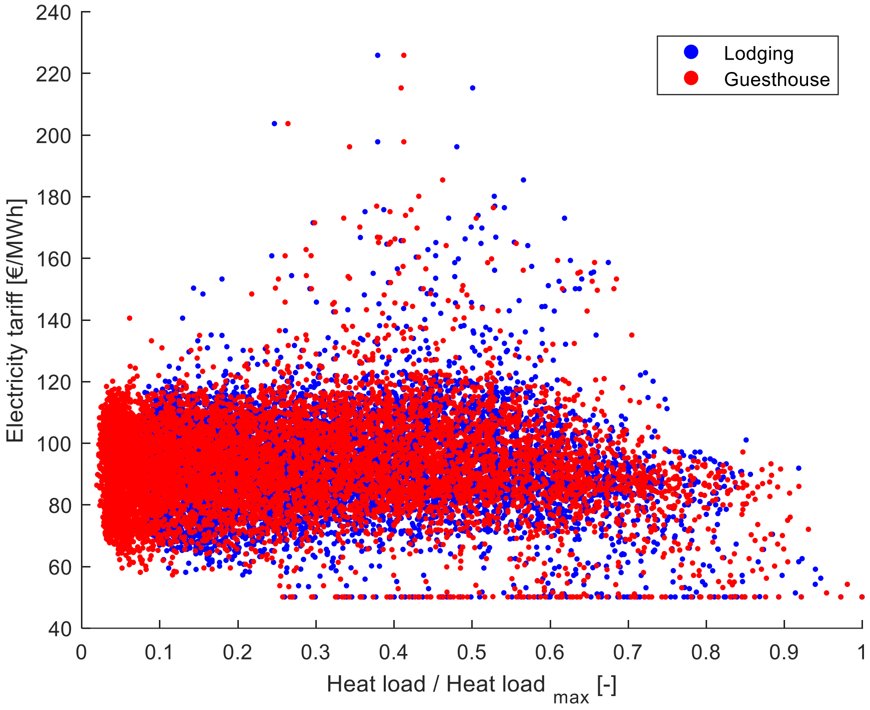
Appendix 18: Specific costs and SOC_{max} / HP_{max} - ratios for user category “Guesthouse” and different PV penetration levels (Source: own graph)



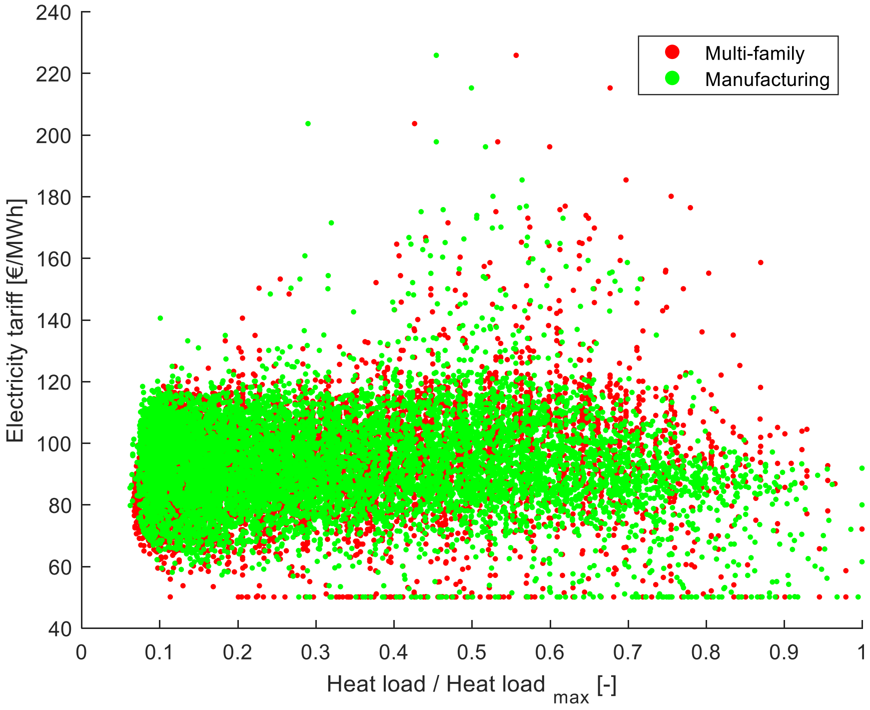
Appendix 19: Annual costs and SOC$_{max}$ levels for user category "Manufacturing" with an annual heat demand of 300 MWh and different PV penetration levels (Source: own graph)



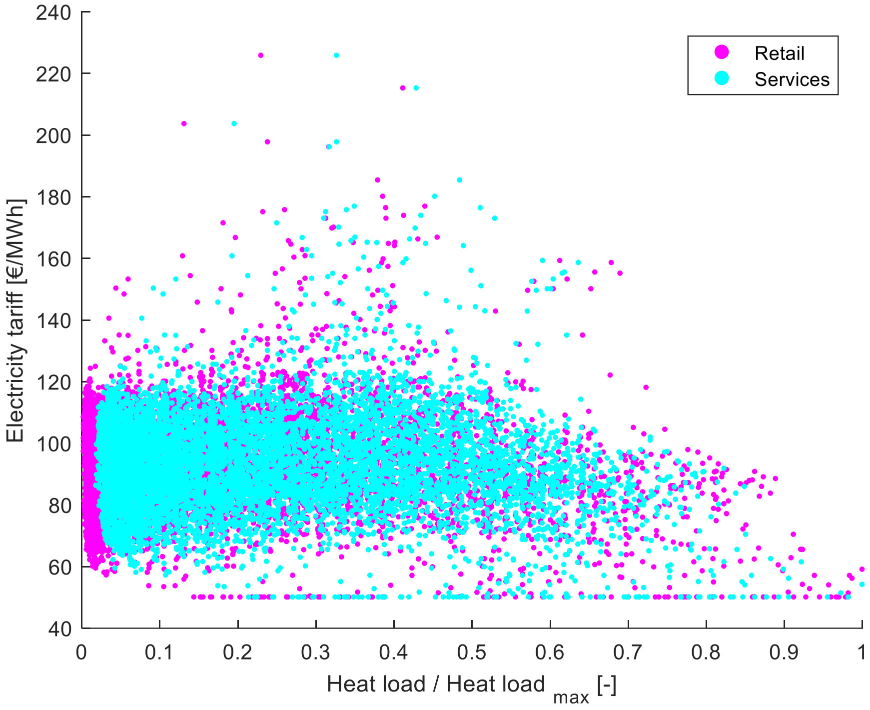
Appendix 20: Specific costs and SOC$_{max}$ / HP$_{max}$ - ratios for user category "Manufacturing" and different PV penetration levels (Source: own graph)



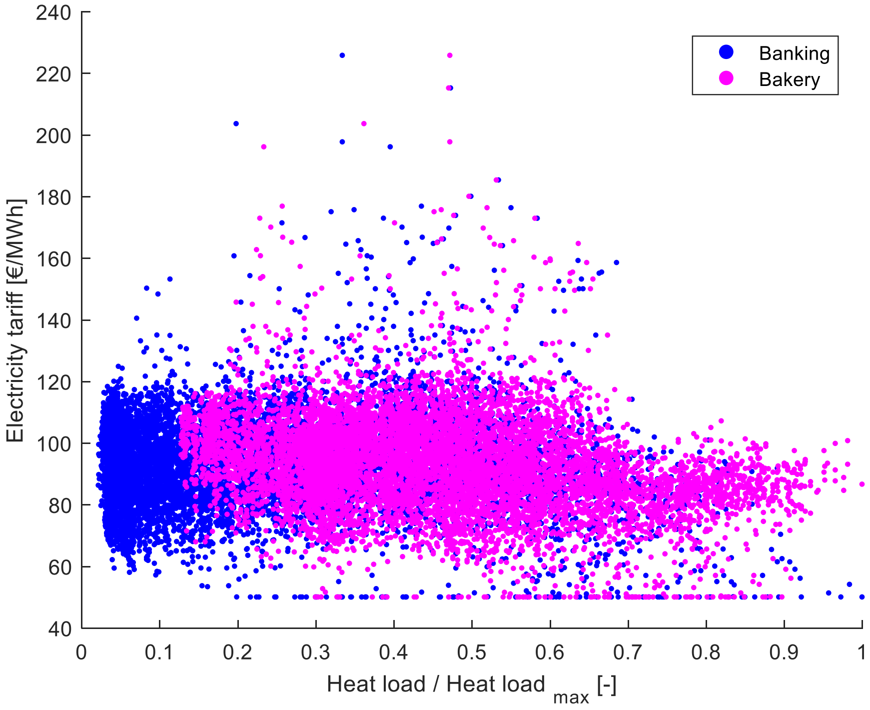
Appendix 21: Correlation of electricity tariff and heat load for user category "Lodging" and "Guesthouse" (Source: own graph)



Appendix 22: Correlation of electricity tariff and heat load for user category "Multi-family" and "Manufacturing" (Source: own graph)



Appendix 23: Correlation of electricity tariff and heat load for user category “Retail” and “Services” (Source: own graph)



Appendix 24: Correlation of electricity tariff and heat load for user category “Banking” and “Bakery” (Source: own graph)