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Effects of the tenants electricity law on energy system layout and landlord-tenant relationship in a multi-family building in Germany

Braeuer F, Kleinebrahm M and Naber E

Karlsruhe Institute of Technology, Institute for Industrial Production

fritz.braeuer@kit.edu

Abstract. Multi-family buildings (MFB) accommodate 53% of the German apartment stock. Although PV-systems on single-family buildings are widely implemented, the PV-potential on MFBs has barely been touched. Therefore, the German government introduced the *Mieterstromgesetz*, the tenants electricity law (TEL), in 2016. This law exempts electricity directly produced and consumed in a building from certain charges and taxes. Within the TEL framework, the landlord acts as the local electricity provider and can profit from selling electricity to the tenants and tenants can save electricity costs. This paper analyses the techno-economic effects of the TEL on the energy system layout of a MFB in Germany. Furthermore, it gives implications on how the TEL affects the tenant-landlord relationship. In this analyses, a MILP model is used to maximize the net present value (NPV) and determines the optimal layout and dispatch of the energy system. The model can choose to invest in PV, CHP and a battery storage system. Additionally, one to six electric vehicles (EVs) are integrated into the model. The novelty of this paper is the model-based analysis of the German *Mieterstromgesetz* considering EVs. The results show that the combination of PV and CHP is the most profitable system layout with NPVs up to 31.9k€. An optimized charging strategy increases the self-consumption rate and the NPV substantially compared to a fast-charging-strategy. Thus, the TEL can create a symbiotic relationship between landlords and tenants.

1. Introduction

The building sector accounts for a big share of the German energy consumption, which is mainly related to space heating and cooling. Thus, it is mainly regarded as an energy sink. Nonetheless, recent development in the sector of single family buildings (SFB) has proven that as a prosumer home owners can actively contribute to the energy transition process. By installing a photo voltaic (PV) system on their roof or integrating a combined heat and power (CHP) unit, they become an additional energy source. Nevertheless, this development is mostly restricted to single-family buildings. Although 53% [1] of German household units are set in multi-family buildings (MFBs), this potential energy source remains mostly untapped. To foster this potential, in 2016, the German government amended the *Mieterstromgesetz*, the tenants electricity law (TEL), which is regulated in the renewable energy act (EEG)[2] and the combined heat and power act (KWKG)[3]. The main goal of the TEL is to create a legal framework to increase the amount of locally produced and consumed electricity from renewable energy sources. Doing so, the law regulates and incentivizes landlords of MFBs to invest in PV-systems and CHP-units in their buildings and to operate as electricity provider for the tenants in a tenant electricity model (TEM). In this TEM tenants can voluntarily participate and directly consume the self-produced electricity in their building and can reduce their spending for electricity. According to TEL, landlords operating a TEM have to offer electricity to participating tenants at least 10% cheaper than the retail prices of the local basic electricity provider (BEP). As 52.4% of the German apartment stock is rented and about 80% of these are located in MFBs [1], TEMs might have a substantial effect on the future electricity mix in Germany. This paper evaluates the energy system of a MFB within the special framework of the TEL. It computes the maximum net present value (NPV) of the energy system from the landlord's point of view considering PV, CHP, energy storage technologies, a varying number of electrical vehicles (EVs) and the current legal framework. For applying the constructed model a MFB in Karlsruhe, Germany, built in 1978 and with 10 apartments is used. The results of this paper address the following questions:

(i) How does the TEL influence the optimal sizing and operation of an energy system in a MFB?
(ii) How do EVs and different charging strategies influence the profitability of a TEM and the layout of an energy system?
(iii) How does the TEL influence the tenant-landlord relationship?

To answer these questions, a mixed-integer optimization model (MILP) is implemented. The model maximizes the NPV of a landlord's investment and determines the optimal sizing and dispatch of the electricity generation and storage units. The analysis varies the number of EVs, charging strategy and the tenants' electricity price. Rent levels and building operation costs are not considered.

In the following, section 2 gives a short overview of the TEL and its economic framework as well as a summary of recent studies on energy systems modeling in MFB and landlord's investment decision processes. In section 3, the methodological approach and the optimization model are presented. Then, section 4 presents the model results and section 5 discusses these results and gives a critical reflection on the methodology. Finally, section 6 gives concluding remarks and an outlook on topics of future research.

2. State of the art

The TEL regulates that, if landlords operate the PV-system or CHP-unit, they act as an energy provider for the tenants. Landlords must provide electricity to a fixed price either directly-produced or coming from the grid. The electricity contract has a maximum run-time of one year and has to be renewed thereafter. Additionally, participation cannot be linked to the rental agreement, thus, participation in a TEM is voluntarily. The following requirements need to be fulfilled in order for a TEM to conform to the TEL.

- Self-produced electricity must be consumed in immediate geographical proximity.
- The public grid must not be utilized for the transmission of self-produced electricity for direct consumption.
- Electricity prices for tenants must be less than 90% of the price of the BEP

Conformance to these requirements enables to profit from the following subsidies:

- Exemption from grid fees, levies and taxes on directly-consumed electricity except the EEG-surcharges.
- A tenant electricity premium (TEP) is paid to the PV-operator for directly consumed PV-electricity. A similar premium is paid for direct consumption of CHP-electricity.

In scientific literature the TEL is investigated by the following authors. [4] and [5] give a compact overview of the TEL for PV-self-consumption. [6] present possible business cases and discuss the socio-cultural hurdles of implementing a TEM with PV-generation. [7] present the legal and economic framework for a CHP-use case. [8] present a comprehensive collection of studies on the TEL. Among the different articles, [9] elaborate on the political background of the TEL and discuss future developments. [10] analyses the profitability of a TEM utilizing a PV- and CHP-generator with a fiscal focus. A variety of scientific publications focuses on a model-based approach to study PV-self-consumption and CHP integration in buildings. A comprehensive number of studies analyzes the self-consumption of PV-energy in buildings. While most studies focus on SFBs, considerably fewer optimize the energy system in MFBs. [11] simulate the energy system for four different building types considering the PV- and heating installations. They focus on the increase in self-consumption and found out that the installation of PV on a large-residential building can yield higher returns on investment than smaller buildings due to higher self-consumption rates. [12] investigate the cost-optimal energy system of a new MFB in Germany. They apply a MILP-Model to identify the cost-optimal investment and operation of the system. They conclude that the installation of a CHP-unit and a PV-system is optimal as they complement each other. The high heat demand in winter and the resulting high electricity output of the CHP-unit correlates with low energy production of the PV-system, vice-versa in summer. Similarly, [13] formulate a MILP to determine the optimal size and operation of an energy system for heat and electricity supply. They model the German market and legal framework accurately but do not consider EVs nor a TEM.

[14] is identified as the only peer-reviewed publication mentioning the TEL. [14] study the electricity self-supply of a MFB with non-subsidized PV-electricity with and without an energy storage in Austria and Germany. The authors use a multi-objective MILP approach to minimize electricity cost and maximize self-consumption. Furthermore, they investigate the tenant-landlord relationship for different values of the weighted average cost of Capital (WACC). The WACC considers increase in operational cost and rent. While [14] raise an interesting research question, they do not apply their model to the specifics of the German TEL TEL. Neither do they consider heating nor electric mobility. [15] present a comprehensive Excel-tool for a detailed description of the TEL regulations. With only minor flaws, the tool is suited to obtain a quick assessment of the profitability of individual technology combinations, while EVs are not taken into account. Nonetheless, one can observe deficiencies in scientific publications that properly asses the energy system of MFBs. Especially the influence of the TEL and EVs has rarely been studied.

Investment decisions in building service equipment such as PV, CHP, batteries with a service life of more than 15 years are considered long-term investments. These decisions are based on diverse economic objectives or management strategies and are set depending on individual preferences and building future prospects[16]. Apart of the economic expectations related to personal attitude or enterprise philosophy, other tangible and intangible criteria such as comfort, eco-friendliness and reputation can be decisive criteria[17]. However, actuarial return, payback assessment, NPV and visualization of financial implications are the methods of choice in building related investments decision-making[18]. From both perspectives of owner-occupier and landlords, an optimization of the NPV is regarded as adequate[18]. Despite the appropriateness of a NPV based approach, most of the identified studies do not maximize it.

Before encountering the decision-making situation, awareness and acquaintance with the TEL are perquisites. Then, motives and barriers trigger the decision making process. These can vary across landlords. For more details on motives and barriers in retrofit and for investments into building service equipment refer to [19, 20, 17, 21, 22, 23].

3. Methodology/Model

The model used to determine the energy system of the MFB is based on [24]. They developed an MILP model to identify optimal design and operation of the energy supply system of a residential building. The model calculates the energy flows in the system in an hourly resolution to match the households' energy demand for one representative year. For determining the optimal system layout and operation *NPV* maximization is set as objective and calculated over a time period of 20 years. The decision variables are energy flow, the size of the technological units and the binary variables for the operation of the CHP-unit as well as the differentiation between different remuneration levels. A schematic overview of the modelled energy system is given in figure 1. The model is implemented in Matlab and solved with the CPLEX solver.

For this paper, multiple EVs are implemented in the model and modelled according to [25]. The *NPV*

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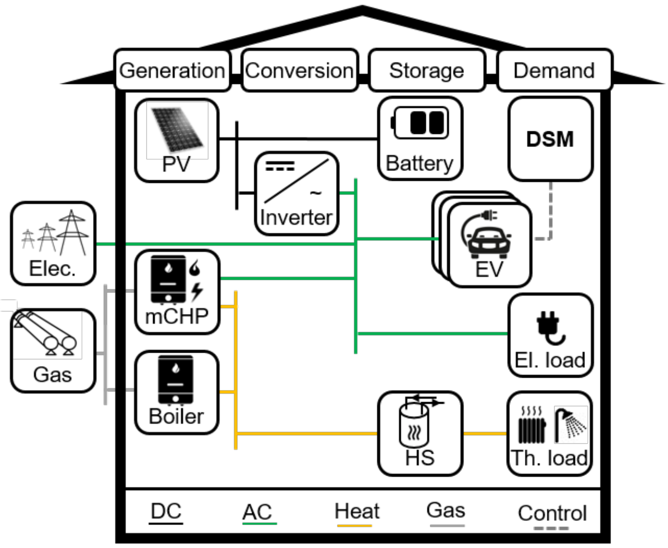

Figure 1. The modelled energy supply system (Elec:electrolysis, FC: fuel cell, el: electrical, th: thermal)

(equation 1) is the difference between the discounted investment (C^l_{inv}) and the discounted annual cash flow (acf). The investment for each technology l in equation 2 consists of an initial investment in the year $a = 0$, a discounted reinvestment after the calendar lifetime (clt) of technology l is reached and a discounted residual value after the considered investment period A. The annual cash flow is represented in equation 3. It includes a term for operation and maintenance, which is a percentage of the installed capacity (cap^l). Hourly electricity flows (P^t) are differentiated between electricity directly consumed ($P^{t,l}_{direct}$) and fed into the grid ($P^{t,l}_{feedin}$) for every technology l. The technologies considered are PV, CHP, a battery storage system and electricity from the grid. Therefore, the cost for directly consumed electricity $c^{l,a}_{direct}$ can be positive as in the case of PV or negative for the grid. Furthermore, except for c_{feedin} the electricity prices rise every year by a fixed rate r_{el}. Finally, the model considers variable costs ($c^{l,a}_{el,prod}$) due to electricity production ($P^{t,l}_{el,prod}$) as in the case of the CHP.

The specific costs and earnings for directly consumed electricity are further explained in equation 4, 5 and 6. Equation 4 shows the earnings for directly consumed PV-electricity. The landlords' earnings are compiled of the tenants' electricity price (c_{tenant}), a percentage of the price of the BEP (c_{basic}), and the tenant electricity premium(c_{TEP}). Their expenditures consist of the EEG-levy (c_{EEG}), value added taxes (VAT) and cost for metering and invoicing ($c_{M\&I}$). (The tenant electricity premium and the feed-in tariff are gradually reduced from a size of the PV-system smaller than $10kWp$, smaller than $40kWp$ and smaller than $100kWp$.) For CHP, equation 5 is composed similarly. There is a CHP-premium for directly consumed electricity (c_{CHPP}) and a premium for avoided grid charges (c_{AGC}). For electricity from the grid, landlords have to pay electricity fees of their electricity provider ($c_{landlord}$) and simultaneously sell the purchased quantity to the tenants for the TEM retail price (c_{tenant}).

$$\max NPV, NPV = -\sum_{l\in L} C^l_{inv} + \sum_{a=0}^{A} \frac{acf^a}{(1+i)^a} \tag{1}$$

$$C^l_{inv} = c^{l,a=0}_{inv} \cdot cap^l + \frac{c^{l,a=clt^l}_{inv} \cdot cap^l}{(1+i)^{clt^l}} - \frac{clt^l_{rem}}{clt^l} \cdot \frac{c^{l,a=A}_{inv} \cdot cap^l}{(1+i)^A} \tag{2}$$

$$acf^a = \sum_{l=1}^{L} -c^l_{O\&M} \cdot cap^l + \sum_{t=1}^{8760} (P^{t,l}_{direct} \cdot c^{l,a}_{direct} + P^{t,l}_{feedin} \cdot c^l_{feedin} - P^{t,CHP}_{el,prod} \cdot \frac{c^{CHP,a}_{el,prod}}{\eta^l}) \tag{3}$$

$$c^{PV,a}_{direct} = c^a_{tenant} + c_{TEP} - c^a_{EEG} - VAT - c^a_{M\&I} \tag{4}$$

$$c_{direct}^{CHP,a} = c_{tenant}^{a} + c_{AGC}^{a} + c_{CHPP} - c_{EEG}^{a} - VAT - c_{M\&I}^{a} \tag{5}$$

$$c_{direct}^{grid,a} = c_{tenant}^{a} - c_{landlord}^{a} \tag{6}$$

The assumed prices are based on the year 2018. The input parameters are shown in the appendix table 2. The building is assumed to be in Karlsruhe, Germany, TRY-region 12 (test reference weather year of the DWD). The building consists of 10 apartments with a total number of 38 occupants. The area of the roof is $176m^2$, the total electricity consumption per year without EVs is $44,666kWh$ and the total heating consumption is $92,517kWh$ for space heating and $27,208kWh$ for domestic hot water. The driving profiles of the EVs are derived from the German mobility panel[25]. For the analysis, the number of EVs is varied between 0 and 6 EVs. Additionally, the tenant electricity price is altered. The values range between 85% and 90% of the BEP price. The results are compared using the *NPV* for the landlords' and the discounted energy cost savings (ΔC_{el}) for the tenants' point of view for all households over the investment period. ΔC_{el} defines the difference between the electricity cost for a reference price ($c_{el,tenant,ref}$) and the energy cost for the TEM electricity price.

4. Results

Table 1 shows the model results for an increasing number of EVs. The upper part of the table shows results of an optimized charging strategy and the lower part results of fast charging strategy, where EVs are charged with its full power capability as soon as the EV arrives at the home charging station. The results show that the *NPV* increases with a higher number of EVs. More EVs lead to a higher total energy demand ($44.7MWh$ per year for zero EVs, *EV0*, and $51.7MWh$ for six EVs, *EV6*), which leads to a higher self consumption rate. The objective function states that directly consumed electricity generates higher profits than feeding electricity into the grid or buying it from the grid. The effect is most visible comparing the optimized and fast charging strategy. In the optimized strategy, the model has a certain amount of freedom to decide when to charge the EV. Therefore, it shifts many charging periods into high PV- and CHP-production periods, resulting in up to 13% higher self-consumption rates for the optimized case compared to fast charging. In the latter fast charging case, the model has no freedom to decide on the EV charging periods. Furthermore, only in the cases of four or more EVs and optimized charging, it is profitable to install PV-systems bigger than $10kWp$. Above this threshold, the feed-in tariff decreases from $0.122€\backslash kWh$ to $0.1187€\backslash kWh$. The higher investment for a bigger PV-system is only feasible when the self-consumption rate increases substantially. In contrast in the fast-charging-case, the self-consumption rate increases only slightly and no PV-system greater than $10kWp$ is installed. On the other hand for six EVs, the installed CHP-capacity in the fast-charging-scenario is greater than in the optimized-charging-scenario. This can be explained through the overlap of charging-periods and heat-production-periods. Noteworthy, in none of these cases does the model install a battery storage system.

Figure 2 shows the discounted cash flows for the investment period of the respective energy system component over 20 years and the resulting *NPV*. A shows the optimized charging strategy and B shows the fast charging strategy, both for six EVs and 90% of the BEP price. The figure shows that investment in a PV-system by itself is already profitable. However, a TEM with both a PV-system and a CHP-unit creates a higher NPV. The figure shows that the highest expenditures and returns are generated by the CHP-unit. The earnings from CHP are divided into a thermal and an electric component. The operational costs for heating from CHP are passed on to the tenants. The model dimensions the CHP-unit to maximize the directly consumed electricity and reduce its feed-in. This can bee seen in the difference from graph A to B. In B, the optimized charging of the EVs reduces the fed-in electricity of the CHP to zero.

In the presented scenario, electricity consumed directly from the grid generates a positive cash flow. This is explained by the positive difference between tenants electricity price and grid purchase price. Due

Optimized charging		***EV0***	***EV1***	***EV2***	***EV3***	***EV4***	***EV5***	***EV6***
NPV	$k€$	23.3	23.8	25.9	27.7	30.6	31.1	31.9
ΔC_{el}	$k€$	14.9	15.0	15.5	16.0	16.9	17.0	17.2
cap^{PV}	kW_p	10.0	10.0	10.0	10.0	13.2	13.6	14.5
cap^{CHP}	kW_{el}	4.6	4.6	4.6	4.6	4.7	4.8	4.8
$r_{self-consumption}$	%	46.3	46.8	48.9	50.7	52.7	53.0	53.5
$r_{self-coverage}$	%	77.5	77.6	78.4	78.8	81.9	82.4	83.0
Fast charging								
NPV	$k€$	23.3	23.8	24.2	25.0	26.2	26.4	26.7
ΔC_{el}	$k€$	14.9	15.2	15.4	15.9	16.7	16.8	17.0
cap^{PV}	kW_p	10.0	10.0	10.0	10.0	10.0	10.0	10.0
cap^{CHP}	kW_{el}	4.6	4.7	4.7	4.9	5.0	5.1	5.1
$r_{self-consumption}$	%	46.3	46.5	46.7	47.0	47.3	47.4	47.5
$r_{self-coverage}$	%	77.5	76.6	76.2	75.8	74.3	74.1	73.8

Table 1. Results for multiple EVs and a tenant electricity price of 90% of the BEP price. The upper results show an optimized charging strategy and the lower results a fast charging strategy.

to economies of scale the landlord is able to obtain a lower grid purchase price than the respective tenant would be able to negotiate for his sole purchase quantity. At prices below 87% of the BEP, landlords have to spend money. Nevertheless, the financial burden for the landlord is minor.

Figure 3 shows the results of varying tenants' electricity prices in percentage of the BEP price for the 10 participating households with 6 EVs. The solid and dashed line indicate the landlords' NPV of the optimized charging strategy and the fast charging strategy respectively. The dotted line indicates the discounted electricity cost saving(ΔC_{el}) of the tenants, optimized and fast charging. In case of fast-charging, at around 88% the NPV is almost as high as ΔC_{el}. Increasing c_{tenant}, the investment is more beneficial for the landlord than for the tenants and vice versa. If tenants would agree to charge their EVs in an for the landlord optimized manner the NPV of the landlords would rise while ΔC_{el}would remain the same. In the optimized scenario, to reach a state where the NPV and $\Delta C_{el}$are equal, c_{tenant} would need to be reduced to 87%. In this state, the NPV is still higher than following a fast-charging strategy at c_{tenant} of 89%. The findings emphasizes the symbiotic relationship between landlords and tenants.

5. Discussion and critical reflection

The results show that for MFBs PV-systems and CHP-units are complementary technologies. This is in line with findings of [12]. Under current prices, the installation of a battery storage system is not profitable. Simultaneously, integrating EVs in the system leads to a higher energy demand, which increases the profitability of the TEM. When the demand increase coincides with a higher degree of demand flexibility, as for the optimized charging process of EVs, even greater NPVs can be reached. For this case, it is more profitable to install more PV-capacity than a greater CHP-unit. The heat demand constrains the capacity expansion of the CHP-unit. Furthermore, the results show that the profitability depends strongly on the self-consumption rate. This rate depends on the electrical load of the households and eventually on the EV-charging pattern. Therefore, assuming perfect foresight and a representative load profile offers a high degree of uncertainty. Moreover, the financial risk of landlords for buying electricity from the grid is low. As a result, the highest risk is in over-sizing the technology dimensions resulting in low self-consumption rates. Additionally, the findings emphasizes the symbiotic relationship between landlords and tenants. Usually, these parties are trapped in an principal-agent dilemma (landlord-tenant dilemma), which is based on opposing interests. The results show that a reduction of the tenant electricity prices would increase the electricity cost savings for tenants. This could be an incentive for tenants to follow an optimized charging strategy. Ultimately, this could lead

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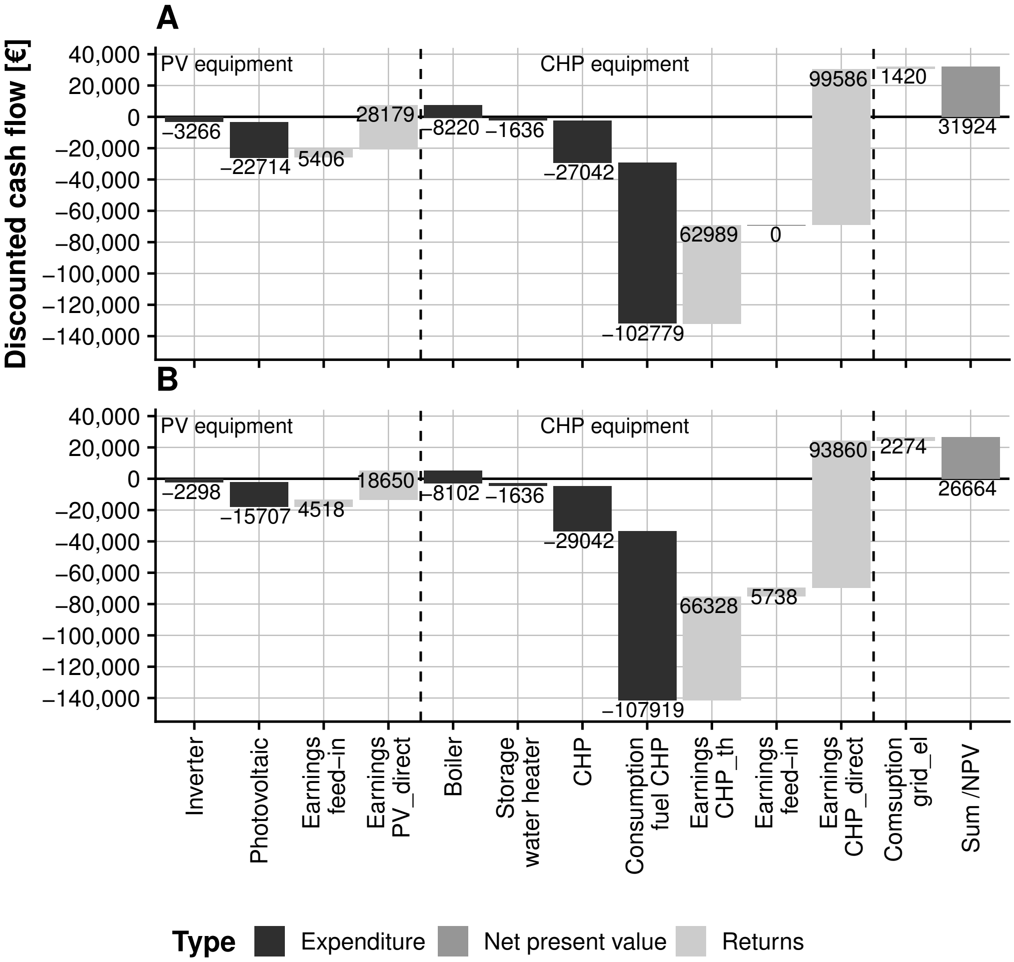

Figure 2. Discounted cash flow and *NPV* sorted by system components and operation (six EVs, $c_{tenant} = 90\%$). A shows optimized charging strategy, B shows the fast charging strategy.

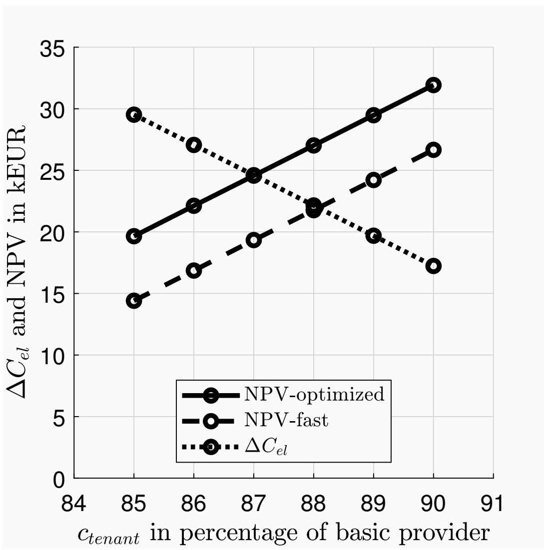

Figure 3. NPV and ΔC_{el} for 6 EVs for varying c_{tenant} in percentage of electricity price of the basic provider. Shown is the case of optimized charging and fast charging for six EVs. (The lines are for graphical understanding and do not resemble model results.)

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to an increase in the NPV, electricity cost savings and CO_2-mitigation. The current installation rate of PV-systems that participate in a TEM in Germany since 2017 is constant. The total installed capacity is $9.74MW$[26]. It seems that awareness and acquaintance with the TEL is the most prominent hurdle for its successful implementation. While this contribution considers solely the NPV, a more detailed insight into other economic performance indicators could reveal different effects. Finally, some of disputable assumption and constraints of this study are mentioned in the following. For the analysis all tenants participate in the TEM continuously over the investment period of 20 years. Then, landlords profit from scaling effects and acquire electricity to better conditions than tenants. An electrical and heating load of one year is used, as well as driving and charging behavior of EV-owners. The EV-charging infrastructure is given and integrated into the MFB's electricity grid. No additional grid charges are considered.

6. Conclusion and outlook

With their high energy demand, MFB are well suited to make a substantial contribution to the German energy transition. The newly introduced TEL incentivises landlords and tenants to increase the self-consumption rate for directly produced electricity from PV-systems and CHP. This paper investigates the optimal energy system for a MFB that applies a TEM. The objective is to maximize the NPV for landlords considering a varying number of EVs. The EVs are charged with an optimized or a fast charging strategy. Additionally, the tenant electricity price is varied between 85% and 90% of the BEP price. For future studies, one should apply a holistic approach that includes heating and building refurbishment. The results indicate that he profitability depends strongly on the heat driven dispatch of the CHP-unit. Additionally for general applicability of the results, future studies need to consider different building types, construction ages and renovation states. They should focus on different locations, varying PV-potential, different electric load and heating load resulting in a alternate CHP-potential. Furthermore, investigations should be conducted that consider the variety of decision making techniques for investors in the building sector. Finally in order to properly assess the tenant-landlord relationship, other factors as rent and operational costs need to be included.

7. Appendix

Parameter	Unit	Value
$c_{el,basic}$	$€\backslash kWh$	0.2946
$c_{el,landlord}$	$€\backslash kWh$	0.2551
$c_{el,tenant,ref}$	$€\backslash kWh$	0.2858
c_{EEG}	$€\backslash kWh$	0.1134
c_{gas}	$€\backslash kWh_{el}$	0.066
$c_{inv}^{PV,a=0}$	$€\backslash kW_p$	1350
$c_{inv}^{inverter}$	$€\backslash kW$	250
c_{inv}^{CHP}	$€\backslash kW_{el}$	5000
$c_{inv}^{battery,a=0}$	$€\backslash kW_{el}$	600
c_{inv}^{boiler}	$€\backslash kW_{th}$	175
A	$years$	20

Parameter	Unit	Value	
i	%	4	
r_{el}	%	2	
c_{TEP}	$€\backslash kWh$	0.037	$cap < 10kW$
c_{TEP}	$€\backslash kWh$	0.0337	$cap < 40kW$
c_{TEP}	$€\backslash kWh$	0.0211	$cap < 100kW$
c_{feedin}^{PV}	$€\backslash kWh$	0.122	$cap < 10kW$
c_{feedin}^{PV}	$€\backslash kWh$	0.1187	$cap < 40kW$
c_{feedin}^{PV}	$€\backslash kWh$	0.1061	$cap < 100kW$
c_{CHPP}	$€\backslash kWh$	0.04	$cap < 50kW_{el}$
c_{AGC}	$€\backslash kWh$	0.001	$cap < 50kW_{el}$
c_{feedin}^{CHP}	$€\backslash kWh$	0.11826	$cap < 50kW_{el}$

Table 2. Input parameters

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