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Renewable Electricity in German Multi-Family Buildings: Unlocking the Photovoltaic Potential for Small-Scale Landlord-to-Tenant Power Supply

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Abstract: The implementation of photovoltaic and home storage systems in multi-family houses (MFHs) in Germany lags significantly behind their development in single-family houses. The Landlord-to-Tenant (L2T) power supply model is meant to reduce this gap, yet few projects have been implemented to date. In this model, the landlord must fulfill the tenants' power demand through a combination of photovoltaic generation and storage and electricity from the grid, for which the landlord pays an auxiliary electricity price that greatly influences the financial viability of a project. Our contribution focuses on the impact of electricity price variations and recent policy changes on the financial viability of small-scale L2T concepts. We considered component investment costs, building sizes, photovoltaic yields, and future developments. Recent policy changes have improved the financial viability of L2T projects, increasing the maximal auxiliary electricity price for which an investment is viable by 13 ct/kWh for a four-party MFH. Minimal auxiliary electricity prices justifying the installation of home storage systems (HSSs) decreased by 9 ct/kWh from 2020 to 2023. Autarky rates are substantially different across the considered scenarios, with the autarky rate being defined as the percentage of consumption of self-generated energy relative to the total energy consumption. For a 22-party MFH the autarky rate decreases by 17% compared to a 4-party MFH. HSSs have the potential to increase autarky rates while maintaining the financial viability of L2T projects.

Keywords: prosumer modeling; Mieterstrom; Landlord-to-Tenant power supply; MILP; residential solar systems; home storage systems

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Academic Editor: Ludovico Danza

Received: 31 January 2025
Revised: 25 February 2025
Accepted: 27 February 2025
Published: 1 March 2025

Citation: Celi Cortés, M.; van Ouwerkerk, J.; Gong, J.; Figgener, J.; Bußar, C.; Sauer, D.U. Renewable Electricity in German Multi-Family Buildings: Unlocking the Photovoltaic Potential for Small-Scale Landlord-to-Tenant Power Supply. *Energies* **2025**, *18*, 1213. https://doi.org/10.3390/en18051213

1. Introduction

The German federal government has set the goal of achieving climate neutrality by 2045 through the amendment of the Climate Change Act 2021, expanding its CO_2 reduction targets from 55% to 65% by 2030 and setting a minimum CO_2 reduction target of 88% by 2040 [1]. In order to achieve these goals, it is essential to realize the reduction targets in all areas, including the residential sector. Energy-related emissions by German households amounted to 80.2 million tonnes of CO_2 equivalent in 2022, representing 10.8% of the total emissions in the country [2]. The challenge of cutting emissions in this sector has been approached with the nationwide installation of residential photovoltaic (PV) systems in the last two decades: by 2022, PV systems in single-family households were producing around 2.1% of the total gross electricity generation in Germany [3]. Home storage systems (HSSs) coupled to PV systems have similarly achieved remarkable penetration in Germany. They are the main driver for stationary battery storage, with 5.49 GWh of installed capacity, which accounts for 79% of the total stationary battery capacity [4]. While this represents a significant development in the decentralization of energy generation and storage for single-family houses, a wider-spread integration could be achieved by the further development of Landlord-to-Tenant (L2T) power supply (Mieterstrom) and other models in apartment buildings and blocks.

Through the L2T regulatory framework, presented in Section 2.1, it is possible for tenants living in multi-family houses (MFHs) to be supplied with electricity generated in or in immediate proximity to their building. In this model, the landlord must fulfill the tenants' power demand, complementing local renewable generation with electricity from the public power grid (auxiliary electricity). The tenants pay the landlord an L2T electricity price for the total demand, while the latter pays an auxiliary electricity price for electricity taken from the grid to supplement local generation. The need for solutions such as L2T supply is made evident by the low share of MFHs with a PV installation. It is estimated that only around 50,000 MFHs, or 1.5% of the total MFHs in Germany, are equipped with PV systems, as opposed to around 1.7 million PV systems in single- and two-family houses [3]. The estimated number of PV systems installed in MFHs includes not only L2T but also other models, such as solar power for homeowners' associations and total PV feed-in by the landlord. According to a case study of a large building stock, the alternative model of district electricity sharing can result in 20% higher revenues compared to L2T [5]. The main non-financial barriers for the low adoption rates of PV systems on MFHs include the complex regulatory environment and bureaucracy around the existing models. In the case of owners associations, the parties have to agree on the management of installation and operation of the systems [3]. In the case of the L2T regulatory framework, landlords become power suppliers to their tenants, with all the responsibilities that this represents. This can drive landlords away from implementing an L2T project, especially in privately owned MFHs.

In 2017, a report commissioned by the Federal Ministry for Economic Affairs and Climate Action estimated that around 360,000 existing buildings with a total of 3.8 million housing units (HUs) could be suitable for adoption of an L2T model in Germany [6]. A 2024 study by the German Economic Institute claims this estimate is conservative and calculates that there is a potential for 1.9 million buildings to adopt the L2T model [7]. Furthermore, the study identifies barriers such as the need for technically differentiating between self-generated solar power and grid electricity by virtual meters and smart meters and the eventual need for costly renovations if meters in existing buildings are located within individual housing units. Figure 1 shows the number of new L2T projects realized per year from 2017 to May of 2023. Our analysis of the "Marktstammdatenregister" (MaStR) database of the Federal Network Agency shows merely 6367 L2T projects in operation, most of which include an HSS, with a share of 64.13%, while the rest opt for a PV-only solution. A recent source estimates the amount of L2T projects at 9000 [7]. This estimation, combined with the results of our analysis of the MaStR database, which shows an increasing number of new projects in recent years, evidence an accelerated rate of adoption. This could be motivated by regulatory changes and decreasing investment costs for PV and HSS systems. One of the main motivations for the installation of HSSs in contrast to PV-only solutions could be to hedge against rises in electricity prices, similarly to the case of single-family houses [8]. Furthermore, we consider that the installation of an HSS could improve the robustness of the project against future regulatory frameworks.

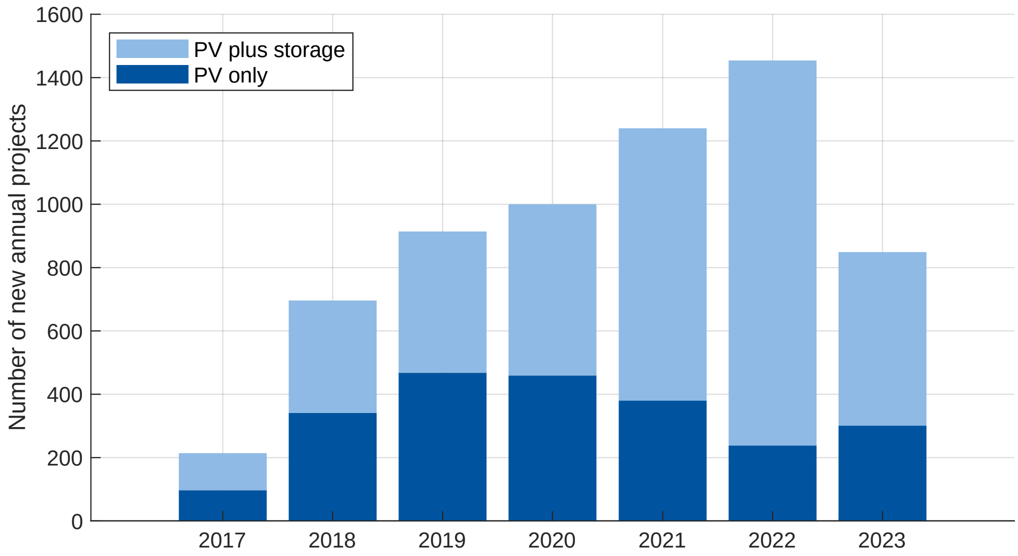

Figure 1. Number of new Landlord-to-Tenant power supply (L2T) projects per year, including photovoltaic (PV) installations with and without storage. Own analysis based on data from the "Marktstammdatenregister" (MaStR) database, accessed in May 2023 [9].

If we observe the average system sizes of L2T projects in operation (see Figure 2), we find that mean PV powers range from 12.8 kWp to 17.4 kWp while mean energy capacities of HSSs range from 12.3 kWh to 18.5 kWh across the considered years. The dominance of small-scale projects is highlighted by the narrow system size range. Additionally, the relatively low number of L2T projects in operation indicates a low overall power and energy capacity compared to what is available in the single- and two-family housing sector.

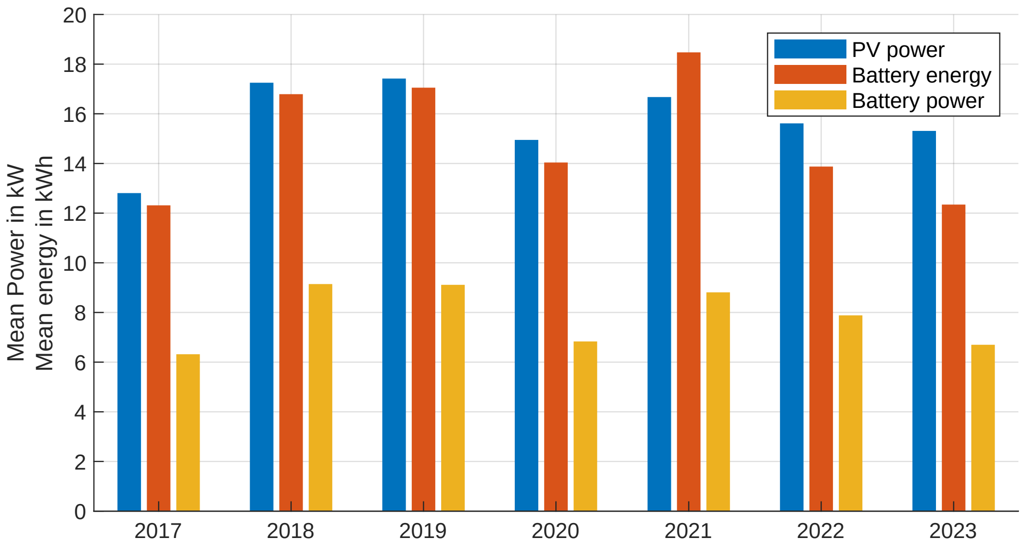

Figure 2. Mean PV power, home storage system (HSS) energy, and HSS power of new L2T projects per year. Own analysis based on data from the MaStR database, accessed in May 2023 [9].

The number of realized L2T projects is small compared to the projection of 360,000 suitable existing buildings. There are several reasons that can explain this limited implementation. Within the L2T regulatory framework, tenants are free to choose their electricity supplier, while landlords must ensure a continuous power supply at all times, fulfilling the role of an electricity supplier [10]. The free choice of electricity supplier creates financial uncertainty for landlords, while assuming the role of the electricity supplier poses technical and transactional challenges. Another reason why L2T projects in existing residential buildings are often considered uneconomical are the high costs for a physical summation meter, as required by the regulatory framework [11].

Nonetheless, there are a range of projects which prove that it is possible to implement solutions under the current regulatory framework. For instance, BürgerEnergie Nord implemented L2T projects with PV powers ranging from 22 kWp to 58 kWp in existing buildings [12]. Moreover, larger projects in existing buildings are also possible, like a project in Saxony-Anhalt that couples a 100 kWp PV system with a 20 kW_{el} combined heat and power unit [13]. More recently, larger scale L2T projects in existing building stock have been planned [5,14], such as the 2023 implementation of 400 kWp for 132 HUs in Hannover, to be realized under the contracting model, where the L2T developer company assumes all investment risks and supply responsibility [15,16]. There are also projects that remodel or combine existing buildings with new developments [17], such as a project that incorporates new housing to existing building stock, implementing 320 kWp of PV power for 72 existing HUs and 24 additional HUs in Freiburg [18]. L2T projects in new buildings are also very present in the recent landscape, exemplified by a selection of projects by [19], with PV powers ranging from 18 kWp to 337 kWp, often complemented with batteries and/or heat pumps.

The planned implementation of large-scale projects may change recent statistics regarding mean PV powers and HSS energies. However, this does not solve the need for renewable integration in smaller existing and new residential buildings in a country where over half (52.4%) the population lives in rented accommodation, topping the European Union ranking [20]. Regional requirements for the installation of PV systems in new buildings [21,22] as well as recent changes in federal policy have the potential to nudge stakeholders towards more photovoltaic installations.

Tax breaks for investment and installation costs of PV systems and HSSs [23,24], the abolition of the "Erneuerbare-Energien-Gesetz" (EEG) levy [25], and the abolition of the PV feed-in limit [26] have been recently enacted. In addition, it is estimated that with the introduction of the smart meter law in Germany, which allows for the use of virtual summation metering as opposed to the cost-intensive physical summation metering, around 50% more residential buildings have the potential to adopt the L2T concept [11,27]. The L2T supply company Einhundert Energie is already implementing a large-scale project in existing buildings using the virtual summation meter model to supply a total of 450 HUs [11].

When analyzing the scientific literature explicitly concerning the L2T model, we found model-based approaches to optimize the integration of technologies such as electric vehicles and heat pumps, as well as an evaluation focusing on the role of L2T from an energy community approach. Baum et al. perform an economic evaluation of the implementation of heat pumps within the L2T framework, considering regulatory conditions that applied in 2018 [28]. Braeuer et al. employ a mixed-integer linear programming (MILP) approach to optimize the layout and dispatch of energy systems that incorporate heat pumps and electric vehicles by maximizing the net present value (NPV) from the perspective of the landlord in the context of the L2T regulatory framework applicable at the time [29]. More recently, Haelsig et al. focus on the evaluation of L2T as an electricity sharing option for large housing associations [5]. In contrast to model-based studies, Moser et al. propose a qualitative analysis of the L2T concept at the socio-technical landscape, regime, and niche levels [30]. Quitzow analyzes narratives of prosumage at the city level in Berlin and indicates that the

L2T law has mostly resulted in large-scale initiatives by real estate companies instead of the expected small-scale implementation in privately owned buildings [31].

We identified a gap in the literature regarding the potential analysis of L2T electricity supply for smaller MFH buildings and the influence of electricity price variations on economic feasibility and on HSS installations within the latest regulatory paradigm. We found that the inclusion of smaller MFHs is key to realize the integration of decentralized renewable power for tenants. Around 21.87 million HUs are in buildings with three or more units (MFHs), which is around 52.55% of the total amount of residential units in Germany [32]. Further, small to average MFHs (3–12 HUs [33]) represent 91.7% of the total MFH building stock as well as 80.2% of the total living area in MFHs [34]. Specific knowledge gaps in the current literature include the evaluation of the financial viability of small-scale L2T projects, for example, in privately owned buildings. Furthermore, there is a gap concerning the impact of recent policy changes on the viability of L2T projects in general and small-scale projects in particular. Changes to policy such as the waiver of the value-added tax (VAT) for PV and HSS systems, changes in feed-in tariffs, feed-in limits, and subsidies have a considerable impact on the viability of small-scale projects. New insights could be key in motivating new projects in this category, since L2T projects have traditionally been profitable mostly only for large companies instead of the intended implementation in privately owned MFHs.

The financial viability of L2T concepts is increasingly shaped by electricity pricing and evolving regulatory frameworks. Recent changes in regulations, along with the economic potential of small-scale L2T solutions in residential buildings and MFHs, have created the opportunity to explore how these factors influence the adoption of such models. The novelty of this research lies in its focus on the interaction between key stakeholders—tenants, system operators, and auxiliary electricity providers—and how these relationships affect pricing strategies and investment decisions. Furthermore, the study explores the impact of decreasing technology costs and varying PV yields on the autarky and profitability of small-scale L2T solutions. By addressing these aspects, this work offers valuable insights into how L2T models can play a significant role in supporting Germany's energy transition, while also incentivizing the implementation of small-scale projects that contribute to a more sustainable and decentralized energy system.

2. Materials and Methods

In this section, we presented the L2T base model with its financial, technical, and contractual relationships, followed by the modeling and analysis procedure, introducing the prosumer topology and the methodology for our sensitivity analysis. Further, a description of the optimization approach and the objective function that integrates the L2T concept are introduced. Finally, we provide a brief overview of the MILP optimization Framework for Optimizing Sector-Coupled Urban Energy Systems (FOCUS) [35,36] developed at RWTH Aachen University.

2.1. The Landlord-to-Tenant Electricity Supply Model

The L2T model is a German regulatory framework that enables the use of locally generated PV power by tenants of MFHs without having to invest in or own any hardware [37]. In addition to the PV system, it is allowed to install an HSS to buffer PV generation for its later consumption.

Figure 3 shows the financial, energetic, and contractual relationships within the L2T base model. In this arrangement, the end customers are the tenants living in the MFH, with the autonomy to choose whether to enter into an L2T contract with the plant operator. The plant operator serves as the electricity supplier, ensuring a continuous and uninterrupted power supply to the tenants. For the times when locally generated power is not available or sufficient to cover the current power demand, it is possible to draw power from the public grid in order to fulfill the obligations of an electricity supplier. This is called the auxiliary electricity and is bought by the plant operator from an electricity trader by means of an auxiliary power contract. As a result, the total power supplied to the tenants is composed of locally generated electricity, or L2T electricity, and auxiliary electricity. For the total power supplied to the tenants, an L2T electricity price is paid to the plant operator, as agreed in the L2T supply contract. By law, this price may not exceed 90% of the local basic supply tariff (Grundversorgungstarif) [10]. The basic supply tariff is the default tariff for the supply of electricity if a consumer has not entered into a specific contract with an electricity provider [38]. It is regulated by law and its amount varies by location, hence the specification of the local basic supply tariff when determining the price cap for the L2T electricity price.

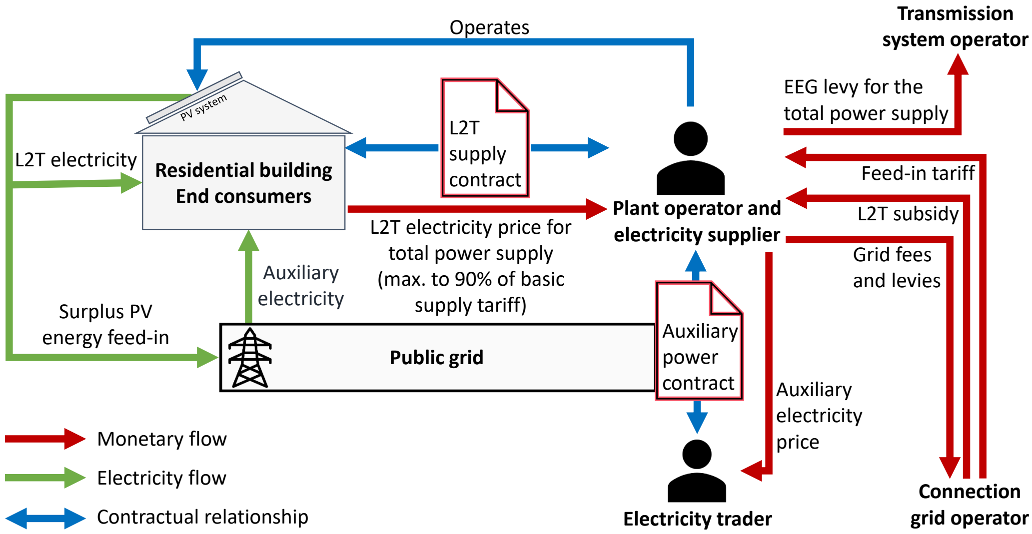

Figure 3. Landlord-to-Tenant supply model, featuring financial, energetic, and contractual relationships. EEG stands for "Erneuerbare-Energien-Gesetz". Own illustration based on the visualization in [37].

Similarly to the use of PV systems in single-family owned houses, it is possible to feed in surplus power generated by the PV system. For this energy, a feed-in tariff is paid to the plant operator by the connection grid operator [39]. In addition, the L2T subsidy is paid to the plant operator for each kWh of locally generated electricity (L2T power) that is supplied to the tenants [39]. Further, the plant operator pays grid fees and levies to the connection grid operator for the power drawn from the public grid in the context of the auxiliary power contract. For the purposes of this study, we assumed that the grid fees and levies are included within the auxiliary electricity price.

Additionally, the so-called EEG levy was paid by the plant operator to the transmission system operator for the total power supplied until its abolition, which became effective from the 1 July 2022 [25]. In our analyses, we considered this levy depending on the year of the regulatory scenario in question.

2.2. Modeling and Analysis Procedure

In this work, we analyzed scenarios for different regulatory frameworks corresponding to the years 2020 and 2023, as well as a future scenario of 2030. These regulatory settings include variations in PV feed-in limits, levies, tariffs, subsidies, and tax breaks. This approach allows for the evaluation of regulatory changes on scenarios that consider different building sizes (MFH I–MFH IV) with varying numbers of housing units in five German cities. In this way, we captured the influence of varying energy demands and city-dependent PV yields.

For the purposes of this study, the prosumer topology and component connections stay constant for all scenarios considered. Figure 4 shows the prosumer topology used as an input for the optimization. The prosumer topology consists of a PV system, an HSS, and separate inverters for the PV system and the HSS, as well as the public grid and the consumer demands, which are summarized for the sake of computation-time optimization. The consumer demands included in the prosumer topology consider the energy consumption of different types of tenants, according to statistics on the German demographic. The details on the modeling of the tenants' energy demands can be found in Appendix B.1. We did not consider the thermal demand of the households when defining the topology of the prosumer, since its coverage is not part of the L2T concept evaluated and as such has no bearing on the objective function of the optimization. The proposed topology indicates the input for the modeling framework and describes the components that can be installed. However, whether an HSS is installed, as well as its size, will depend on the result of the optimization. A description of the models corresponding to the components shown in Figure 4 can be found in Appendix A.

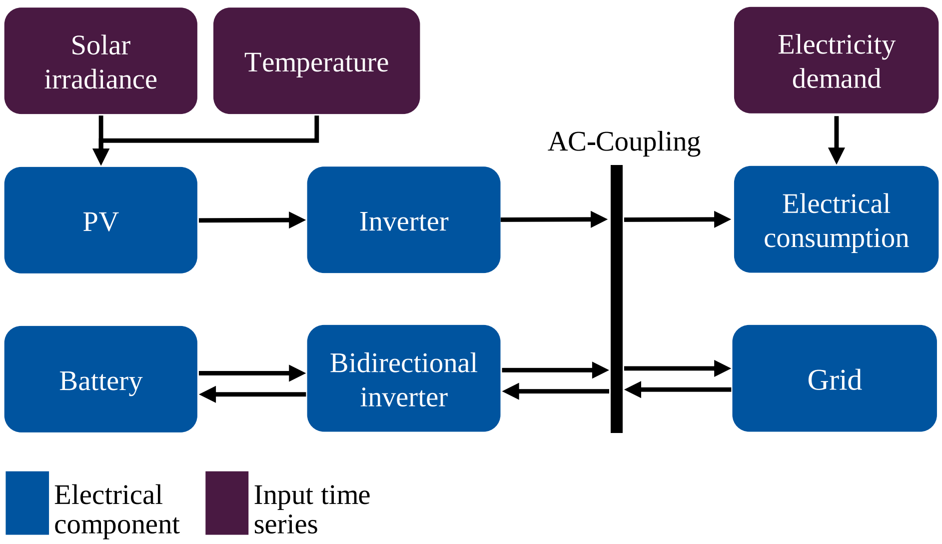

Figure 4. Simplified prosumer topology as an input for the optimization framework.

In the main part of our study, we performed scenario-dependent sensitivity analyses, varying the auxiliary electricity price and the L2T electricity price across a range from 10 to 60 ct/kWh. This resulted in 2601 individual optimizations needed to establish a solution space for each sensitivity analysis. All optimizations were performed using a modeling resolution of 15-min time steps. In this solution space we show the variation in optimization results such as the annuity of the project, the size of the PV system, and the size of the HSS for each combination of prices. By evaluating the investment annuity, we intended to assess the viability of a project under diverse pricing conditions. We show and discuss the solution spaces of annuity, PV system size, and HSS size for a reference building size or MFH and a reference city. The detailed setup of the scenarios and reference MFH and city are described in Section 2.5.

2.3. Optimization Approach

As an economic viability metric and objective function for the optimization program, we chose the investment annuity under the assumption of constant cash flows for the duration of the investment horizon. Component sizes can be freely optimized by the framework, albeit considering upper limits in the case of PV size, and are considered in the objective function through the influence of investment and reinvestment costs, as well as residual values on the investment annuity.

The summarized objective function is shown in the following equations:

$$\frac{(1+i)^T \cdot i}{(1+i)^T - 1} \cdot \left(-\sum I - \sum RI \cdot (1+i)^{-T_{RI}} + \sum R \cdot (1+i)^{-T} \right) \tag{1}$$

$$+\sum M + \sum RE - \sum CO \tag{2}$$

Equation (1) shows the term of the objective function related to capital investment, which is multiplied by an annuity factor considering the end time of the investment horizon T and the fixed discount rate i. I represents the sum of all initial investment costs for the components at the beginning of the investment. RI represents the reinvestment costs for any component that are incurred at the end of life T_{RI} of the component, if the end of life comes before the end of the investment horizon T. If the component has a service life that exceeds the investment period, a residual value R is considered as an income at the end of the investment horizon and is discounted accordingly. The residual value R is calculated using the method of linear depreciation.

Equation (2) represents the balance of variable costs and revenues for one year. This includes the sum of fixed annual maintenance costs M that are calculated as a percentage of the investment costs of each component (see fixed OM in Table A4) and the sums of revenues RE and costs CO that represent the monetary flows shown in Figure 3.

The monetary amount of each flow relevant to the variable costs and revenues balance depends on a specific energy flow. To illustrate an example of the scale and distribution of energy flows for an L2T prosumer, we present a Sankey diagram. By representing the energy flows for a selected scenario and price combination, we provide an overview of the composition of the operating costs and revenues. The Sankey diagram for a prosumer incorporating an HSS is briefly presented in Appendix B.4.

The optimization horizon for any given optimization is one year. Due to the assumption of constant cash flows for every year, it is possible to consider the annuity of the investment for the total investment horizon in the objective function while optimizing only one year of prosumer operation.

2.4. FOCUS Framework

FOCUS is an open-source tool in the domain of energy system optimization, with high flexibility, designed to generate optimization models that range from the individual prosumer level to the broader city level [35,36]. FOCUS was developed using Python 3.7 and leverages MILP for its optimization processes. The framework utilizes the Pyomo library [40], which is a Python-based optimization modeling language, for the definition of optimization models and supports a wide range of popular solvers, such as Gurobi, CBC, and CPLEX [41–43]. Thanks to its modular structure, an important feature of FOCUS is its ability to parallelize the solution process, which significantly reduces the runtime for scenarios comprising a large number of optimization problems. The framework not only includes physical characteristics and technical limitations but also incorporates political regulations into the model. Such a holistic approach is crucial for creating implementable energy solutions and developing business models.

For the purpose of this research, prosumer models of the investigated MFHs are built using the FOCUS framework. The prosumer model involves instantiating and communicating with various component models, which are building blocks of this prosumer.

It also incorporates prosumer-related regulatory constraints to ensure a comprehensive representation of the investigated prosumer, including the L2T framework, which was integrated into FOCUS in the context of this study. Component models, as presented in Appendix A, are created with the provided Python classes in FOCUS for PV panels, a battery home storage, power electronic devices, a virtual component for electric consumption, and a grid connection. These components are parameterized to fit the scenarios of this research. They define and pass on component-related optimization variables and technical conditions in the form of constraints to the prosumer model, where they are added to the overarching optimization problem. Additionally, each component model is able to calculate investment costs, operating costs, and revenue that are generated by the component under various operating conditions. The cost structure is a crucial aspect implemented in the framework, providing insights into the financial implication of different energy solutions and supporting the target of pursuing high economic benefits. Finally, the optimization objective, maximizing the annuity of the overall prosumer, is added to the problem through the energy management system. FOCUS facilitates both sizing optimization, determining the most appropriate sizes for energy components, and operation optimization, ensuring efficient operation within the prosumer at every time step. This approach ensures that both the design and operational aspects of the energy system are optimized for the best possible outcomes.

2.5. Scenario Definition

This section describes the range of scenarios defined for optimization and analysis. For the later analysis, several combinations of different multiple-family houses or MFHs are defined. In Germany, small-to-average MFHs (3–12 housing units or HUs [33]) represent 91.7% of the total MFH building stock as well as 80.2% of the total living area in MFHs [34]. The remaining MFHs are classified as large MFHs [33,34,44], with over 12 HUs. Most MFHs (53.7%) present configurations of 3 to 4 HUs, followed by 7 to 12 HUs (19%), 5 to 6 HUs (18.6%), and over 12 HUs (8.7%, with an average of 22 HUs) [34]. Based on these data, we defined four different MFH configurations to represent existing residential buildings in Germany. Further, the annual electricity demand per HU is assumed to be 3190 kWh [45]. The assumptions for the selected configurations are listed in Table 1. Among the MFHs defined, we chose MFH I as the reference configuration. This configuration represents MFHs with 3 to 4 HUs, which account for over half of all MFHs in Germany.

Another important parameter for the scenario definition is the PV potential of each MFH configuration. The maximum installable PV power can be calculated considering the number of HUs per story and the living area per HU. A configuration of two HUs per story is assumed for MFHs I and II, while a configuration of three HUs per story is assumed for MFHs II and IV. This is based on common layouts [44] as well as statistics about the number of stories as a function of the number of HUs [33] in German residential buildings. Parting from the total living area per story, the gross floor area of the building is determined by using the gross floor area to living area ratio of 1.88 [46]. With a gross floor area-to-PV usable area ratio of 0.488 [47], the area available for a PV installation is calculated. Further, a PV power-to-available PV area ratio of 0.1844 [48] is calculated and applied to the available PV area, resulting in the maximum PV values shown in Table 1 (in kWp, rounded).

Finally, Table 1 lists annual metering costs, that depend on the total electricity demand as well as on the installed power generation of a building. As reference values, we assumed costs that correspond to the price ceiling given by the Government for metering point operators for mandatory installation and operation [49,50] that would apply according to each MFH configuration.

Table 1. Selection of multi-family house (MFH) configurations, varying the number of housing units (HUs), the maximal installable photovoltaic (PV) power, and relevant assumptions.

Parameter	Unit	Selection of Multiple-Family Houses				Reference
		MFH I	MFH II	MFH III	MFH IV	
Number of HUs		4	6	12	22	[33,34,44]
HU living area	m^2	74.8	74.8	66.2	63.1	[33]
Floor layout	HUs/story	2	2	3	3	[33,44]
Electricity demand per HU	kWh/a	3190				[45]
Total electricity demand	kWh/a	12,760	19,140	38,280	70,180	
Max. installable PV power	kWp	25	25	34	32	[33,46–48]
Metering costs	EUR/a	130	170	360	560	[49,50]

In order to consider recent changes in German regulations concerning L2T supply, as well as the installation and operation of PV and energy storage systems in residential buildings in general, three regulatory scenarios have been defined, corresponding to the years 2020, 2023, and 2030. Before the announcement in 2023 of a virtual billing model with smart meters, the high component and installation costs of previously available billing concepts was a clear deal-breaker for many L2T projects in existing buildings [11,27]. For this reason, the billing costs in Table 1 are assumed for 2020 in order to provide a meaningful evaluation of the effect of policy-enacted changes in subsidies and tariffs.

Table 2 shows the relevant economic and regulatory parameters for the different scenario years considered. The considered regulatory changes between 2020 and 2023 include lifting the feed-in power limit of 70% of the installed PV power for residential buildings [26,51], the waiver of the VAT for the purchase and installation of PV and battery systems, including power electronics, and the abolition of the EEG levy. Further, the future scenario, 2030, has been defined according to the degression mechanism and rates for both PV feed-in tariff and L2T subsidy published by the government [52,53], as well as other assumptions regarding the continuity of the other regulatory measures discussed.

Since both the PV feed-in tariff and L2T subsidy are calculated proportionally according to the size of the PV system [39], the rates assumed in Table 2 are the result of calculating with the maximum installable PV power for each MFH, as seen in Table 1. These rates are by law [39] fixed for 20 years, based on the current rates at the time of the installation of the PV system, so they can be assumed for the whole investment horizon. All tariffs and subsidies assumed correspond to the installation of the systems in January of a given year. The scenario year 2023 (present) is chosen as the reference regulatory configuration.

Further, irradiance and temperature data from the five largest German cities by population are employed to instantiate the optimization model for different combinations of years and MFHs. Berlin was chosen as the reference city due to the significance of its population and its average PV yield among the considered cities. Table A3 shows the specific annual PV yields and coordinates of the irradiance data for Hamburg, Cologne, Berlin, Frankfurt, and Munich. In this way, the effect of recent policy changes can be evaluated by comparing the years 2020 and 2023 for different MFHs and cities.

The input data utilized in this work are presented in Appendix B. These data include the electrical demand profiles generated for a typical MFH in Germany, the aforementioned irradiance and temperature data as inputs for the PV model, as well as various techno-economic parameters used to instantiate component models in the FOCUS framework.

Table 2. Relevant economic and regulatory parameters for different years for the Landlord-to-Tenant power supply (L2T) model. EEG stands for "Erneuerbare-Energien-Gesetz" (EEG) and VAT stands for value-added tax.

Parameter	Unit	2020	2023	Future: 2030	Reference
PV feed-in limit	% of P_N	70	100	100 $^{(*)}$	[26,51]
L2T price limit	% of basic supply tariff	90	90	90 $^{(*)}$	[10]
EEG levy	ct/kWh	6.756	0	0	[25,37]
PV feed-in tariff MFH I	ct/kWh	9.70	7.54	6.64 $^{(o)}$	[39,52,53]
PV feed-in tariff MFH II		9.70	7.54	6.64 $^{(o)}$	
PV feed-in tariff MFH III		9.67	7.42	6.54 $^{(o)}$	
PV feed-in tariff MFH IV		9.68	7.44	6.55 $^{(o)}$	
L2T subsidy MFH I	ct/kWh	1.20	2.56	2.27 $^{(o)}$	[39,53,54]
L2T subsidy MFH II		1.20	2.56	2.27 $^{(o)}$	
L2T subsidy MFH III		1.17	2.54	2.25 $^{(o)}$	
L2T subsidy MFH IV		1.18	2.54	2.25 $^{(o)}$	
VAT component costs	%	19	0	19	[23,24]
Investment horizon	years	20		20	
Discount rate	%	3		3 $^{(*)}$	[55]

$^{(*)}$ assumption: same as 2023, $^{(o)}$ own calculation.

3. Results

In order to evaluate the viability of an L2T project, it is essential to view it as an investment from the perspective of the landlord or energy system operator. With the help of sensitivity analyses, we investigated the effects of pricing on the profitability of an L2T investment. First, we analyzed the financial viability of the L2T using the example of our reference building size MFH I under the regulatory conditions for 2023 and the city of Berlin. In the context of the sensitivity analyses, we optimized the MFH energy system for different combinations of auxiliary and L2T electricity prices, representing the solutions in three different heat maps. Each point in a heat map is the result of an individual optimization and represents the optimized annuity (Figure 5), and optimal PV size (Figure 6) or HSS size (Figure 7).

3.1. Financial Viability of the L2T Model

Figure 5 shows the investment annuities of a project for different price combinations for reference scenario MFH I and a fixed PV yield for the city of Berlin. The solution space in the heat map results from the variation in electricity prices with a step width of 0.01 EUR/kWh. In this solution space we can interpret project annuities equal to or higher than zero to be financially viable. Solutions above the break-even curve result in negative investment annuities for the landlord or operator while solutions below this curve result in positive investment annuities. We further constrained the solution space by incorporating upper L2T electricity prices that correspond to 90% of the local basic supply tariff seen in the legend, as prescribed by law [10]. These constraints are represented by vertical dotted lines for a variety of local basic supply tariff, highlighting the dependence of upper L2T electricity price limits on current market situations.

A realistic basic supply tariff for 2023 amounts to 0.40 EUR/kWh, based on our own calculations using values from ref. [56]. If we assume this value for the local basic supply tariff, the upper L2T electricity price limit is 0.36 EUR/kWh, represented by the third vertical dotted line in Figure 5 (from left to right). In this case, the maximal viable auxiliary electricity price of 0.57 EUR/kWh is found at the intersection with the break-even curve, corresponding to price combination A. For this price point, the calculated annuity is EUR 26. Even though this optimization result fulfills the condition of positive annuity, there could be other operation, transaction, and billing costs that have to be lower than the found annuity in order for the project to stay viable. Further, the annuity has to be high enough to justify the investment effort according to the utility function of the individual landlord. If we assume the auxiliary electricity price to be equal to the basic supply tariff at 0.40 EUR/kWh, we arrive at an annuity of EUR 882. This price combination is denoted by point B in Figure 5. As an example, price combination B amounts to an annuity of EUR 865 in MFH I for the scenario year 2030 (see Figure A2) and to an annuity of EUR 2457 in MFH IV for the scenario year 2023 (see Figure A5). These investment annuities could be better suited to cover additional expenses and fulfill the investment expectations and even provide leeway for the installation of an HSS beyond the optimal sizing. Given the slope of the break-even curve, we observed that the investment is always profitable if the auxiliary electricity price does not exceed the local basic supply tariff, for the basic supply tariffs observed. If the auxiliary electricity price were coupled to the basic supply tariff, this relationship would enforce a minimum annuity designed to provide a certain financial leeway to make the investment sufficiently attractive. Further, this relationship should account for market effects on L2T electricity prices, since tenants are free to choose alternative electricity providers.

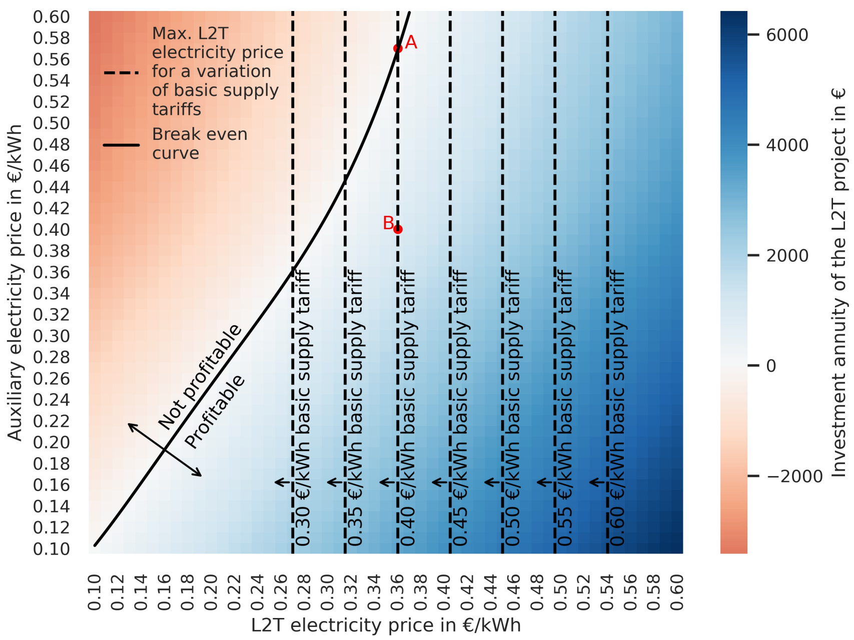

Figure 5. Investment annuity of the L2T project from the perspective of the landlord or energy system operator for different price combinations. The results are shown for multi-family house (MFH) I for the city of Berlin within the regulatory framework of 2023. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

Continuing with the example for a basic supply tariff of 0.40 EUR/kWh, we assumed that the operator will set the L2T electricity price to the maximal price allowed by law of 0.36 EUR/kWh and that the auxiliary power provider will set the electricity price to the maximal price for which the project is still viable (0.57 EUR/kWh), corresponding to price combination A. If the L2T electricity price is lower than any alternative available to the tenants, a Nash equilibrium is achieved. This is because there is no unilateral change in strategy for any of the three parties (operator, auxiliary power provider, and tenants) that will improve their outcome. The operator is not allowed to increase the L2T electricity price; if the auxiliary power provider increases the price, the project ceases to be viable and there is no business case; and if the tenants choose an alternative electricity provider other than the operator, their energy costs will increase. Conversely, if the alternative price is equal to the L2T electricity price, then a weak Nash equilibrium is achieved, since the tenants are indifferent to a change in supplier. If the alternative electricity price available to the tenants is lower than the L2T electricity price, no Nash equilibrium is achieved.

3.2. Optimal Sizing of PV Systems

Figure 6 shows the optimal PV system sizes for each price point, corresponding to the optimization results for the MFH I scenario for Berlin, as seen in Figure 5. Thus, we continue to highlight the break-even curve that is related to the annuity of the scenario. Here, we observe that the variation in the L2T electricity price does not influence the viability or size of the PV system. This happens as the optimization model maximizes the investment annuity, thus minimizing the total costs incurred by the operator in order to cover the power demand. The income perceived by the operator for the total power supply is defined by the total energy demand and the L2T electricity price, neither of which are related to PV size. The income from PV feed-in is also decoupled from L2T electricity price variations as it depends solely on investment costs, feed-in tariffs, and total energy demands. The PV size is influenced mainly by the auxiliary electricity price, since this price is paid for every kWh of energy consumption that cannot be covered by the PV generation, either directly or shifted in time through the HSS. In the case of MFH I, the maximal possible size, as constrained by the rooftop size, is reached for quite low auxiliary electricity prices, evidencing the profitability of a PV system. A PV size of 24 kWp is reached at an auxiliary electricity price of 0.12 EUR/kWh. For higher auxiliary electricity prices, the PV size achieves the maximal installable value of 25 kWp.

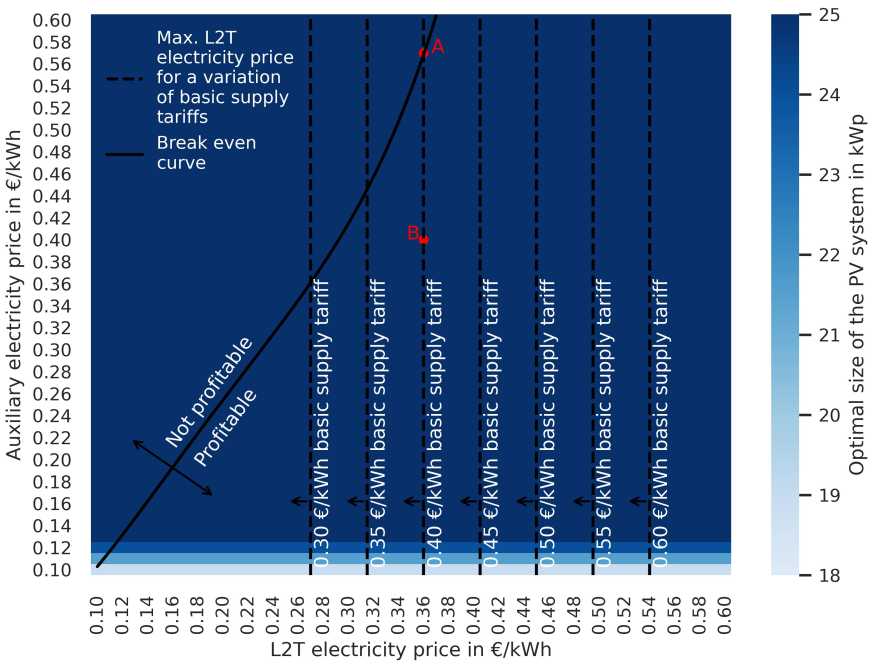

Figure 6. Optimal PV system sizes for configuration MFH I within the current regulatory framework of 2023, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

3.3. Optimal Sizing of Home Storage Systems

Figure 7 shows the optimal HSS sizes for each price point, corresponding to the optimization results for the MFH I scenario for Berlin, as presented in Figure 5. The break-even curve related to the annuity of the scenario is shown to identify viable component sizes. It can be observed that HSSs are only viable for auxiliary electricity prices that could be expected following the energy crisis spurred by the Russian invasion of Ukraine [36]. High auxiliary electricity prices justify the installation of HSSs in order to minimize the total costs of energy supply to the tenants. The results of the mathematical optimization show the first installation of an HSS for the auxiliary electricity price of 0.36 EUR/kWh, albeit with a negligible size of 0.14 kWh. This is due to the fact that component sizes are defined as continuous variables within the MILP model, which can assume minimal values if this serves the global optimum. Further, we considered HSS sizes starting from 1 kWh as actual installations. Auxiliary electricity prices have to amount to at least 0.39 EUR/kWh for an HSS of at least 1 kWh of energy capacity to be implemented. Moreover, these price increases would have to be sustained in the long term in order to justify the investment. The size of the installed HSS for price combination A is 15.4 kWh, while it amounts to 2.7 kWh for price combination B. Example sensitivity analyses for the optimal battery sizes in MFH I for the scenario year 2030 and MFH IV for the scenario year 2023 are presented in Figure A3 and Figure A6, respectively.

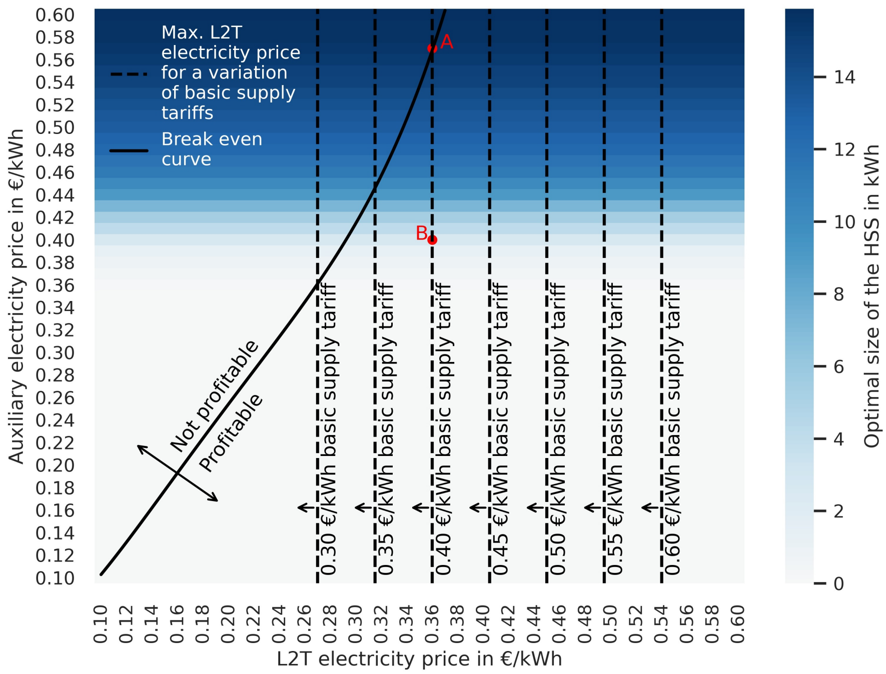

Figure 7. Optimal HSS sizes for configuration MFH I within the current regulatory framework of 2023, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

3.4. Autarky Rates and the Installation of Home Storage Systems

Figure 8 shows the autarky rates for each price point, corresponding to the optimization results for the MFH I scenario for Berlin, as presented in Figure 5. Since the maximal installable PV system size is reached at low auxiliary electricity prices (see Figure 6), further increases in autarky are driven by the installation of HSSs As such, the autarky rates vary with increasing HSS size. For auxiliary electricity prices ranging from 0.13 EUR/kWh to 0.35 EUR/kWh, we observe a constant autarky rate of 35%. This is consistent with the onset of the maximal PV system size (see Figure 6) and the absence of HSS installations (see Figure 7). Between auxiliary electricity prices of 0.36 EUR/kWh and 0.38 EUR/kWh, autarky rates increase marginally, consistent with the incipient installation of HSSs. For auxiliary electricity prices of 0.39 EUR/kWh and upwards, autarky rates increase steadily, reaching a maximum of 69.1% for a price of 0.60 EUR/kWh. This increase is consistent with the installation of larger HSSs. The autarky rates for price combination A and price combination B are 68.3% and 41.8%, respectively. Conversely, autarky rates in MFH IV for the scenario year 2023 are significantly lower (see Figure A5). In this scenario, price combination B shows an autarky rate of 24.5%, with autarky rates ranging from 24% to 28.7% across the scenario. This represents a difference of 17.3% in autarky rates between the smallest building configuration (MFH I) and the largest building configuration (MFH IV) for the present scenario year (2023) and a realistic price combination. It is worth noting that the revenue generated by the L2T subsidy, obtained by the landlord for the supply of the tenants with locally generated PV electricity, amounts only to 2.9% of the total revenues for building configuration MFH I and scenario year 2023 (price combination B).

The onset of HSS installation, and with it the initial increase in autarky, will depend on the auxiliary electricity price. With constant increases in autarky comes an increase in the slope of the break-even curve, as can be seen in Figure 8. This change in the slope represents the robustness against the high auxiliary electricity price provided by HSS installation. This effect becomes more relevant with increasing L2T upper limits. When observing the break-even curve in scenario MFH IV for scenario year 2023, we notice that there is no increase in the slope (see Figure A7). This is consistent with the low increases in autarky following the onset of HSS installation. HSS installations in MFH IV start at a similar auxiliary electricity price (0.41 EUR/kWh) as in MFH I (0.39 EUR/kWh) and achieve similar HSS sizes (see Figures 7 and A6). However, this does not translate to similar increases in autarky due to the significantly lower ratio of installable PV power to annual electricity demand of MFH IV compared to MFH I. Due to the building layouts (see Table 1), the maximal roof area available for PV installation does not increase proportionally to the number of HUs with increasing building size. Thus, MFHs I and MFH IV show ratios of installable PV power to annual electricity demand of the building (henceforth, PV to demand ratios) of 1.96 kWp/MWh and 0.46 kWp/MWh, respectively.

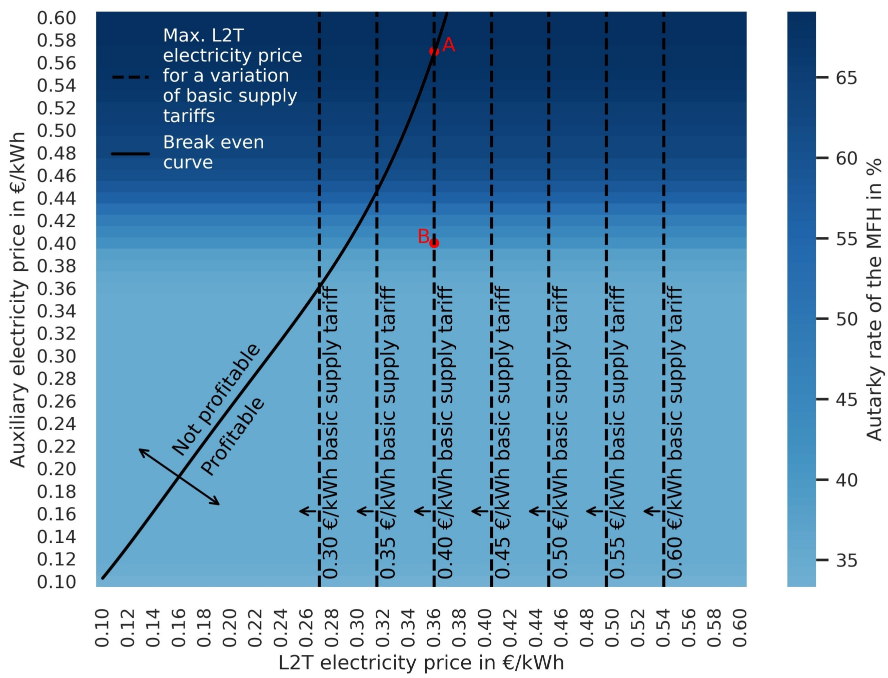

Figure 8. Autarky rate for configuration MFH I within the current regulatory framework of 2023, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

3.5. Financial Viability of Home Storage System Installations

In the following, we identify the minimal auxiliary electricity prices starting from which the installation of an HSS of at least 1 kWh energy capacity is financially viable, as presented in Figure 9. This is compared for all building sizes in the reference city and for all cities with the reference building size. These values are extracted from the sensitivity analyses of each scenario, analogous to the identification of 0.39 EUR/kWh as the minimal auxiliary electricity price for which an HSS is installed in the MFH I scenario for the scenario year 2023 and the city of Berlin (see Figure 7). As such, this price point can be found in Figure 9a,b. The results show that HSSs start to be economically viable at an auxiliary electricity price consistent with current electricity prices [56]. We observed that the installation of HSSs becomes more profitable for the current (2023) and future (2030) scenarios. This is mainly explained by the waiver of the VAT in the case of 2023 and the further projected investment cost reductions for HSSs from 2023 to 2030. In addition to this, the steady decrease in the feed-in tariffs motivates the increase in PV energy utilization, which requires the installation of larger HSSs. When considering different building sizes, no clear trend is identified. MFHs I and III present equal minimal auxiliary electricity price values while MFHs I, II, and III converge at the same value for the year 2030. Overall minimal auxiliary electricity price variations between building sizes range from 0 ct/kWh to 3 ct/kWh. These variations in the objective value of the optimizations are explained by marginal variations in feed-in tariffs and L2T subsidies across building sizes, as well as varying ratios of installable PV power to annual energy demand. As can be expected, the installation of an HSS becomes increasingly viable with the increasing specific PV yield in different cities. This is evidenced by the lower minimal auxiliary electricity price required for an installation. The largest gap in minimal auxiliary electricity prices for an installation in the scenario year 2023 corresponds to 3 ct/kWh between Munich and Hamburg, cities that present the highest and lowest annual PV yields, respectively. On average, minimal auxiliary electricity prices needed for the installation of an HSS decreased from 2020 to 2023 by 9 ct/kWh and are projected to decrease by 2.4 ct/kWh from 2023 to 2030. In conclusion, the main factors driving the reduction of minimal auxiliary electricity prices that justify HSS installation are the waiver of VAT in 2023 by lawmakers and the steady decrease in feed-in tariffs, which motivates the increase in PV energy utilization. This, in turn, requires the installation of larger HSSs.

Finally, we compared the maximal possible auxiliary electricity price for which a project is still viable for different L2T electricity price limits. This is evaluated for all considered building sizes, MFHs I–IV, for all scenario years in the reference city (Figure 10), as well as for all considered cities with the reference building MFH I (Figure 11). The maximal auxiliary electricity price values for these Figures are extracted from the sensitivity analyses of each scenario, analogous to the identification of price combination A in the reference scenario MFH I for the scenario year 2023 in the city of Berlin (see Figure 5). As such, price combination A can also be found in Figures 10 and 11. Maximal auxiliary price values represent the intersections between the L2T price limits and the break-even curve. Thus, Figures 10 and 11 capture changes in the slope of the break-even curve of each scenario in a discrete manner. Further, the maximal auxiliary electricity price can be treated as an indicator of economic viability. The higher the maximal auxiliary electricity price that is justifiable in a scenario, the more profitable the scenario.

Figure 10 represents the variations in maximal auxiliary electricity prices for different building sizes (MFHs I–IV) in the reference city of Berlin. In general, maximal auxiliary electricity prices increase drastically from scenario year 2020 to scenario year 2023. On average, maximal auxiliary electricity prices increase by 13 ct/kWh in scenario MFH I, for the considered basic supply tariffs. This can be mainly explained by the abolition of the

EEG levy that took effect in 2023, reducing costs for the energy system operator by 6.756 ct for each kWh supplied to the tenants. For the 2020 scenario of Berlin with MFH I and the combination of a basic supply tariff of 0.30 EUR/kWh and a maximal auxiliary electricity price of 0.26 EUR/kWh (price combination C, under the 2020 average household electricity price of 0.31 EUR/kWh [57]), the amount paid for the EEG levy amounts to 16.5% of the total annual costs, including capital costs. Further, the overall investment costs in 2023 decrease due to the tax breaks that eliminate the VAT. Finally, the L2T subsidy that the energy system operator receives per kWh of renewable energy supplied was increased by 1.36 ct. These effects are more than enough to compensate for the decrease in the PV feed-in tariff by 2.16 ct/kWh that results in a 22% decrease in PV feed-in revenue. In conclusion, the increase in maximal possible auxiliary prices and thus the profitability from 2020 to 2023 can be explained by changes in policy regarding the abolition of the EEG levy, reductions in investment costs thanks to tax breaks for components, and the increase in the L2T subsidy.

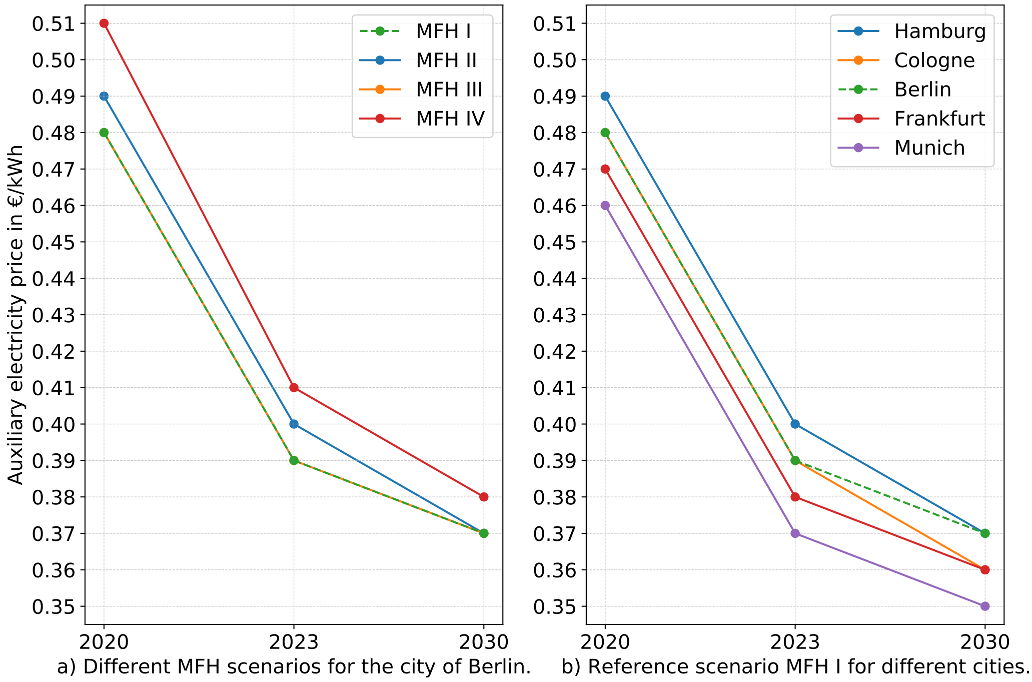

Figure 9. Minimal auxiliary electricity price for which the installation of an HSS is viable. On the left-hand side, it is evaluated for all building sizes and the reference city of Berlin. On the right-hand side, it is evaluated for the reference building size MFH I and different cities.

Further, we identified a decrease in the maximal auxiliary electricity prices, and thus the profitability, of scenarios with increasing building size. On average, maximal auxiliary electricity prices decrease by 8 ct/kWh when comparing MFH I to MFH IV in the scenario year 2023, for the considered basic supply tariffs. This is explained by the decreasing PV-to-demand ratios with increasing building size. MFHs I and II show ratios of 1.96 kWp/MWh and 1.31 kWp/MWh, respectively. In contrast, MFH III presents a ratio of 0.89 kWp/MWh and MFH IV presents a ratio of 0.46 kWp/MWh. We observed a significant increase in the higher maximal auxiliary electricity price when comparing basic supply tariffs of 0.35 EUR/kWh and 0.40 EUR/kWh in MFH I for the scenario years 2023 and 2030. This is explained by the increase in the slope of the break-even curve with increasing autarky rates, as explored in Figure 8. This characteristic decreases with decreasing PV-to-demand ratios in MFH II and MFH III. In MFH IV, the configuration with the lowest PV-to-demand ratio, no change in the slope of the break-even curve can be identified (see Figure A7). This effect cannot be observed for scenario year 2020 and the considered basic supply tariffs since the minimal auxiliary prices for the installation of HSSs are significantly higher than in scenario years 2023 and 2030 (see Figure 9). This inhibits the increase in autarky rates, preventing changes in the slope of the break-even curve.

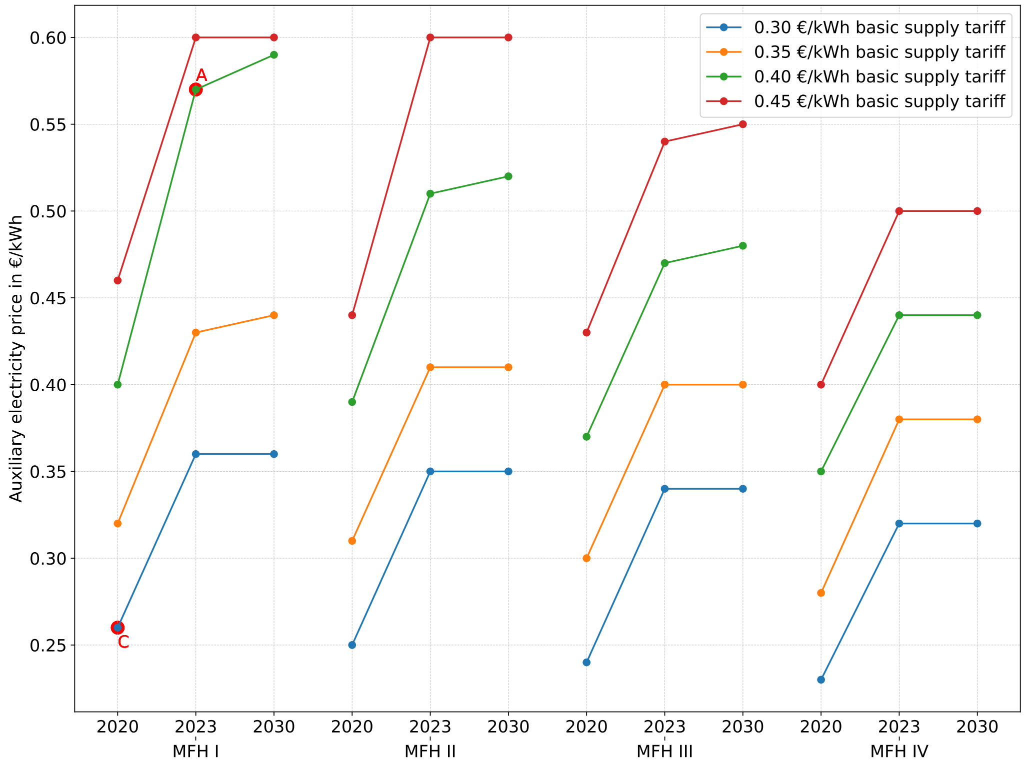

Figure 10. Maximal auxiliary electricity prices for a viable investment across all scenario variations (2020, 2023, 2030) and building sizes (MFH I–MFH IV) for the reference city of Berlin.

3.6. The L2T Model for Different Building Sizes and Cities

Figure 11 shows the maximal auxiliary electricity prices for a viable investment for local basic supply tariffs ranging from 0.30 EUR/kWh to 0.45 EUR/kWh across all scenarios for the reference building size MFH I. Here, we considered the regulatory framework and different PV and battery investment costs for the scenario years 2020, 2023, and 2030. In addition to the effects observed in Figure 10, it can be observed that the viable prices increase from left to right with the progression of cities shown along the axis. This is because the cities are ordered by their specific annual PV yield, as shown in Table A3. The lowest yield corresponds to the city of Hamburg and the highest to the city of Munich. On average, maximal auxiliary electricity prices increase by 5.75 ct/kWh when comparing Hamburg to Munich in the scenario year 2023, for the considered basic supply tariffs. With increased PV yield comes increased revenue from PV energy feed-in and decreased costs for the total energy supply to the tenants, as well as slight increases in revenue from L2T subsidies due to the consumption of locally generated energy. This increases the overall profitability of the investment.

The increase in the maximal auxiliary electricity price from 2020 to 2023 is significant across all cities and is greater for higher basic supply tariffs, consistent with the analysis in Figure 10. When considering a basic supply tariff of 0.30 EUR/kWh, the maximal auxiliary electricity price stays constant or decreases from 2023 to 2030, while it increases for higher basic supply tariffs. This behavior can be explained by decreases in feed-in tariffs and the L2T subsidy in the year 2030, which affect scenarios with the lowest basic supply tariff especially, since the installation of larger HSS is not justified. Scenarios with higher basic supply tariffs are better suited to take advantage of the projected investment cost decreases for HSS. Increases from 2023 to 2030 cannot be observed in the case of the basic supply tariffs of 0.40 EUR/kWh (Frankfurt and Munich) and 0.45 EUR/kWh, where viable auxiliary electricity prices saturate at 0.60 EUR/kWh, since this was the highest auxiliary electricity price considered in our analysis.

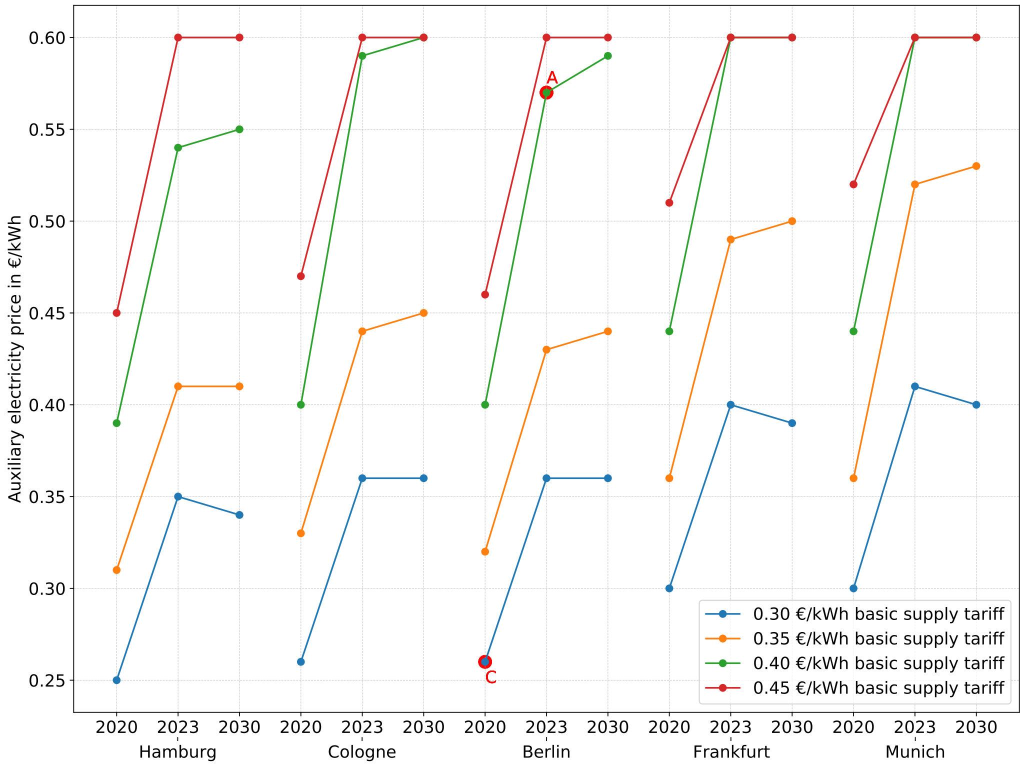

Figure 11. Maximal auxiliary electricity prices for a viable investment across all considered years and selected cities in Germany for the reference building size MFH I.

4. Discussion

Our study identifies a significant gap in the development of L2T projects for photovoltaic power generation and storage in residential buildings, compared to the more common installation of PV and HSS systems in single-family residences. The results show that the financial viability of these projects is strongly influenced by auxiliary electricity pricing and the prevailing regulatory framework. Specifically, investments become consistently profitable when auxiliary electricity prices remain below the local basic supply tariff, emphasizing the critical role of strategic pricing by system operators and auxiliary electricity providers. Additionally, factors such as optimal PV system sizing—constrained by rooftop availability and building dimensions—directly impact achievable autarky rates, with smaller buildings generally benefiting from a more favorable PV-to-demand ratio than larger ones.

We observed that variation in the L2T electricity price does not influence the size of the PV system. The PV size is mainly influenced by the auxiliary electricity price, since the total costs of supplying energy to the tenants are minimized by the optimization. Higher auxiliary electricity prices justify increased local generation to minimize costs. However, the maximal possible PV system size, as constrained by the rooftop size, is reached for low auxiliary electricity prices. This evidences the profitability of PV systems across all scenarios. The effect of increased auxiliary electricity prices becomes more evident in the case of HSSs. Here, we observed that with the current regulatory framework and system costs (2023), the minimal auxiliary electricity price for which an HSS becomes viable in a four-party MFH amounts to 0.39 EUR/kWh. Even though this represents an improvement compared to the scenario year 2020, where the minimal auxiliary electricity price for a profitable HSS installation is 0.48 EUR/kWh, the optimal installation of an HSS is still only realized for high auxiliary electricity costs sustained in the long-term. Conversely, the installation of an HSS can still be profitable even if it does not represent the financial optimum. Our results show that investment annuities are sufficiently high to provide financial leeway for the installation of HSSs. This is consistent with the substantial deployment of HSSs in L2T projects to date. One of the main motivations for this deployment could be to hedge against rises in electricity prices, as identified by [8] in the case of single-family houses.

Since the maximal PV potential is reached for most auxiliary electricity price points and is constrained by the available rooftop area, the installation of an HSS represent the only measure to increase the autarky of the system. However, the achievable autarky rates are constrained by the ratios of installable PV power to annual electricity demand of the building. These ratios decrease with an increasing number of housing units, and thus of total electricity demand, due to constraints in the maximal roof area available for PV installation. We observed that the autarky rate of the smallest building configuration is 17.3% higher than the autarky rate of the largest building configuration considered (4- and 22-party MFHs, respectively). An HSS can help increase autarky while maintaining financial viability; however, their viable installation is limited as the building size increases. In larger MFHs, there is a significantly lower ratio of installable PV power to annual electricity demand of the MFH. This means that the achievable autarky rates and thus the size of the installable HSS does not increase proportionally with building size.

Moreover, the integration of advanced technologies and smart solutions could play a key role in increasing the adoption rates and efficiency of L2T projects. Smart meters, Internet of Things-enabled monitoring systems, and sophisticated building management tools facilitate dynamic pricing, real-time energy optimization, and efficient consumption measurement, thereby improving overall energy management and enabling the transfer of innovative solutions across different market contexts. In particular, technological advancements are key in strengthening the efficacy of L2T models, where the use of smart meters and blockchain technology could simplify energy billing processes and reduce administrative costs. However, the current regulatory framework presents significant challenges, resulting in high transaction costs that limit the widespread adoption of L2T models. Technology transfer plays a crucial role in overcoming these challenges by making knowledge, innovations, and advancements more accessible through scientific research, policy initiatives, and commercialization efforts [58]. Given the complexity of technology transfer, feasibility studies are necessary to evaluate which technologies can be effectively transferred and how economic and regulatory factors impact their adoption. Addressing these regulatory barriers is essential to fully take advantage of technological innovations and increase the development of sustainable energy solutions in urban residential settings.

Our research has several strengths, including a comprehensive scenario-based analysis covering multiple years (2020, 2023, and 2030) and a detailed evaluation of the effects of building size and PV yield variations on project feasibility. However, the study has the following limitations: it relies on price and investment cost assumptions for future scenarios, faces uncertainties related to future regulatory developments, and is constrained by fixed rooftop potentials that limit PV installation capacity. Finally, the analysis relies on MILP optimization with perfect foresight. In reality, the control algorithms that perform energy management may not achieve the optimal behavior calculated by our models. Addressing these limitations in future research could further refine our understanding of L2T project dynamics and support the development of more robust, scalable renewable energy strategies in the residential sector.

5. Conclusions

Our study showed that the financial viability of L2T projects in residential buildings is critically influenced by auxiliary electricity pricing, regulatory changes, and building-specific factors, with the integration of smart technologies offering a promising avenue for enhanced energy management and autarky. Our findings suggest that investments become profitable when auxiliary electricity prices remain below the local basic supply tariff, and that strategic pricing by providers significantly affects overall project feasibility, with optimized PV and HSS installations increasing self-consumption and reducing grid dependency, especially during peak emission periods. These insights highlight the novelty of our work in linking the evaluation of financial viability of small-scale L2T projects with regulatory dynamics in the German residential sector. In addition, policy measures, such as introducing a minimum autarky quota or mandatory HSS installation and establishing a minimum autarky rate for L2T subsidy qualification, could provide additional benefits without compromising investment viability.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en18051213/s1. Sensitivity analysis results of investment annuity, optimal HSS size, and optimal PV size for MFH I and years 2020, 2023, and 2030 for the cities of Cologne, Frankfurt, Hamburg, and Munich. Sensitivity analysis results of investment annuity, optimal HSS size, and optimal PV size for MFH I, II, III, and IV and years 2020, 2023, and 2030 for the city of Berlin. Sensitivity analysis results of autarky rate for MFH I and IV and year 2023 for the city of Berlin.

Author Contributions: Conceptualization, M.C.C., J.v.O., J.F. and C.B.; methodology, M.C.C., J.v.O. and J.G.; software, M.C.C. and J.G.; validation, M.C.C. and J.v.O.; formal analysis, M.C.C. and J.v.O.; investigation, M.C.C.; data curation, J.F.; writing—original draft preparation, M.C.C. and J.G.; writing—review and editing, M.C.C. and J.v.O.; visualization, M.C.C. and J.F.; supervision, J.F., C.B. and D.U.S.; project administration, J.v.O., J.F., C.B. and D.U.S.; funding acquisition, C.B. and D.U.S. All authors have read and agreed to the published version of the manuscript.

Funding: The research for this paper was performed within the InEEd-DC project supported by the German Federal Ministry of Education and Research under grant number 03SF0597.

Data Availability Statement: The original contributions presented in this study are included in the Supplementary Materials, https://www.mdpi.com/article/10.3390/en18051213/s1. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Component Modeling

Appendix A.1. Home Storage System (HSS) Model

The component size is equal to the energy capacity of the battery system, while the usable energy capacity of the system is determined by Equation (A1):

$$e_{min} \cdot S_{size} \leq E_t \leq e_{max} \cdot S_{size} \qquad \forall t \in T \tag{A1}$$

where the energy factors e_{min} and e_{max} are percentages of the total energy capacity and E_t is the battery energy at any given point in time. In this study, the size of the battery system in kWh is equated to the usable energy capacity by setting e_{min} to 0% and e_{max} to 100%.

The following equations limit the input and output powers of the battery system:

$$P_{input,t} \cdot \eta_{in} \leq \frac{1}{e_{e2p}^{in}} \cdot S_{size} \qquad \forall t \in T \tag{A2}$$

$$P_{output,t} \cdot \frac{1}{\eta_{out}} \leq \frac{1}{e_{e2p}^{out}} \cdot S_{size} \qquad \forall t \in T \tag{A3}$$

where e_{e2p}^{in} and e_{e2p}^{out} are energy-to-power ratios set to the E2P value found in Table A4.

The following equation shows the conservation of energy in the battery model:

$$E_t = E_{t-1} + \eta_{in} \cdot P_{input,t} \cdot \Delta t - \frac{1}{\eta_{out}} \cdot P_{output,t} \cdot \Delta t \qquad \forall t \in T \tag{A4}$$

where η_{in} and η_{out} are the input and output efficiencies of the storage. The initial SOE of the battery model is set to 50%, as listed in Table A4.

Appendix A.2. Inverter Model

Due to the large amount of optimizations needed for this study, a simplified inverter model included in FOCUS was chosen, which assumes a constant efficiency, as shown in the following equation:

$$P_{input,t} \cdot \eta = P_{output,t} \qquad \forall t \in T \tag{A5}$$

where the input and output powers can be either DC or AC, depending on the defined direction, and η is the one-way efficiency, as listed in Table A4.

The maximum power of the inverter at any given time is defined by the component size, as shown in Equation (A6):

$$P_{DC,t} \leq S_{size} \qquad \forall t \in T \tag{A6}$$

where the power is limited at the DC side, as modeled in this work. Whether the power is limited by the DC or AC side depends on the component connections entered into the FOCUS framework and can be defined freely.

Appendix A.3. PV System Model

In the case of the PV model, the output power is given by a time series of PV generation factors multiplied by the component size, as shown in Equation (A7):

$$F_{PV,t} \cdot S_{size} = P_{PV,t} \qquad \forall t \in T \tag{A7}$$

where the component size S_{size} represents the rated PV power in kilowatt-peak. With the FOCUS framework, it is possible to input PV generation factors directly or, as in this work, to generate them according to the following PV model [59]:

$$P_{PV,t} = \frac{I_{POA,t}}{I_{STC}} \cdot [1 + \gamma \cdot (T_{cell,t} - T_{STC})] \qquad \forall t \in T \tag{A8}$$

where $I_{POA,t}$ is the plane of array irradiance transmitted to the PV cells, as calculated in Appendix B.2; I_{STC} and T_{STC} are the irradiance and cell temperature at standard testing conditions (STCs), equal to 1000 W/m² and 25 °C, respectively [48,59,60]. γ is the temperature coefficient of power of a particular PV system (see Table A4). The cell temperature $T_{cell,t}$ is obtained with the following equation [60]:

$$T_{cell,t} = T_{air,t} + \frac{I_{POA,t}}{I_{NOCT}} \cdot (NOCT - T_{NOCT}) \qquad \forall t \in T \tag{A9}$$

where I_{NOCT} and T_{NOCT} are the irradiance and air temperature at nominal operating cell temperature (NOCT) conditions and are equal to 800 W/m² and 20 °C, respectively [48,60]. NOCT is the nominal operating cell temperature for a specific PV system, as listed in Table A4.

Appendix B. Model Input Data

In this section, we present the time series employed as input profiles for our optimization framework, as well as the techno-economic component parameters relevant to our study.

Appendix B.1. Demand Data

In order to prepare realistic electrical demand profiles for the scenarios listed in Table 1, load profiles generated at quarter-hourly resolution with the synPRO tool from Fraunhofer ISE [61,62] were utilized. The different available profiles were assigned to a German household type and weighted with their demographic share [63], creating a normalized residential building profile, which was then multiplied with the total annual demand of each scenario to generate the input demand profile for the optimizations. The household types, their demographic share in Germany, and their assumed synPRO load profiles are shown in Table A1.

Table A1. Composition of the electricity demand profile of an MFH based on German demographics.

Household Type	Share in Germany	Profile Assumption
1 person	40.85%	One person under 30
2 persons under 65	24.29%	Two full-time employees
2 persons over 65	9.78%	Two persons over 65
3–5 persons	25.08%	Family with two parents and two children

Appendix B.2. Irradiance and Temperature Data

Both solar irradiance and temperature data were extracted from the test reference year (TRY) data published by the German Meteorological Service (DWD) at an hourly resolution [64]. For this study, the present-day TRY data set for an average year based on observational data spanning from 1995 to 2012 was utilized. For every city considered in this work, several location-accurate data sets are made available by DWD. The coordinates of each location picked for this work are listed in Table A3.

The temperature data are given in degrees centigrade and can be entered into the FOCUS framework without modification. The solar irradiance data, however, are given as direct horizontal irradiance and diffuse horizontal irradiance and need to be converted to the effective irradiance transmitted to the PV cells so that they can be used as an input by the framework's PV model described in Appendix A.3. In order to calculate this effective irradiance, several solar irradiance models from the solar energy system modeling Python library pvlib [65,66] were employed.

In a first step, the solar positions were calculated for the pertinent coordinates at each time step, then the direct normal irradiance was calculated with the help of the Boland model, using the solar zenith calculated in the previous step as well as the global horizontal irradiance resulting from the addition of the direct horizontal and diffuse irradiance time series. Following this, the total irradiance on the tilted surface was calculated based on the values calculated in the previous steps for a surface tilt of 35 degrees and a surface azimuth of 180 degrees (south-facing), using the isotropic sky model. In addition, the angle of incidence of the solar vector on a surface was calculated with these surface tilt and azimuth parameters. With the angle of incidence, the incidence angle modifier that describes irradiance losses on the PV cells' surface could be calculated and finally applied to the previously calculated irradiance on the tilted surface, obtaining the final input time series in W/m² for the PV model implemented in the FOCUS framework. Table A2 shows the methods of the pvlib library utilized for the calculations.

When applying the calculated effective irradiance on the tilted surface and the corresponding ambient temperature in the PV model in Appendix A.3, parameterized with the NOCT and temperature coefficient found in Table A4, specific PV yields are obtained for each considered city, as shown in Table A3.

Table A2. Methods of pvlib used to calculate the effective irradiance time series as an input for the optimization framework.

Method	Calculation Step	References
pvlib.solarposition.get_solarposition	Calculate solar positions	[65–67,67,68]
pvlib.irradiance.boland	Calculate direct normal irradiance	[65,66,69,70]
pvlib.irradiance.get_total_irradiance	Calculate irradiance on tilted surface	[65,66,71,72]
pvlib.irradiance.aoi	Calculate angle of incidence on a surface	[65,66]
pvlib.iam.physical	Calculate incidence angle modifier	[65,66,73,74]

Table A3. Specific annual PV yield before inverter losses for the considered cities and data set coordinates.

Parameter	Hamburg	Cologne	Berlin	Frankfurt	Munich
Specific PV yield in kWh/kWp/a	965.1	1001.9	1013.5	1129.0	1141.2
Latitude	53.5485° N	50.9412° N	52.5153° N	50.1076° N	48.1399° N
Longitude	9.9922° O	6.9566° O	13.3939° O	8.6899° O	11.5778° O

Appendix B.3. Component Parameters

This section presents a breakdown of all component parameters (listed in Table A4) used to instantiate the FOCUS framework in order to perform the optimizations in our study.

- PV system: Ref. [75] shows a 13% decrease in PV prices from 2018 to 2021, arriving at 1180 EUR/kWp with VAT. This is equivalent to an annual price decrease of 4.5%. With this, we calculate the 2020 price to be 1236 EUR/kWp, or 1039 EUR/kWp without VAT. Ref. [76] indicates a PV price of 1250 EUR/kWp and assigns 12% of costs for the inverter. Based on this, we assume a price of 1100 EUR/kWp for 2023. Using this price and the annual price decrease calculated previously, we obtain a value of 797 EUR/kWp for 2030. The fixed operation and maintenance (OM) costs as a percentage of the investment costs are set to 1.0% and the service life is set to 32 years [77]. The NOCT and temperature coefficient parameters are taken from [48].
- HSS: Ref. [4] shows a 63% decrease in HSS prices from 2013 to 2021, landing on 920 EUR/kWh without VAT. Further, the price for 2022 is noted at 1197 EUR/kWh, with the price increase being attributed to the war in Ukraine. Assuming a constant annual price decrease, we calculate an 11.7% reduction per year, arriving at an HSS price of 1042 EUR/kWh for 2020. Applying this annual reduction to the price for 2022, we arrive at a price of 1057 EUR/kWh without VAT for 2023. To calculate the price for 2030, we take the 2016 HSS price of 1618 EUR/kWh [8], subtract the VAT, obtaining 1360 EUR/kWh, and reduce it by 54%, as projected by [78], to arrive at 626 EUR/kWh. The fixed (OM) costs are set to 1.0% [79,80]. In addition, we choose a service life of 15 years [81], a round-trip efficiency of 96% [82], and an energy-to-power ratio (E2P) of 2 h [4]. A state of energy (SOE) of 50% is assumed at the beginning of the optimization.

- PV and HSS inverters: Based on the study by [83], we assume a specific price of 110 EUR/kW for both inverters. We assume the fixed OM costs to be equal to the OM costs for the PV system and HSS since they are often integrated systems. Further, we set the lifetime of both inverters to 15 years [84]. We set the efficiency of the PV inverter to 96% and that of the HSS inverter to 94.6%, rounded to 95% for numerical efficiency [82].

Table A4. Overview of techno-economic component parameters employed in this study. All prices are listed without VAT. HSS stands for home storage system. OM stands for operation and maintenance, NOCT stands for nominal operating cell temperature, E2P stands for energy to power, and SOE stands for state of energy.

Generation and Conversion Components								
Component	**Year**	**Invest. Costs**	**Unit**	**Fixed OM**	**Service Life**	**Efficiency (One Way)**	**NOCT**	**Temperature Coefficient**
PV system (Excl. Inverter)	2020 2023 2030	1039 1100 797	EUR/kWp EUR/kWp EUR/kWp	1.0%	32a	Variable	45 °C	−0.39%/°K
Inverter PV	all	110	EUR/kW	1.0%	15a	96%		
Inverter HSS	all	110	EUR/kW	1.0%	15a	95%		
Storage Components								
Component	**Year**	**Invest. Costs**	**Unit**	**Fixed OM**	**Service Life**	**Round-trip Efficiency**	**E2P Ratio**	**Initial SOE**
HSS (excl. inverter)	2020 2023 2030	1042 1057 626	EUR/kWh EUR/kWh EUR/kWh	1.0%	15a	96%	2h	50%

Appendix B.4. Energy Flows Within a Prosumer

Figure A1 shows a Sankey diagram, describing the shares and total amounts of energy flowing in the MFH energy system. In this diagram, the energy flows from the components on the left-hand side to the components on the right-hand side. Further, the diagram shows the cost and revenue components relevant to every energy flow. The example optimization result corresponds to the scenario MFH I for 2023 in Berlin and the price combination of 0.45 EUR/kWh for the auxiliary electricity price and 0.36 EUR/kWh for the L2T electricity price. This price combination was chosen in order to include the energy flows to and from the battery system in the example, since the installation of a battery system is only optimal for auxiliary electricity prices in this range.

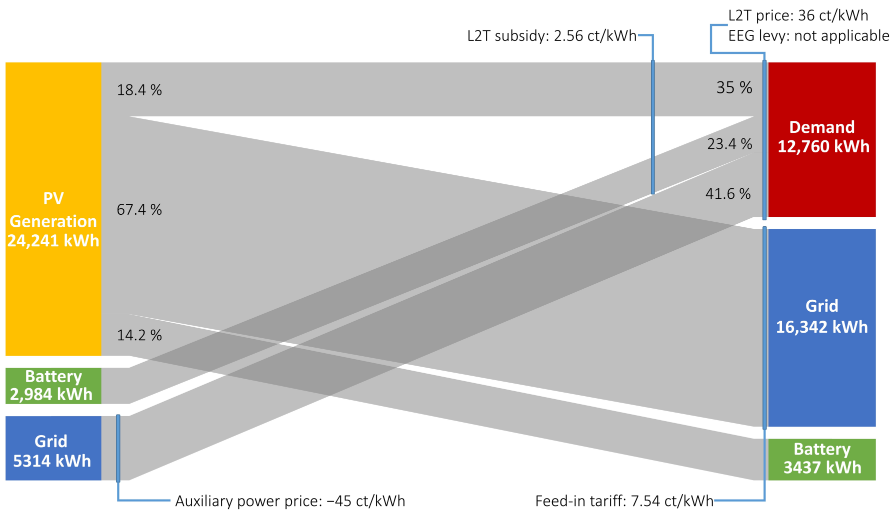

Figure A1. Sankey diagram of energy flows and cost and revenue components for an example price combination of the scenario MFH I for 2023 in Berlin.

Appendix B.5. Sensitivity Analysis of Selected L2T Scenarios

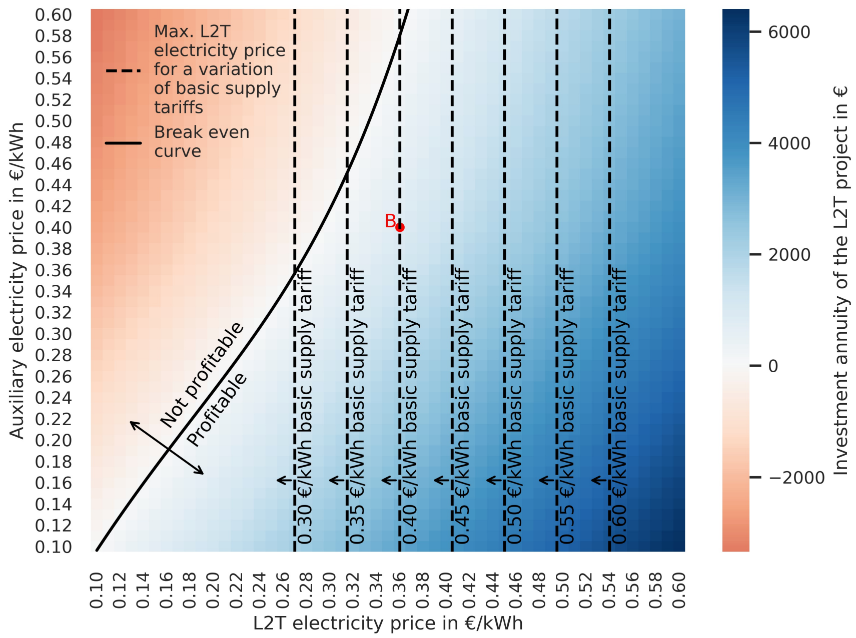

Figure A2. Investment annuity of the L2T project from the perspective of the landlord or energy system operator for different price combinations. The results are shown for MFH I for the city of Berlin within the regulatory framework of 2030. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

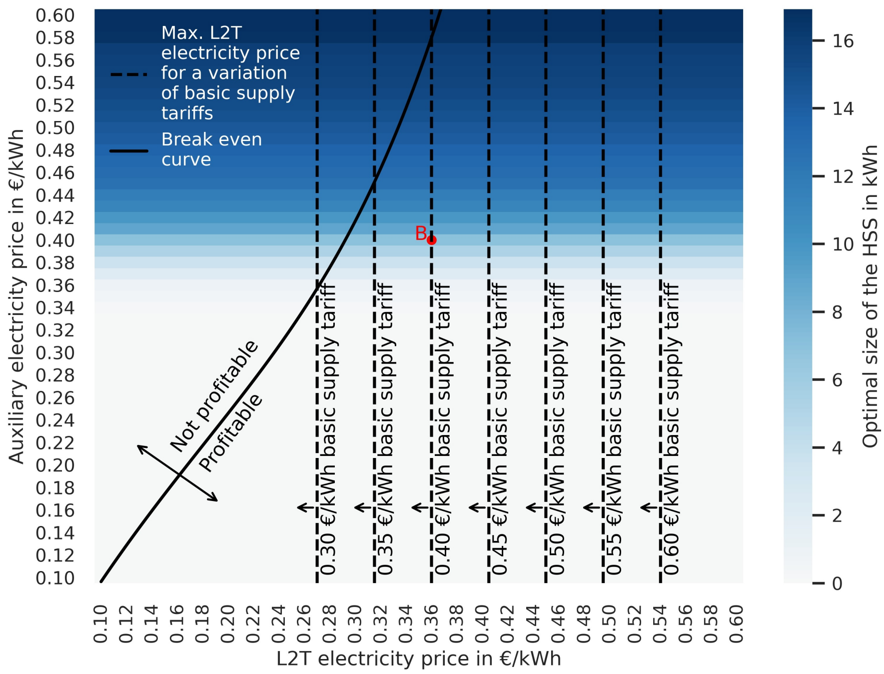

Figure A3. Optimal HSS sizes for configuration MFH I within the current regulatory framework of 2030, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

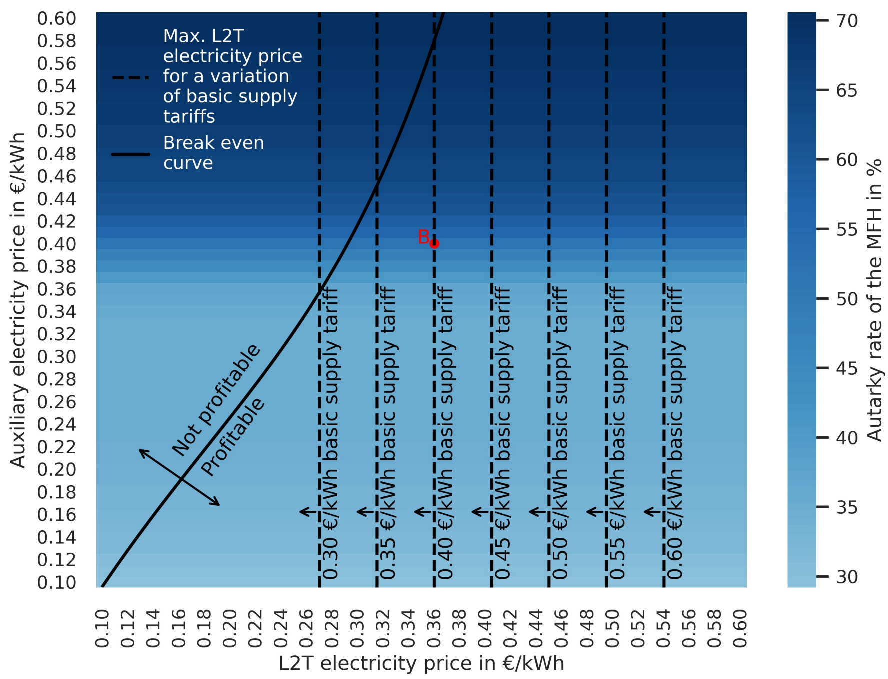

Figure A4. Autarky rate for configuration MFH I within the current regulatory framework of 2030, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

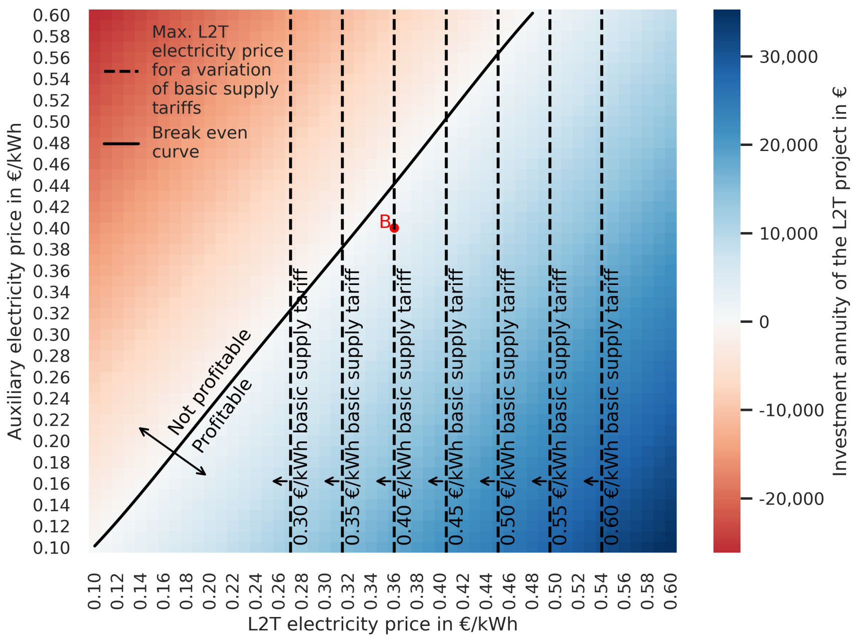

Figure A5. Investment annuity from the perspective of the landlord or energy system operator for different price combinations. The results are shown for MFH IV for the city of Berlin within the regulatory framework of 2023. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

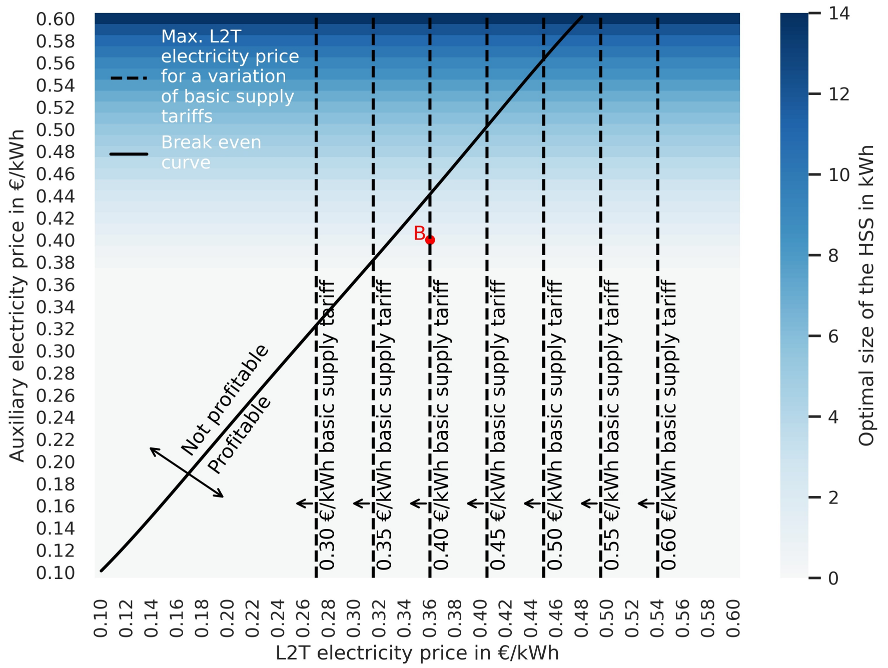

Figure A6. Optimal HSS sizes for configuration MFH IV within the current regulatory framework of 2023, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

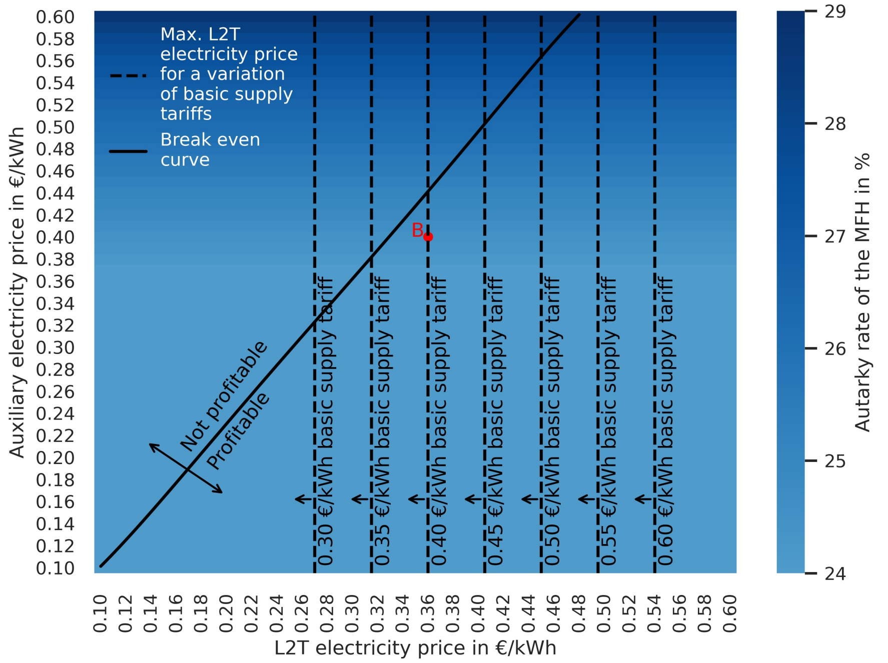

Figure A7. Autarky rate for configuration MFH IV within the current regulatory framework of 2023, for the city of Berlin. Point A indicates the intersection of the break-even curve and the reference basic supply tariff. Point B indicates that the auxiliary electricity price is equal to the reference basic supply tariff. Arrows indicate the solution space.

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