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Economic potential of demand side management based on smart metering of youth hostels in Germany

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***Abstract*— Additional electricity meters behind the grid access point can improve understanding of energy consumption patterns and thus, adjust consumption behavior. For this study, smart meters were installed in three hostels, out of which two are analyzed further in this paper. Starting from an onsite inspection, all appliances were assigned to reasonable groups for sub-metering. Based on data for the year 2021, the sites are characterized according to the sub-metering concept. In addition, load profiles for type-days are derived, which allows to establish a baseload during COVID lockdown and compare it to consumption patterns for normal occupation. In the prescriptive part, the demand profiles are analyzed regarding their economic potential for load shifting. Consumption data for one week with normal occupation is used as input for techno-economic modeling. The mixed-integer model minimizes electricity purchasing costs for different scenarios including dynamic tariffs and onsite generation from photovoltaics.**

***Index Terms*—Demand response, Load monitoring, Mixed integer linear programming, Smart meters, Tariffs**

I. INTRODUCTION

Smart metering systems are an essential part of the digital infrastructure. In Germany, the Metering Point Operation Act (Messstellenbetriebsgesetz – MsbG) regulates the rollout of such metering equipment [1]. Despite the current legal uncertainty regarding the market declarations on the rollout of smart metering systems and high bureaucratic hurdles, the topic is gaining momentum [2]. Recently, the German government passed the draft bill of the Federal Ministry of Economics and Climate Protection (BMWK) to relaunch the digitization of the energy transition. The new rules should remove hurdles with a comprehensive package of measures. It aims to accelerate the rollout of smart meters and the introduction of dynamic tariffs [3, 4]. In a recent study, 49 % of meter operators said they had already successfully started the rollout [5]. After all, most of the remaining companies are in the status of preparing for the rollout. However, nearly all participants of the survey rate ensuring cost-effectiveness when applying price caps as the biggest challenge. Since 2020, the installation obligation has been extended to electricity consumers with a consumption of 6,000 kilowatt hours or more. This can include, for example, households that have an electric car or a heat pump. The individual benefit can result from the increased transparency of consumption and the potential savings identified from this. The greatest macroeconomic benefit of smart metering systems, the achievement of consumption savings, together with the other possible applications under the current legal framework, is not sufficient to achieve an overall economic benefit for the rollout of smart metering systems [6]. The decisive increase in benefits results from a reduction in the need for grid expansion - especially in the distribution grids. Reference projects show that in existing (rural) distribution grids additional capacity from renewable energy plants can be connected if it were possible to reduce the feed-in by up to 5 % of the annual energy quantity of each plant in case of need. In the context of this study, both aspects will be considered together. This is based on the findings from the federal funding for the pilot program for energy-saving meters (“Einsparzähler”) [7]. With the help of metering systems and value-added services, energy savings at end customers are to be initiated and measured. In this specific case, customers from the hospitality sector are to be analyzed. The economic value of energy savings results from a reduction in procurement costs. However, cost reductions can also go hand in hand with an optimization of the time of procurement by making consumption more flexible. Therefore, it is to be investigated what potential can be achieved by demand response (DR) measures.

[8] provide an extensive review of DR programs. Accordingly, DR are “actions by customers that change their consumption (demand) of electric power in response to price signals, incentives, or directions from grid operators.’’ As such, DR corresponds to the changing behavior of customers in the short-term. Whereas the incentive-based DR is more event-oriented and focuses on load interruption or at least reductions, the whole range of price-based DR deals

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with dynamic pricing schemes to encourage customers to respond flexibly to price signals. A review on the benefits and challenges of DR in general is discussed in [9]. The issue of establishing a business case for DR is highlighted, which should be able to distribute the efficiency gains among the different parties. Benefits from DR can arise, e.g., from providing services to the grid in terms of system reliability and by saving energy costs. The impact of both program schemes for household customers in the Netherlands can be evaluated in an integrated approach [10]. [11] investigate DR from the non-domestic sector by UK experiences, which also includes the hotel and catering sector. It is argued that hotels are well suited to provide demand response as thermal loads are appropriate for shifting. [12] analyze the demand response potential in hotels for the Canary Islands. It is stated that the shifting potential of touristic facilities depends on climatic, technical, and economic variables like the ambient temperature and the occupancy of the hotel. Similar to [11], [13] show the feasibility of demand response for the hotel sector on heating, ventilation, and air conditioning (HVAC) systems in Brazil. The demand flexibility in residential and non-residential buildings is modeled in [14] based on ambient conditions of Spain. Non-residential building types include hotels, which were aggregated to a larger portfolio of flexible customers.

The contribution of this research is summarized as follows:

- proposing a detailed analysis of quarter-hour electricity consumption data of youth hostels in southern Germany based on a sub-metering level,
- deriving standardized load-profiles for seasons and type-days,
- application of an optimization model to evaluate potential cost savings in electricity purchasing.

Sec. II presents the data sources and the methodology of this work. In Sec. III the main results are presented, primarily regarding the modeling exercise. Finally, in Sec. IV the fundamental conclusions are drawn.

II. MATERIAL AND METHODS

This study is based on smart metering data of the year 2021, derived from two youth hostels in southern Germany. Starting with a descriptive analysis of the sites, the analysis is continued with a statistical evaluation of measured data. The last subsection describes how the demand side management is implemented in the optimization model.

A. Descriptive analysis of electricity consumption

1) Youth hostel A: Based on the main meter, the total electricity consumed was about 90 MWh in 2021. As Fig. A 1 (see Appendix) shows, the daily electricity load was unevenly distributed over the year due to COVID-related travel restrictions. Starting by the end of May, the daily demand increased between 300 and 400 kWh per day. That level remains until mid-November when the demand was reduced to about 200 kWh per day. The maximum was reached in the last week of the year when the daily demand was measured with 425 to 450 kWh. The submetering concept comprises different consumption units. Thus, the total consumption can be attributed to:

- Basement 1 and 2,
- Kitchen,
- Lobby/Hall, and
- 1st and 2nd floor.

The basement floors host the laundry store, heating system based on fuel oil, cold room, and lighting. In the kitchen, the electricity appliances consist of hot air ovens, cooling equipment, dish washers, lighting, and ventilation. The lobby and hall are equipped with coffee machines, beverage dispenser, TV set, lighting, and office appliances. The first and second floor are mainly equipped with lighting, underfloor heating in the showers, and smaller kitchen appliances. In Figs. A 2 and A 3 (see Appendix), the daily electricity demand is subdivided into the specific consumption areas. According to the dichotomy of the total demand, the figures represent a week with very low occupancy due to COVID restrictions in winter (Fig. A 2), and the opposite in summer (Fig. A 3). In the winter week, the main consumption areas are basement one and lobby/hall. These areas stand for the baseload demand that is not directly related to the occupancy of the youth hostel. Regarding the high occupancy in summer, basement one and lobby/hall are again the areas with the highest consumption, which has doubled in total for both. In addition, the electricity demand for the kitchen and the floors with rooms are recognizable for that week. The strong position of the submetering areas of basement one and lobby/hall also remains for the entire year. According to Fig. A 4 (see Appendix), exactly 75 % of the total demand is caused in these two areas of the site. The floors with the guest rooms and the kitchen contribute to the demand in equal parts. Basement two has a minor impact on the annual consumption.

2) Youth hostel B: The site offers about 140 beds on two floors. Based on the main meter, the electricity consumption was about 107 MWh in 2021. The occupancy rate and thus the energy demand is comparable to the first site. As Fig. B 1 shows (see Appendix), the daily electricity demand was also unevenly distributed over the year due to COVID-related travel restrictions. Starting by the end of May, the daily demand increased between 400 and 500 kWh per day. That level remains until mid-November when the demand was reduced to about 200 kWh per day. Again, comparable to the first site, a spike was reached in the last week of the year when the daily demand was measured with 425 to 450 kWh. The submetering concept comprises different consumption units. Thus, the total consumption is attributed to

- Kitchen,
- Ventilation,
- Heating system, and
- Bistro.

Due to economic reasons, a larger portion of the electricity demand was not measured with sub-meters, e.g., the laundry room, elevator, and lighting. In the kitchen, the electricity appliances consist of hot air ovens, cooling equipment, and dish washers. The electricity demand for ventilation can be attributed to six rooms with different use, e.g., kitchen, bistro, and the electrical control center. The heating system is based on natural gas. Nonetheless, additional electricity is used for pumps and the control unit. The bistro is equipped with beverage refrigerator, coffee machine, and microwave oven. In Figs. B 2 and B 3 (see Appendix), the daily electricity demand is subdivided into the specific consumption areas. Due to COVID-related travel restrictions, the figures represent a week with very low occupancy in winter (Fig. B 2), and the opposite in summer (Fig. B 3). In the winter week, the main consumption areas are the kitchen and ventilation. The daily average is slightly above 20 kWh. These consumption units stand for the baseload demand that is not directly related to the occupancy of the youth hostel. Regarding the high occupancy in summer, kitchen and ventilation are again the areas with the highest demand, which are about seven-fold as high as before. However, the quota for unrecorded demand is 81 % in winter and 67 % in summer. This basic structure remains for the entire year. Kitchen and ventilation represent ca. 30 % of the total demand whereas about 68 % was not considered by sub-metering.

B. *Calculation of type-day profiles*

The infrastructure for smart metering was set up as part of the project “Einsparzähler”. All data is automatically transmitted every quarter-hour to a database, from which it can be retrieved for each metering point. For processing the data, a software suite was implemented in Python, which is available on GitHub [15]. In a first preprocessing step, each quarter of the week is cleaned by removing the 5 % and the 95 % quantile, since defective equipment or consumption peaks do not contain information about consumption patterns. In the subsequent aggregation of quarter-hours, a day type was assigned (Weekday, Saturday, Sunday) as well as a season. This sub-step is carried out in a similar way to [16], so comparability is given.

C. *Modeling the effects of demand side management*

The modeling framework IRPopt (Integrated Resource Planning and Optimization) is used to assess the flexibility potential of the youth hostels. The basic modeling approach and the software architecture are presented in [17–20]. The mathematical optimization model allows for a policy-oriented, technology-based, and actor-related assessment of varying energy system conditions. The integrated multi-modal approach is based on a six-layer modeling framework built on existing high-resolution modeling building blocks. IRPopt represents a bottom-up techno-economic optimization model, implemented in GAMS/CPLEX, for solving mixed-integer problems (MIP). In terms of this work, the model optimizes the procurement of electricity for the customer. In a second step short-term profits are maximized for the sales department. This leads to optimally dispatched energy flows between the technical components of the energy system for an individual final consumer but also the whole interrelated operator’s portfolio. While the model has been applied for different case studies at different spatial levels [21–23], this work focuses on the costs and benefits of dynamic tariffs for the youth hostel, given a certain level of flexibility of its electricity demand. The mathematical formulation of the shifting mechanism relies on the work of [24].

Thus, the model decides whether a certain amount of the load can be increased or decreased per time step. The constraints guarantee that only a maximum share of the load is shifted. Moreover, a load shift must be compensated within a given period. For this study, the focus is on the short-term economic potential of DR, i.e., the hourly maximum load shift is assumed with 10 % of the initial demand that must be balanced within 1.5 hours (*DR potential low*). In a second step, the parameters describing the load shift potential are doubled to 20 % and 3 hours (*DR potential high*).

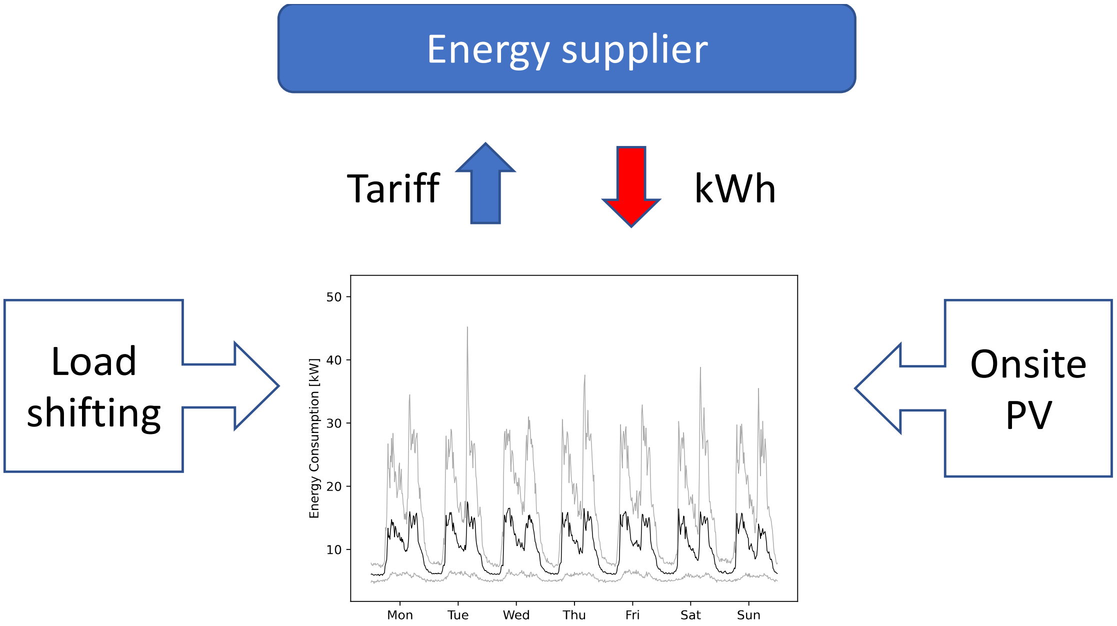

Figure 1: Defining elements of the energy system model.

An overview of the energy system is presented in Fig. 1. The central building block of the model is the load profile of the youth hostel. Since the occupancy was unevenly distributed over the year, a typical week is chosen for the analysis of the flexibility potential for both sites. The electricity demand is covered from purchases remunerated with the individual tariff. For this work, the impact of a variable tariff is compared with a flat one. The economic incentive to increase load flexibility is further enhanced by available onsite PV generation. In such a case, the economic advantage is based on the use of hourly tariff spreads and increased self-consumption.

The scenario design is summarized in Tab. 1. Accordingly, the analysis is focused on the impact of a dynamic electricity tariff and the availability of onsite PV generation. The four scenarios are analyzed with IRPopt, which represent the altered characteristics of the tariff and the onsite generation capacity.

TABLE 1: Scenario design.

Onsite generation	**Electricity tariff**	
	Flat	***Dynamic***
w/o PV	I	
with PV	II	III/IV

Based on an indicative estimate of the roof area, the sites can be equipped with PV panels. The annual generation is simulated with about 54 MWh for both sites since the same roof area is assumed for both cases. In the case of a dynamic tariff, the customer has an incentive to shift a certain amount of the electricity demand to hours with lower prices. For the two tariff options, the average price is 32.87 ct/kWh. However, the dynamic tariff is derived from the spot market of the year 2021. It is depicted in Fig. C 1, which shows a wide range of fluctuations in the second half of the year. It is of particular interest how this variability influences the economic DR potential of the sites.

III. Results

This section presents the type day profiles for the electricity consumption per site. In the second part, the economic potential of demand side management is derived from the model-based analysis.

A. *Analysis of type-day profiles*

Type-day profiles are based on the kind of day as well as the season to each quarter hour of a day in 2021. The results for each site are depicted in Figs. 2 and 3 in a quarter-hourly resolution, i.e., 96 data points. Here, Summer, Transition, and Winter represent the seasons used by [16] and are depicted by blue, orange, and turquoise respectively. For both sites, the consumption for winter days is the lowest, while the consumption in summer is the highest. On summer days when travel was not restricted, there is a clear distinction between two peaks as occupants generally leave in the morning hours and return in the evening. The decrease in demand is more pronounced during the midday period at site A.

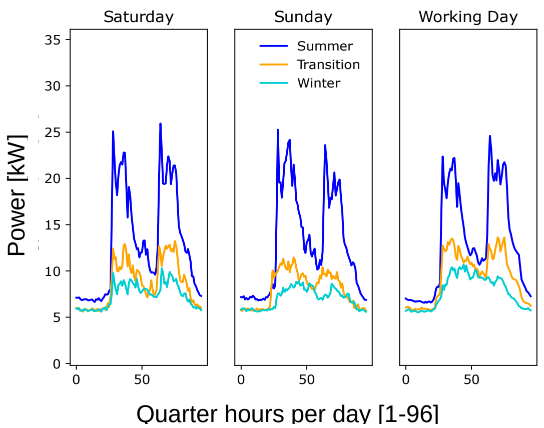

Figure 2: Type-day profile for site A based on data for 2021.

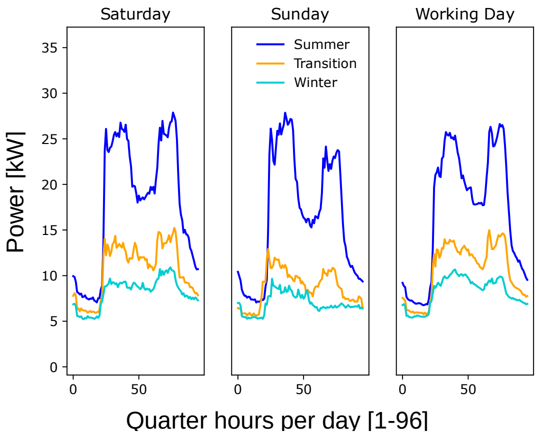

Figure 3: Type-day profile for site B based on data for 2021.

B. *The economic potential of demand side management*

For optimization, a type-week is chosen for the demand profile that is not affected by any travel restrictions (see Figs. A 3 and B 3). The results of the model optimization are summarized in Tab. 2 for sites A and B. Accordingly, the onsite PV generation has a great impact on the electricity purchases. It directly replaces between 20 % and 26 % of the electricity demand, which increases the autarky of each site. Due to the higher overall demand of site B, the self-consumption ratio is 87 % even without any demand response measures.

The introduction of dynamic tariffs activates the potential of demand response. In both cases, the use of onsite PV generation is increased in terms of autarky and self-consumption. However, the economic impact of the dynamic tariff is ambiguous. Although the electricity purchases can be further reduced, the cost savings for site A remain the same when comparing scenario II and III. Moreover, the cost savings are reduced for site B. According to the design of the dynamic tariff based on the hourly spot market price, the higher demand during the day outweighs the effect of lower prices during off-peak period. The initial load shift potential of 10 % of the demand for up to 1.5 hours is not sufficient to increase the cost savings beyond initial levels. Only when the load shift potential is assumed to be 20 % for up to 3 hours does the cost savings for site A increase or reach the baseline level at site B.

In further model runs, the hourly resolution of tariffs and load profiles was replaced with quarter hourly values. In this case, the tariff was based on intraday prices for the year 2021. Nonetheless, the cost savings cannot be further increased compared to the hourly resolution.

TABLE 2: Key performance indicators based on the model

Scenario element	**Scenario characteristic**			
	I	II	III	IV
PV	*No PV*	*PV*	*PV*	*PV*
Tariff	*Flat*	*Flat*	*Dynamic*	*Dynamic*
DR potential	*w/o*	*w/o*	*Low*	*High*
Key performance indicator	**Model results**			
Electricity from Grid (MWh)				
Site A	120.1	95.9	95.2	91.1
Site B	178.4	131.2	130.4	127.5

Autarky				
Site A	-	20%	21%	24%
Site B	-	26%	27%	29%
Self-consumption				
Site A	-	45%	46%	53%
Site B	-	87%	88%	94%
Cost savings				
Site A	-	26%	26%	29%
Site B	-	27%	25%	27%

IV. DISCUSSION

The analysis is entirely based on metering data of the year 2021. This could limit the representativeness of the type-day profiles for use as standard load profiles in terms of [16]. In addition, the data is collected specifically for two selected sites. Nevertheless, added value and insights are derived from the data. First, the profiles for both sites show great similarities which allows the results to be generalized to a certain extent. Second, the travel restrictions in the first months of the year give an indication of the base load consumption that is not affected by occupancy. During this period, the energy consumption data show only minor fluctuations as compared to actual occupancy during summer (Figs. A 1 and B 1). If occupancy remains constant over the course of a year, energy consumption in winter should be similar to that in summer, which applies to industry-specific load profiles [25]. Travel restrictions make it possible to identify a consumption baseline and uncover possible hidden consumers that would otherwise be elusive. In this study, submetering identifies specific consumers that account for nearly 50 % of total demand, such as the cooling system at Site A, or the large deviations from total consumption at Site B. Based on the aggregated submetering data, it is possible to examine the impact of external factors on energy consumption data, which can be explored in a subsequent study.

Regarding the DR potential, consumption data of a week with full occupancy is used to examine the potential for flexibility. As a result, a larger economic impact can be expected from the peak load in the morning and evening. On the other hand, the peak often coincides with price spikes in the electricity market, which cannot always be avoided by the conservative assumption of a shift of up to 3h. Conversely, however, it can also be said that the use of DR could also and especially be worthwhile in times when only weak utilization takes place. The results thus confirm earlier findings in [22] that switching to dynamic tariffs and thus taking the price risk need not always be advantageous for the customer. In this study, the cost savings are primarily due to self-generation of the PV system. The introduction of variable tariffs in combination with a small load shift of 1.5h leads to no improvements at site A and losses at site B. Since self-consumption increases at both sites at the same time, a clearly positive cost effect would be expected without dynamic tariffs. It has to be noted that the pricing data used is also from 2021. The extreme increase and volatility of electricity prices in 2022 would produce different results, but also represent a “black swan” event that is probably not representative for future years. Nevertheless, to convince customers to invest in demand management, certain cost savings must be guaranteed. The energy supplier can generate these returns from the aggregation of flexible customers and optimized procurement as a result. Similarly, grid regulation can provide additional incentives for DR to reward the positive systemic impact on the grid.

V. CONCLUSION

The study has revealed the benefits of a comprehensive sub-metering concept for recording the electricity consumption of commercial customers. At the individual level, a precise understanding of the time series of demand can be achieved and type-day profiles derived. In addition, total consumption can be allocated to individual technical units or parts of buildings, which can induce targeted efficiency measures. The study thus complements research at synthetic load profiles that are often based on industry-typical average values. The electricity demand of the accommodation facilities studied here is mainly composed of cooling, air-conditioning and kitchen-related equipment, which are particularly suitable for flexibilization. Due to travel restrictions in 2021, the data can be decomposed into a baseload portion and a more occupancy-based portion. This can also improve forecasts for individual electricity demand, supporting the utility's design of customized offerings. By knowing the high temporal resolution profile at the level of the technical installations, the interaction of measures can be evaluated with regard to efficiency, onsite generation, and DR on cost savings. The results of the model-based analysis indicate how these components contribute to cost savings and can be prioritized by the customer subsequently.

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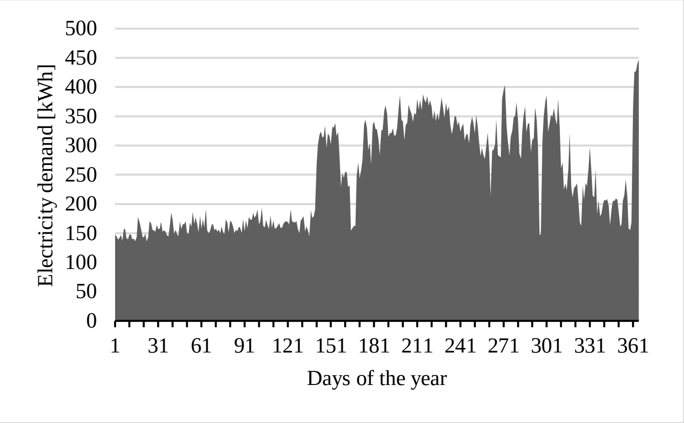
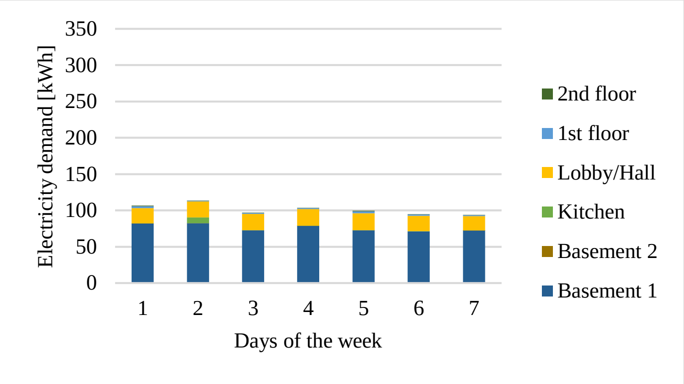
APPENDIX

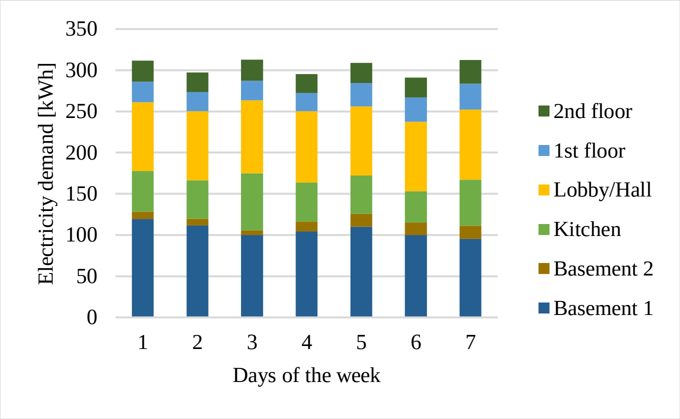
A. *Additional figures and data for site A*



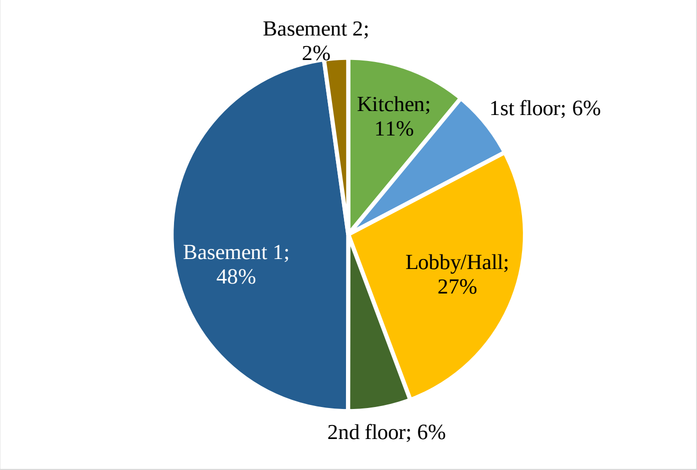
A 1: Aggregated daily electricity demand of site A in 2021.



A 2: Daily electricity demand per sub-metering unit in a winter week (2021/2/1-7).

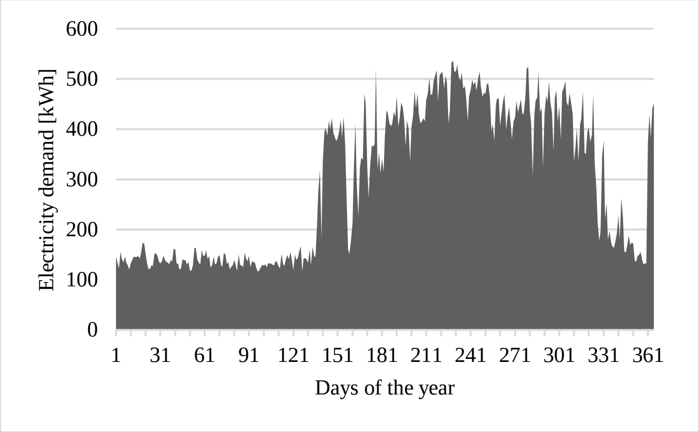


A 3: Daily electricity demand per sub-metering unit in a summer week (2021/8/9-15).

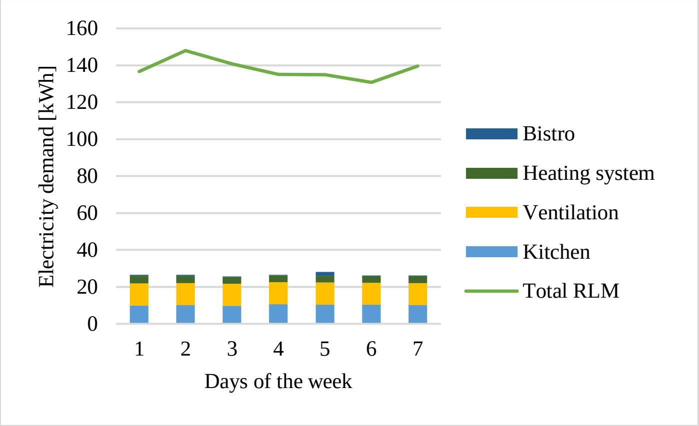


A 4: Contribution of the sub-metering areas to the total electricity demand in 2021.

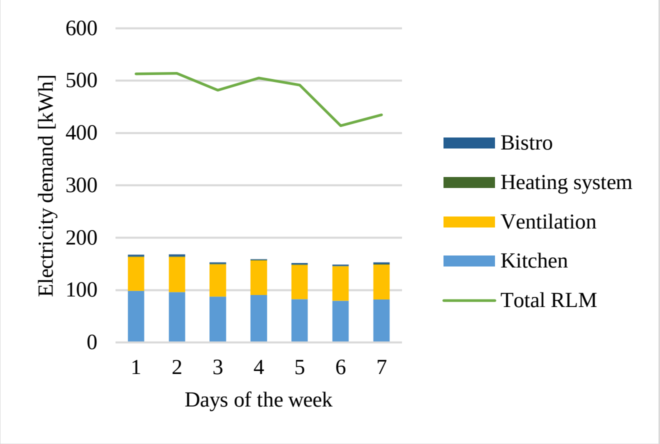
B. Additional figures and data for site B



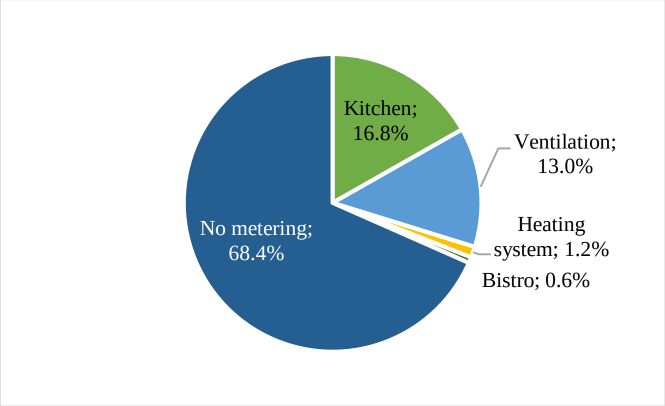
B 1: Aggregated daily electricity demand of site B in 2021.



B 2: Daily electricity demand per sub-metering unit (bars) and the main meter (Total RLM) in a winter week (2021/2/1-7).

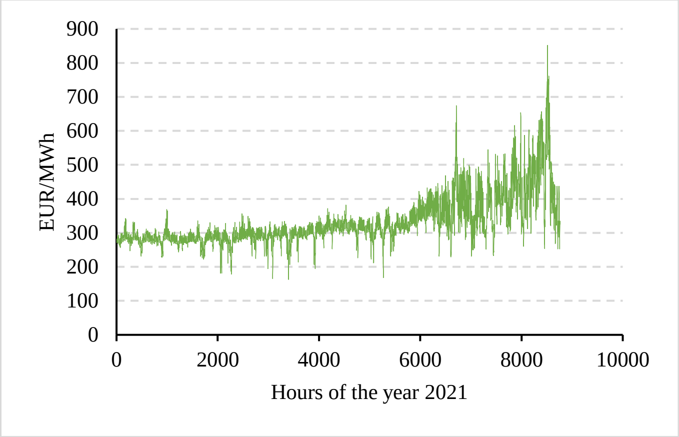


B 3: Daily electricity demand per sub-metering unit (bars) and the main meter (Total RLM) in a summer week (2021/8/9-15).



B 4: Contribution of the sub-metering areas to the total electricity demand in 2021.

C. Additional figures representing model parameters



C 1: Hourly profile of the dynamic tariff based on spot market prices of the year 2021.