Modeling of innovative load and generation time series for cross-sector energy network planning

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Abstract: Due to the complexity in planning an optimal and cross-sectoral energy infrastructure, especially when developing new quarters, a structured approach with a detailed database is necessary. Therefore, a methodology is presented, consisting of several methods coordinated among each other and to the respective input data. With this methodology, detailed load and generation time series for each geographical area to be connected, e.g. buildings or parking areas, are determined in a quarter coherently and based on individual building-topological characteristics. These time series include all relevant energy-related properties in the planning of an energy infrastructure. Finally, the resulting time series are validated after applying the methodology to an exemplary new residential area with residential and non-residential buildings as well as collectively used charging points.

Keywords: energy infrastructure, time series, greenfield planning

1 Introduction

The classical and separate consideration of the sectors electricity, gas and heat is no longer sufficient for planning the optimal energy infrastructure due to substantial sector coupling potentials. Particularly in the development of new quarters (“greenfield planning”), complexity increases significantly due to the degrees of freedom in planning. To enable software-supported planning for new quarters, a detailed database is needed, especially with building- and energy-specific indicators besides forecasted consumption profiles and generation potentials [1]. However, such load and generation time series are currently developed using separate methods without dependencies among them and applied for different sectors or the relevant energy carriers independently, as shown in the meta-study according to [2]. In addition, non-residential buildings (NRB) are sometimes not considered at all or only planned as individual cases. Therefore, this contribution presents a methodology, which allows the determination of individual characteristics as well as coherent load and generation time series, based on the planned building typology and structure for all relevant structures in a new quarter. Besides residential buildings (RB), this also includes NRB and public charging infrastructure for electromobility interdependently.

2 Methodology

The fundamental structure of this methodology follows a bottom-up approach, enabling the construction of a high-resolution and individualized database. Such a level of detail in the database also allows for a structured examination of innovative solutions for the energy supply of a new quarter (e. g., collectively used charging hubs) and their integration into the planning of the corresponding energy infrastructure. To validate the resulting time series, the methodology is applied to an exemplary new residential quarter using freely available data for a Geographic Information System (GIS).

2.1 Structure and preparation of the initial input data

The starting point of this methodology is the processing and analysis of necessary geographic data for the considered new quarter. This includes the areas, location, orientation, building types or uses, etc., of all components relevant to the energy infrastructure of the quarter. For RB, a distinction is made between single-family houses (SFH), end-row houses (ERH), mid-row houses (MRH), and multi-family houses (MFH). For NRB, in turn, six standard types are distinguished, to which a total of approximately 87 % of the energetically relevant NRB in Germany can be assigned to [3]:

• Production, workshop, warehouse, or industrial buildings (NRB 1)

• Office, administrative, or government buildings (NRB 2)

• Accommodation, housing, gastronomy, or catering buildings (NRB 3)

• Commercial buildings (NRB 4)

• Care buildings (NRB 5)

• Buildings for culture and leisure (NRB 6)

In addition, via an input mask, different metrics and probability distributions are deliberately included for input data beyond this geometric area information, such as roof shape, electromobility or resident and household characteristics. This allows for targeted analysis and comparison of different scenarios for the same new quarter.

The goal of this approach is to highlight all relevant connection areas with individual, specific metrics of energy characterization for consumers as well as potential generators. These connection areas include, on the one hand, all buildings, which, based on their building-topological characterization, are differentiated into RB, NRB and mixed buildings (MB), as a combination of RB and NRB. On the other hand, parking areas (PA) with associated charging points (CP) are differentiated according to the scheme in the following Figure 1 into exclusively privately used (pCP), restricted public usage (rCP) and requiring a dedicated, secondary connection (sCP), before they are added as relevant connection areas accordingly. However, for this differentiation, a clear assignment of all buildings in the considered new quarter (RB, NRB, MB) to the existing PA is necessary.

This way a detailed basis of the individual input data for the energetic and usage-specific characterization of each connection area to be considered in the time series generation is created. This includes, among other things, the potentially available area for the installation of photovoltaic (PV) systems, as well as the associated number and rated capacity of CP and relevant building or household characteristics.

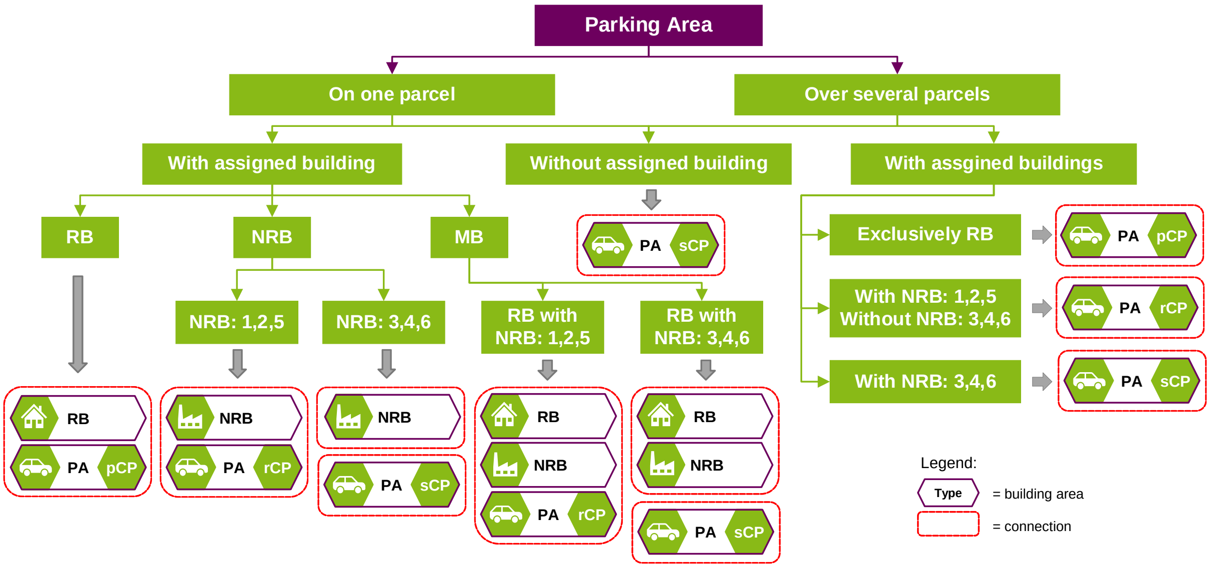


Figure 1: Overview of the differentiation for the parking areas types with the associated connection characteristics

2.2 Load and generation time series

The methodology for deriving specific and individualized load and generation time series is based on the integration of multiple methods that have been coordinated among each other as well as with the underlying input data. These methods are schematically depicted in Figure 2, illustrating their interdependencies. Fundamentally, the methodology distinguishes between different methods in determining the time series depending on the building-topological categorization of a connection area into RB (orange blocks and lines), NRB (blue blocks and lines) and PA (yellow blocks and lines). Each of these methods calculates a time series for a substantial energy-related characteristic of the respective connection area (boxes on the right with purple frames) over a considered time span of one year with a 15-minute resolution.

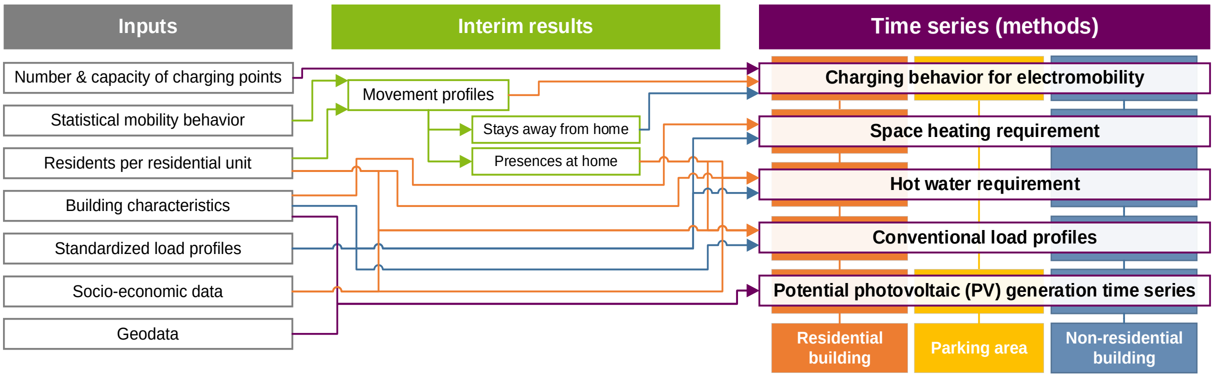


Figure 2: Overview of the methods for calculating time series with their interdependencies

The following sections provide a detailed explanation of the methods depicted in Figure 2 and their interdependencies.

2.2.1 Electromobility

The starting point of the entire methodology is a method based on the approach outlined in [4]. With this approach, initially, a detailed mobility profile is created for each resident of every residential unit (RU) in the entire new quarter based on statistical mobility behavior [4]. In the subsequent determination of specific charging profiles for electromobility, the associated method distinguishes based on the connection and usage characteristics of the CP on the respective PA according to the scheme in Figure 1 from Section 2.1, differentiating between pCP, rCP, and sCP. Accordingly, for each CP, integrated charging profiles are initially determined based on the mobility profiles of the residents of all those RU assigned to the PA with this respective CP [4]. The charging phases of individual residents are coordinated among each other. This happens in a way, that when an associated electric vehicle is at home and not at 100 % state of charge (SOC), it is scheduled for an available but unoccupied CP. This approach therefore enables the representation of collectively used charging hubs. For pCP, these initial charging profiles are subsequently the final time series as well.

Besides these initial charging profiles, the method determines the presence times of each resident in a RU, as well as the periods spent outside their own RU along with the respective reasons included from the mobility profiles of individual residents for the travel. These reasons include work, business, education, shopping, errands, leisure, and companion [4]. For those PA not exclusively used privately, rCP and sCP, public use is added to the initially determined charging profiles. These public charging phases are statistically added to the existing initial charging profile based on the number, start times, and duration of the charging process if at least one CP is available at the respective PA throughout the entire charging process to be added. Each of these three parameters for describing a charging process derives from a statistical analysis of current inventory and usage data regarding the charging infrastructure in Germany, combined with the usage and specific energy-related characteristics of the CP in the context of the considered new quarter.

The duration of the charging processes is based on an evaluation of the 25 vehicle models with electric drive and all associated battery capacities of the respective versions of these models that were most frequently registered as new vehicles in Germany in the year 2022 and 2023 up to and including November 2023 [5]. From this data, with charging capacities (11 kW, 22 kW, 50 kW, 100 kW, 150 kW) and an interval for common charging cycles (Delta-SOC: 20 % – 80 %), intervals for the possible durations of a charging process at a CP with a defined charging capacity are derived as shown in Table 1.

Table 1: Overview of the intervals for the duration of a charging process depending on the charging power

Charging power	11 kW	22 kW	50 kW	100 kW	150 kW
Duration in min	20 – 240	15 – 120	10 – 60	5 – 30	5 – 20

The number of charging processes at a CP is based on the average utilization of public CP in Germany at 12 %, combined with the previously determined intervals for the duration of a charging process [6]. Assuming equally utilized CP in their entirety, the values for the number of charging processes at an CP with a defined charging capacity are derived, as shown in the following Table 2.

Table 2: Overview of the determined number of charging processes per year depending on the charging capacity

Charging power	11 kW	22 kW	50 kW	100 kW	150 kW
Number of charging processes	485	934	1,802	3,604	5,046

The start time, as the last relevant parameter for characterizing a charging process, is determined based on the previously calculated mobility profiles of the residents of the new quarter. For this purpose, a probability distribution for the start time of a charging process is created based on the aggregated times of stay away from home of all residents of the new quarter, as well as the specific reasons for each journey. This probability distribution is presented in Figure 3, exemplarily for a quarter with 373 residents.

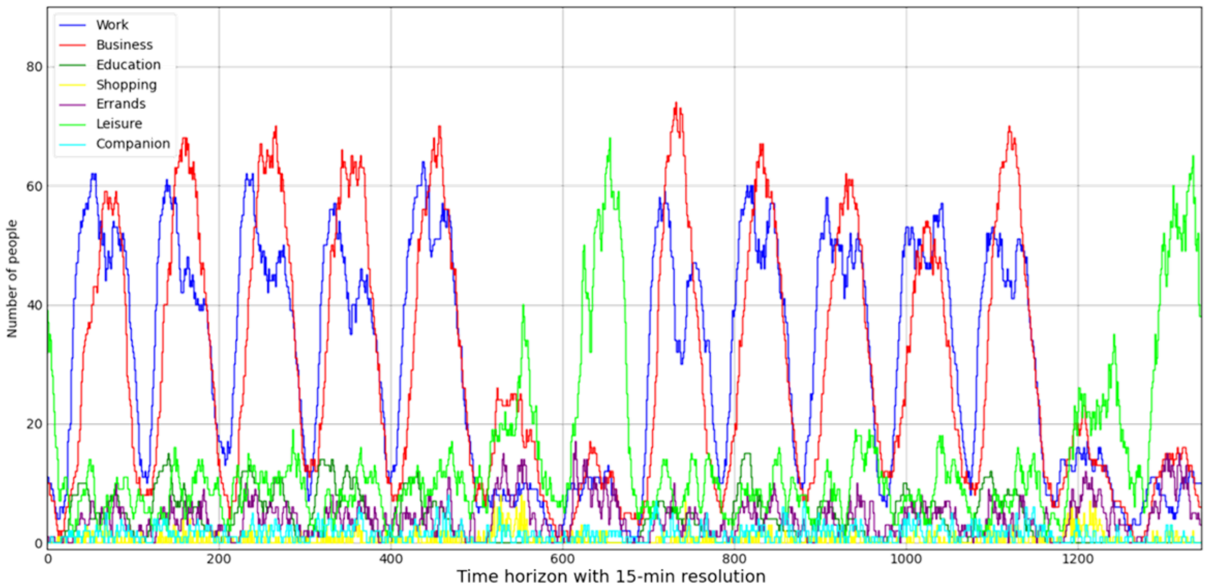


Figure 3: Exemplary two-week excerpt of aggregated data for the residents away from home

The exact composition of this probability distribution differs depending on the building types assigned to a PA, following the standard types for NRB explained in Section 2.1. The exact composition is presented in the following Table 3. If several different NRB standard types are assigned to a PA, the final probability distribution is determined as the weighted average of the distributions associated with these NRB standard types.

Table 3: Overview of the composition of probability distributions for the start time of a charging process

Type	Composition
NRB1	$A \cdot 0{,}70 + B \cdot 0{,}15 + C \cdot 0{,}10 + D \cdot 0{,}00 + E \cdot 0{,}05 + F \cdot 0{,}00$
NRB2	$A \cdot 0{,}50 + B \cdot 0{,}15 + C \cdot 0{,}15 + D \cdot 0{,}00 + E \cdot 0{,}20 + F \cdot 0{,}00$
NRB3	$A \cdot 0{,}15 + B \cdot 0{,}20 + C \cdot 0{,}05 + D \cdot 0{,}00 + E \cdot 0{,}00 + F \cdot 0{,}60$
NRB4	$A \cdot 0{,}20 + B \cdot 0{,}15 + C \cdot 0{,}05 + D \cdot 0{,}50 + E \cdot 0{,}10 + F \cdot 0{,}00$
NRB5	$A \cdot 0{,}60 + B \cdot 0{,}05 + C \cdot 0{,}20 + D \cdot 0{,}00 + E \cdot 0{,}05 + F \cdot 0{,}10$
NRB6	$A \cdot 0{,}15 + B \cdot 0{,}20 + C \cdot 0{,}05 + D \cdot 0{,}05 + E \cdot 0{,}05 + F \cdot 0{,}60$
Without building	$A \cdot \frac{1}{6} + B \cdot \frac{1}{6} + C \cdot \frac{1}{6} + D \cdot \frac{1}{6} + E \cdot \frac{1}{6} + F \cdot \frac{1}{6}$

Legend	
A	Work
B	Business
C	Education
D	Shopping
E	Errands
F	Leisure

2.2.2 Conventional household load

For the determination of conventional household load profiles, methodologically, as shown in Figure 2, an initial distinction is made between the building categories RB and NRB. For RB, a method is used to determine conventional load profiles for each RU based on socio-economic statistics and depending on the specific characteristics of the underlying RU in the considered new quarter. In addition to the presence profiles already determined, these include characteristic indicators of the respective household (H) of a considered RU. These characteristics for characterizing a H are presented in the following Table 4.

Table 4: Overview of characteristic household properties for determining conventional load profiles

Characteristics	Description
H-Type	Single household, multi-person household with or without children
H-Income	Monthly total household income (net)
H-Head	Age of the household head or main income earner

The method for determining conventional load profiles builds upon a method that originated according to [7]. For each RU in all RB in the considered new quarter, initially the degree of equipment with the associated device configuration of common H items for the respective H is determined based on the characteristics presented in Table 4 along with socio-economic statistics. Subsequently, on a daily basis, the use of each device in the H is determined based on socio-economic statistics, as well as the already determined aggregated presence times of all residents in the respective RU. The usage is based on socio-economic statistics, considering the frequency of usage in a day, the respective durations of usage, and the start times of usage to be determined. For the usage times, a distinction is made between devices in the H for which a resident must be present throughout the entire usage (e. g., a stove) and those for which a resident must only be present at the start of usage (e. g., a washing machine). Furthermore, a distinction is made between the type of resulting load profile in active use or interaction of a resident with consideration of presence times (e. g., cooking on the stove, washing process of a washing machine) and "stand-by use" without significant user interaction (e.g., TV on stand-by, refrigerator). Thus, detailed load profiles based on individual devices in an H and their specific usage can be determined, which are then aggregated into an overall conventional load profile.

For NRB, load profiles are determined using the library according to [8] with a method making use of the standard load profiles of the BDEW and following the underlying bottom-up approach of the methodology based on individual building indicators. For this purpose, with the allocation in the following Table 5 the associated BDEW standard load profile is scaled to the annual conventional energy consumption of the considered NRB, thus creating equally high-resolution load profiles for NRB in this methodology.

Table 5: Allocation of the corresponding BDEW standard load profiles for the non-residential building standard types

NRB Type	NRB 1	NRB 2	NRB 3	NRB 4	NRB 5	NRB 6
Associated BDEW Load Profile	G1	G1	G2	G4	G1	G2

Legend: Business on weekdays 8 a.m. – 6 p.m. (G1), Business with heavy to predominant consumption in the evening hours (G2), Shop/barber shop (G4)

2.2.3 Heat demand

When determining the heat demand, similarly to Section 2.2.2 for conventional load profiles, an initial distinction is made between the building categories RB and NRB. For the RB, a methodology is used in which the heat demand is differentiated between space heating and hot water, both with separate methods of determining the respective time series.

The determination of space heating profiles is carried out using the method according to [9], which describes the external balancing of all heat flows around the entire building envelope. This method is implemented based on individual building characteristics used to determine the envelope area and the individual facade areas as well as their orientation. Additionally, detailed building parameters such as relevant thermal transmittance coefficients are considered using standard indicators for new buildings. Based on these detailed building characteristics, a “degree-day-figure”, representing the difference between a target temperature and the daily average, is determined for each building following an exemplary annual temperature profile and a defined target temperature of 21 °C. The final calculation of the space heating demand profile for a building is then carried out based on the “degree-day-figures”, building technical parameters, and all relevant heat flows. This includes both outgoing heat flows or losses depending on the thermal transmittance coefficients and incoming heat flows or gains, such as global solar radiation for the respective building and internal heat gains based on the residents of all RU in the respective building.

Unlike space heating, the determination of the hot water demand profiles for the RB is not implemented for a building but individually for each RU in a building. Furthermore, the hot water demand is not dependent on building technical characteristics and the outside temperature, but rather on the specific user behavior of the residents. This user behavior is modeled in the implemented method based on statistical methods and socio-economic indicators. To achieve this, four different extraction reasons are defined as short extraction, long extraction, bath, and shower, based on [10]. For each of these extraction reasons, three properties — flow rate, duration, and frequency per day — are defined, each with a mean value and an associated standard deviation, assumed to follow a normal distribution. To determine the hot water demand profiles, daily values for the corresponding properties of flow rate, duration, and frequency for each RU are determined based on their respective probability distributions. However, to depict a daily schedule, the probability function shown in Figure 4 for each extraction reason on a day is used following [10].

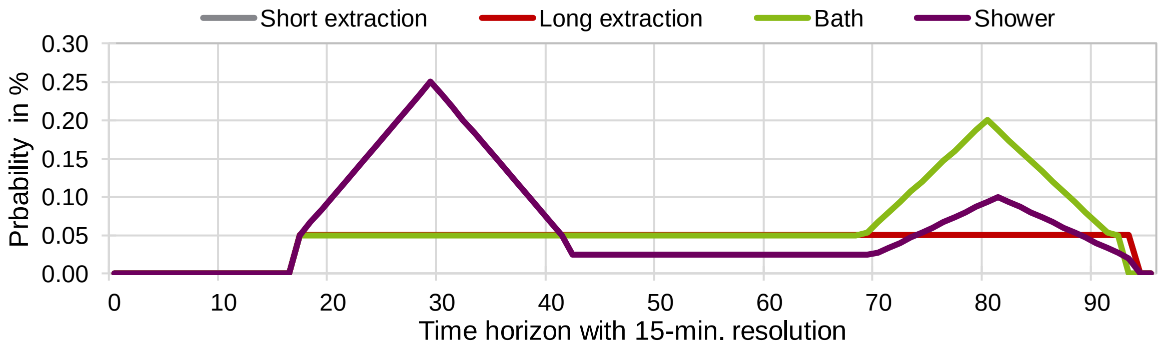


Figure 4: Daily variation of the probability distribution for extraction reasons based on [11]

Based on these extractions, along with the temporal probability function and considering the presence times for the residents of each RU, a hot water demand profile is created on a daily basis. Hence no extraction can take place in a RU if no resident from that RU is present at that time. Finally, these daily profiles are aggregated into one final hot water demand profile.

For the NRB, the heat demand profile is determined analogously to the conventional load in the previous Section 2.2.2, using the library according to [8], and based on individual building indicators. Therefore, the associated standard load profile is also scaled to the annual aggregated heat demand of the considered NRB.

2.2.4 Photovoltaic Potential

The determination of potential PV time series is implemented for each building based on its associated building characteristics with specific GIS data for the respective location of the new quarter. Among these building characteristics, the initial consideration includes the maximum PV nominal power that can possibly be installed on this area. This value is calculated through the two-dimensional projection of the roof area from the input GIS data, taking into account the roof shape and its influence on the existing roof area, along with a standard PV module with 0,2 kWp/m^2 [11]. In this context, the method distinguishes between the roof shapes of flat roof, gable roof, and pitched roof, as depicted in Figure 5.

Figure 5: Overview of the roof shapes considered in the presented method

In addition to the maximum PV nominal power possible, the orientation (azimuth) and tilt of the PV modules on each roof are also considered. The orientation in this method is derived from the minimal oriented bounding box, as shown in Figure 6 for two exemplary RB. These boxes are created to determine the dominant orientation of the building area based on their overall orientation.

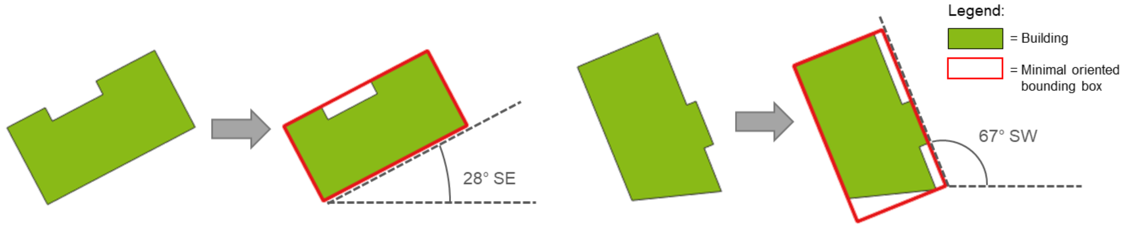


Figure 6: Exemplary application of the minimum oriented bounding box on two residential buildings

In the case of a gable roof or pitched roof, this dominant orientation of a building also defines the orientation of the respective PV modules, whereas on a flat roof, the PV modules are erected independently of the building's orientation. Hence in this case they are installed ideally facing south for optimal PV yield. Just like with orientation, a distinction is made in the tilt between gable roofs or pitched roofs and flat roofs. While PV modules on gable roofs and pitched roofs are installed with the respective roof inclination, PV modules on flat roofs can easily be installed in any inclination using mounting systems. Therefore, the PV modules in this case are assumed to have an optimal inclination of 35° for PV yield [11].

All these individual building characteristics are then used together with the location of the considered new quarter and the associated relevant climate data (weather-related irradiation, temperature) to create individually adapted potential PV generation time series for each building. The concrete implementation is then carried out using the library according to [12].

3 Results

To validate the methodology presented in Section 2, it was applied to an exemplary new quarter in Berlin using freely available GIS data [13]. In the following Figure 7, an exemplary one-week excerpt of the determined time series for a MFH with 8 RUs is shown.

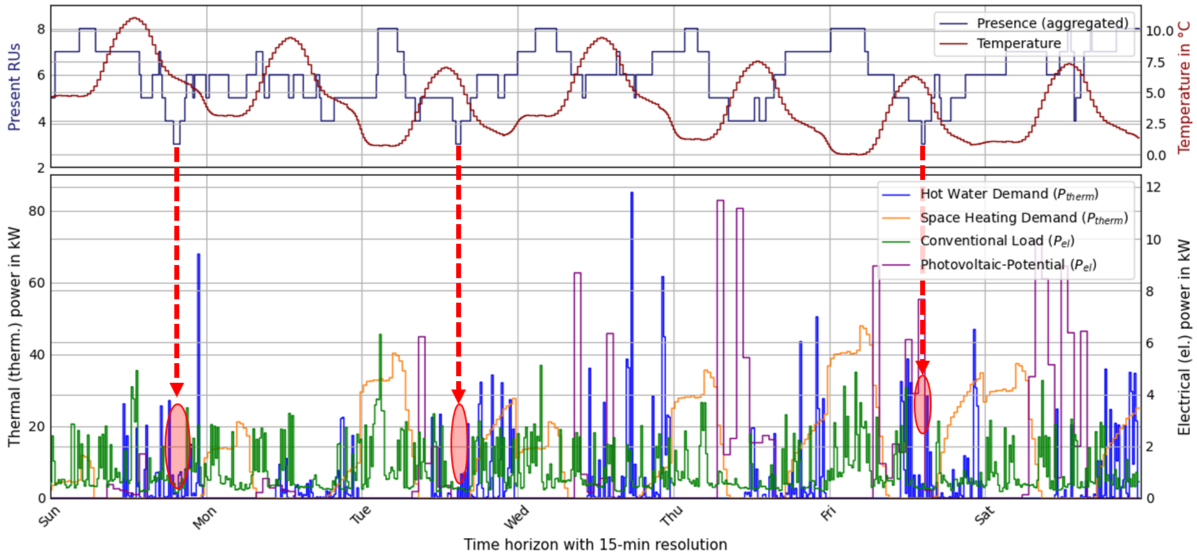


Figure 7: Excerpt of resulting time series for an exemplary residential building in a new quarter

The results clearly depict, alongside the daily cyclical pattern of each time series, the influence of the external temperature trend as a negative correlation with the space heating profile (yellow line, lower graph). Furthermore, the impact of minor aggregated presences (blue line, upper graph), for instance on the dips in the hot water demand time series (blue line, lower graph), is also evident (see red arrows). For this respective MFH, there is no electromobility time series with charging profiles since this MFH in the quarter is assigned to a collectively used PA in the quarter with a separate connection. For such a collectively used PA with 18 CPs and 11 kW charging power each, an exemplary one-week excerpt of the resulting electromobility time series is shown in the following Figure 8.

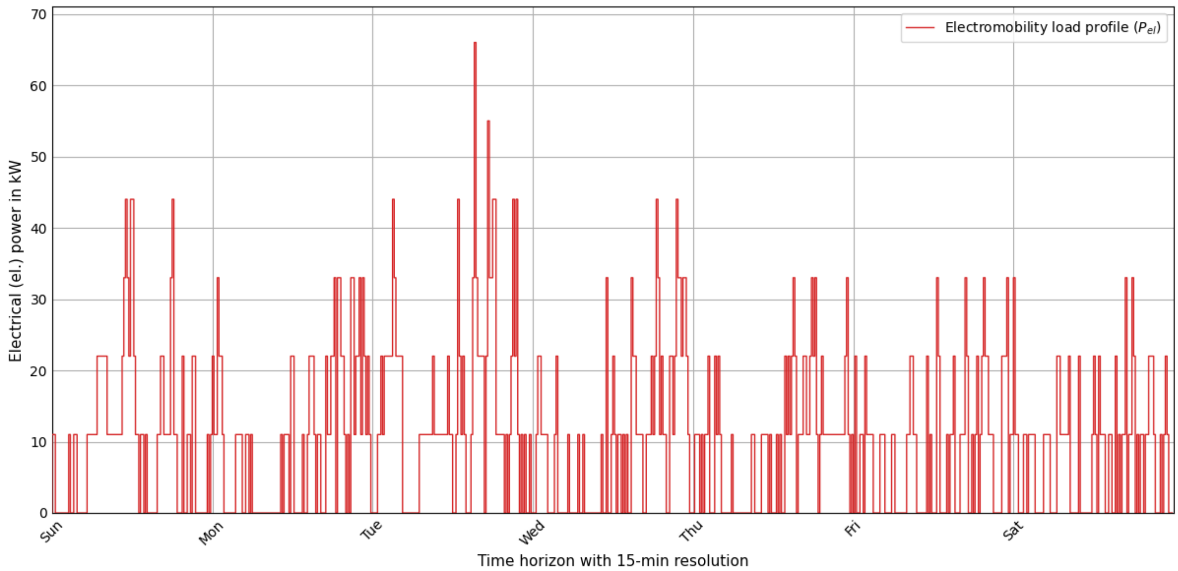
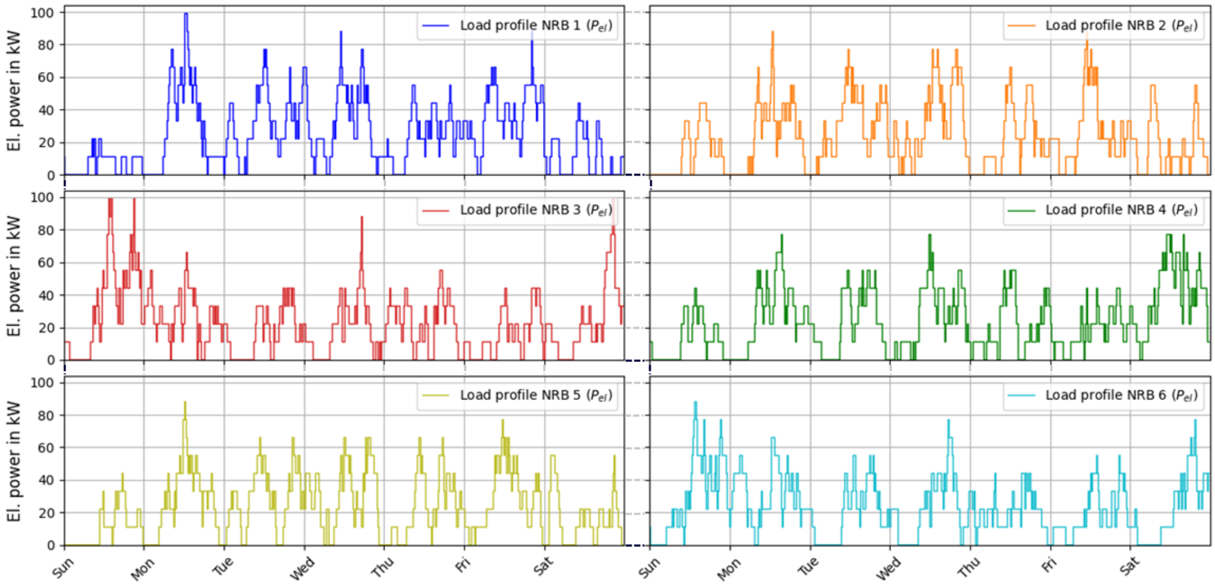


Figure 8: Excerpt of resulting electromobility time series for a collectively used parking area

The PA is collectively used by 14 RBs and is an underground car park in the new quarter. Hence there is no potential PV generation time series determined for this PA. The results show that within the considered week, a maximum of 6 CPs with 11 kW each were in use simultaneously, with an equivalent value of 8 CPs over the entire analyzed yearly period. Furthermore, a tendency of higher charging activity in the later hours of each day is evident. This effect results from the method, which is used to define the mobility behavior for all residents. Initially, the movement profiles with associated trips and modes of transportation are defined for all residents. Only when a resident returns home after a trip or multiple rides with the electric vehicle, the charging phases for the corresponding electric vehicle are scheduled based on the availability of CPs on the corresponding PA.

However, this behavior changes when the charging phases are determined based on a resident's movements and stays instead of their presence times at home. For this purpose, in the following Figure 9, exemplarily for a PA with 18 CPs and 11 kW each as well, excerpts of resulting electromobility time series with associated NRB of the standard types defined in Section 2.1 are shown.



Abbreviations: Non-residential building (NRB), electrical (el.)

Figure 9: Excerpt of determined electromobility time series for a parking area with associated non-residential buildings standard types

The determined time series clearly show, in addition to individual daily patterns, the tendency for the highest charging activity during the day when residents are away from home. Furthermore, the different influences of aggregated residence data of all the residents as well as the specific locations for the composition of the start times of the load profiles are apparent. For example, the standard types NRB 1, NRB 2, NRB 5 show very low charging activity on weekends, as typically less work is done on these days and care facilities are not open. Likewise, the standard type NRB 4 also has low charging activity on Sundays since commercial buildings are usually closed on this day, but it has much higher charging activity on Saturdays when most residents go shopping. Similarly, for standard types NRB 3 and NRB 6, the increased charging activity on weekends due to increased use by residents for leisure, culture, and gastronomy, etc., is evident.

Finally, in the following Figure 10, an exemplary excerpt of the determined time series for a hotel as NRB with standard type NRB 3 is shown. These results also clearly show, in addition to the daily cyclical patterns, the influence of the outside temperature as a negative correlation with the associated heat demand time series (light blue, lower graph). Moreover, the increased conventional load (yellow, lower graph) in the later hours is also evident. This pattern arises from the G2 standard load profile with strong to predominant consumption in the evening hours from the library according to [8], which is assigned to the standard type NRB 2.

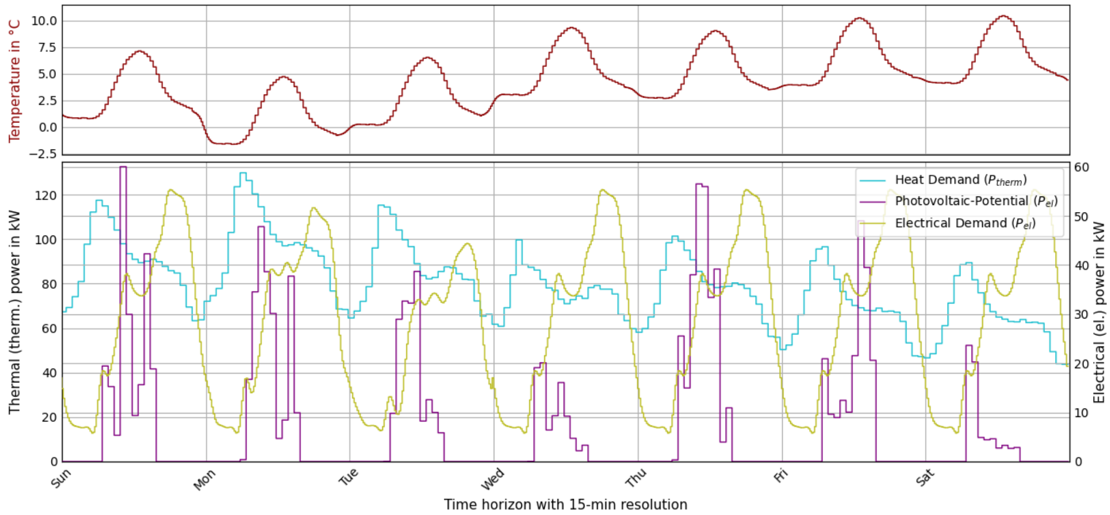


Figure 10: Excerpt of resulting time series for an exemplary non-residential building in a new quarter

4 Conclusion

The methodology presented in this publication enables the creation of innovative, energetic load and generation time series. Following this approach and based on the respective quarter structure an individual, high-resolution database can be created interdependently for all energetically relevant properties of a new quarter. The consideration of the relevant properties as well as their creation within the quarter distinguishes depending on the building topological classification and their respective usage. Besides RB with their individual structures and usages, this also includes methods to create time series for NRB and public CP based on their individual characteristics as well as the usages defined by the residents of the respective new quarter. This allows for targeted, highly detailed analyses of the predicted energetic interconnections and synergy potentials within a new quarter. These include innovative solutions such as collectively used charging hubs as well as energetic supply concepts for buildings spatially connected. This level of detail enables a deeper understanding of the requirements for the energy infrastructure and provides the basis for its energetic optimization.

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