Analysis of Natural Gas and Electricity Load Profiles for the Decarbonisation Strategy of a Commercial Area

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ABSTRACT

The aim of the analysis is to create a database that maps the company-specific energy demand of a commercial area in hourly resolution. The focus is on determining the electricity and heat demand profile of companies in a commercial area using a combination of synthetic and real load profiles. These are necessary to map the heterogeneous energy requirements of industrial and commercial companies in a commercial area as realistically as possible. Due to the limited availability of real consumption data, 323 synthetic electricity and 125 gas load profiles from various studies were used. The comparison shows that synthetic profiles can only reflect the actual requirements of individual companies to a limited extent. However, as the temporal resolution becomes more aggregated and the number of companies increases, the synthetic data approximates the real consumption profile of the entire commercial area. The analysis carried out forms the basis for implementing an energy system model that examines the economic and technical synergies of local energy communities as part of decarbonisation strategies in commercial areas.

Keywords: industry sector, process heat, synthetic load profiles, trade, commerce and services sector

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1. INTRODUCTION

Companies play a key role in the energy transition. Industry accounts for 27 % of the final energy consumption in Germany with 8095 PJ (2024), while companies in the trade, commerce and services sector account for 15 % (AG Energiebilanzen e.V. 2025). The electrification of industrial heating applications and the implementation of heat pumps can contribute to reducing greenhouse gas emissions in industry and the tertiary sector significantly, provided that electricity is generated with low greenhouse gas emissions. From the perspective of companies, however, electrification is only feasible if it is economically advantageous (Guminski et al. 2019).

Local energy communities, in which companies within a commercial area pursue a comprehensive decarbonisation strategy, can support the transformation of companies by increasing

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energy efficiency, reducing primary energy demand and emissions, and generating economic benefits (Rodin and Moser 2021). Energy cooperation between companies includes, for example, the exchange of waste heat or the joint operation of energy generation or storage facilities. To make quantitative statements about potential cost and capacity savings, as well as opportunities for waste heat recovery, in a commercial area, energy system modelling is necessary. For example, the *Open Energy Modelling Framework* (Hilpert et al. 2018) can be used to map the entire area, taking into account reliable consumption (or demand) profiles and industry-specific temperature requirements.

Thermal and electrical load profiles are an important basis for creating suitable numerical models for the energy supply of commercial areas because energy system planning increasingly requires detailed and comprehensive analyses and for balancing energy supply and demand. High-quality, available energy data is decisive. However, the energy demand of companies is heterogeneous across sectors, and real energy consumption data is rarely available for certain consumption segments, in particular in the industrial and tertiary sector (Seim et al. 2019; Gotzens et al. 2020). Studies can be found in the literature in which typical synthetic load profiles for individual companies have been developed to close this data gap. Synthetic electricity load profiles (Seim et al. 2021b; Sandhaas, Kim, and Hartmann 2022; Seim et al. 2021a; Spalthoff et al. 2019; Meinecke et al. 2021; Jesper et al. 2021; Sandhaas et al. 2022; Pezzutto et al. 2019) and synthetic gas load profiles (Jesper et al. 2021; Sandhaas et al. 2022; Pezzutto et al. 2019) generated from typical industry processes or real energy consumption data are available. Heterogeneous demand within an economic sector limits the forecasting quality of the synthetic load profiles. It should also be noted that the synthetic profiles have not been sufficiently compared with reality or validated in some cases (Seim et al. 2021b; Böckmann et al. 2021; Seim et al. 2021a; Meinecke et al. 2021; Sandhaas, Kim, and Hartmann 2022; Fleiter et al. 2018; Sandhaas et al. 2022).

A gas load profile alone is not sufficient to analyse heat requirements, because flow temperatures must also be taken into account. Industrial process heat is usually required at different temperature levels (Fleiter, Steinbach, and Ragwitz 2016). Since the efficiency of renewable energy technologies depends heavily on temperature levels (Fleiter et al. 2023; Agora Industrie and FutureCamp 2022), it is particularly important to take the temperatures of the individual industrial processes (process level) or the minimum possible temperature of a heating network (supply level) into account when creating load profiles.

Instead of generating load profiles for individual companies or economic sectors, this analysis focuses on profiles for an entire commercial area. To achieve this, individual profiles from different economic sectors and their specific process temperature requirements must be combined. The aim of the analysis is to map the energy requirements of a commercial area on an hourly basis for each individual company in the areas of electricity and heat, including temperature requirements.

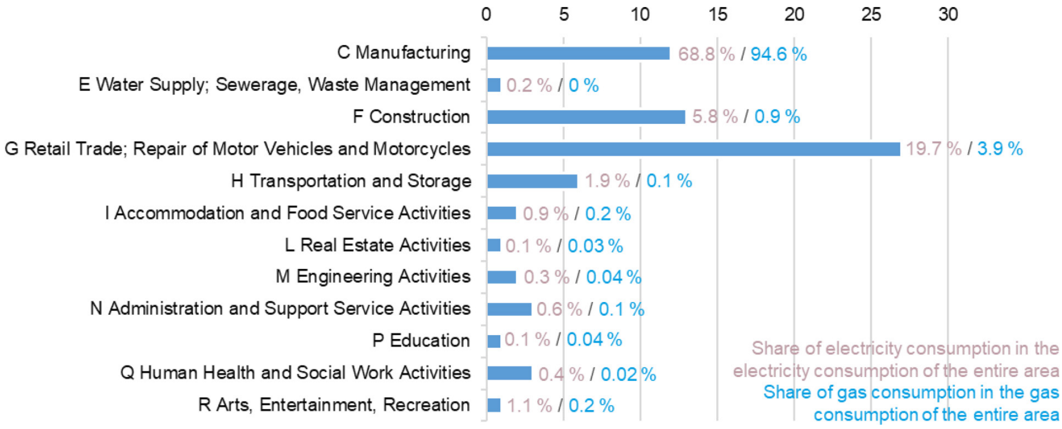
The following section describes the commercial area under investigation. In section 3 the method used to compare different synthetic and measured profiles, and to generate and evaluate profiles of the entire commercial area is introduced. Furthermore, the method for identifying suitable renewable heat generation technologies based on their typical flow temperatures and industry-specific process heat temperature levels is explained. The results are presented and discussed in Section 4.

2. COMMERCIAL AREA INVESTIGATED

The decarbonisation strategy was developed for a real commercial area in Lower Saxony, which served as a case study. The commercial area is predominantly characterised by small and medium-sized enterprises. A few large companies are also located there. Figure 1 shows the number of companies per economic sector and their share of the total energy consumption of the commercial area.

FIGURE 1

Resident companies by economic sector in the commercial area under consideration



The commercial area comprises about 70 companies which are spread over about 1.65 km^2. The area is supplied with electricity and gas. Around 5 GWh of electricity and 100 GWh of gas are purchased each year. Gas is mainly used for heat generation. For the commercial area under consideration, it should be noted that the heating demand of a single company accounts for the largest share of gas consumption. As a result, around 95 % of the heat consumption is generated by a single economic sector (C Manufacturing). This sector's share of electricity consumption is also very high, at just under 70 %. Economic sector G Trade has the second highest consumption, with about 20 % of electricity consumption and about 4 % of gas consumption in the area.

This distribution of energy consumption shows a dominance of a few companies in the commercial area. The consideration of a collective decarbonisation strategy and interaction among a large number of companies in this area can be significantly restricted by this dominance.

Electricity and natural gas load profile data from individual companies were provided for the commercial area. The electricity load profile data is available in quarter-hourly resolution and the gas load profile data in hourly resolution over a period of one year. Not every company in the investigated area records power measurements (RLM; German: registrierende Leistungsmessung), with the result that no reliable energy demand data is available. Therefore, synthetic profiles have to be used to map the overall area demand. The challenge lies in selecting and combining synthetic profiles of different resolutions and validity in order to realistically map demand profiles for electricity, gas and process heat as well as temperature levels.

3. DETERMINATION OF ANNUAL LOAD PROFILES AND CLASSIFICATION OF PROCESS TEMPERATURES

3.1. Classification of industrial sectors

Industrial and commercial energy requirements are individual and form a heterogeneous demand structure across all sectors of the industrial and tertiary sector. The classification of economic sectors (WZ 2008) of the Federal Statistical Office is used to systematise the energy requirements of the industrial and tertiary sector. All companies in Germany are divided into a five-level classification system (Table 1) (Statistik der Bundesagentur für Arbeit 2022).

TABLE 1
Structure of the economic sectors 2008

Structure of Economic Sectors based on WZ 2008			
Level		Example	
1. letter	sections	C	Manufacturing
2. figure	divisions	10	Manufacture of Food Products
3. figure	groups	103	Processing and Preserving of Fruit and Vegetables
4. figure	classes	1032	Manufacture of Fruit and Vegetable Juice
5. figure	subclasses	10320	Manufacture of fruit and vegetable juice

Source: Our own representation based on (Statistik der Bundesagentur für Arbeit 2022)
In the following, the classification by economic sector (WZ 2008) is used at level two, *divisions*.

3.2. Electricity and gas load profiles

Electricity and gas load profiles of individual companies in the commercial area under consideration are available, and these were collected using RLM, as well as the cumulative electricity and gas consumption of all 70 companies. About 84 % of the real electricity consumption and about 94 % of the real gas consumption in the commercial area is continuously recorded by RLM. These electricity and gas load profiles as well as the annual electricity and gas consumption serve as the data basis for the real energy demand. In this context, *consumption* refers to the energy use measured, while *demand* denotes synthetic or estimated values. In case of gas, both can serve as a basis for estimating heat demand.

Various proposals for generating synthetic load profiles can be found in the literature. Regarding this analysis, 323 electricity load profiles from nine studies and 125 gas load profiles from five studies are used (Seim et al. 2021b; Böckmann et al. 2021; Seim et al. 2021a; Meinecke et al. 2021; Huber et al. 2023; Braeuer 2020; Sandhaas, Kim, and Hartmann 2022; Jesper et al. 2021; Pag, Jesper, and Jordan 2021; Pezzutto et al. 2019; Sandhaas et al. 2022; Spalthoff et al. 2019; BDEW 2017, 2024). These differ in their top-down or bottom-up methodology and the resulting synthetic load profiles vary in their temporal resolution and assignment within the industrial and tertiary sector.

Firstly, the synthetic load profiles are converted to a uniform resolution, whereby electricity profiles are resolved on a quarter-hourly and gas profiles on an hourly basis. Additionally, the synthetic profiles are normalised to 1,000 kWh/a. Synthetic and real profiles are categorised according to economic sectors. The real profiles are not weather-adjusted, the synthetic profiles are weather-adjusted. Weather adjustment is relevant for synthetic profiles for the proportion of space heating, while process heating is only slightly dependent on weather conditions. Since the proportion of process heat in the real profiles is high, the influence of weather conditions is low.

Second, the synthetic profiles of different studies are compared with each other if a synthetic profile is available for the same economic sector. The energy requirements are cumulated on a monthly basis and the average daily performance is calculated for the comparison. The cumulative monthly consumption is referenced to 30 days in order to eliminate consumption fluctuations caused by the varying number of days in a month. The seasonality of demand can be derived from the monthly energy demand. In addition, the average daily energy consumption of a working day is shown.

The synthetic profiles of an economic sector are then multiplied by the respective annual energy consumption of a company in the commercial area under consideration from the corresponding economic sector in order to generate a synthetic energy consumption profile. The real and synthetic profiles are then compared. Synthetic annual duration curves are formed and compared with real annual duration curves for each economic sector.

The profiles are also examined at different temporal resolutions:

- ¼-hour or 1-hour profile,
- Daytime (6-hour interval: morning, noon, evening, night),
- Calendar week,
- Month

Additionally, the electricity and gas load profile of the entire commercial area is modelled by superposing the individual synthetic load curves and compared with the real area load profile for electricity and gas.

The coefficient of determination R^2 (equation 1) and the mean absolute percentage forecast error (MAPE) are calculated for all profiles (equation 2) to assess the forecast quality of the synthetic load profiles. The coefficient of determination R^2 is a statistical quality criterion that indicates the proportion of the total variance of a dependent variable that is explained by a regression model; a value of 1 indicates a perfect model fit, while a value of 0 indicates a lack of explanatory power of the model for the variability of the dependent variable.

$$R^2 = \frac{\sum_{i=1}^{n}\left(\hat{y}_i - \bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \qquad \text{Eq. 1}$$

The MAPE measures the forecast accuracy of a model by determining the average absolute percentage error between predicted and actual values.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|\hat{y}_i - y_i\right|}{y_i} \times 100 \qquad \text{Eq. 2}$$

The MAPE is used particularly in time series analysis to quantify the precision of forecasting models; a low MAPE value (< 10 %) indicates a high level of forecasting accuracy, while a high value (> 50 %) indicates a low level of model reliability. Due to its simple interpretation, MAPE is a common metric used in the energy industry to analyse the accuracy of load forecasting. The MAPE tends to assume extreme values for very small load values close to or equal to zero (Hong and Fan 2016).

3.3. Process heat: Temperature requirements

Gas is used for heat generation. Heat has different characteristics such as temperature, so that in energy system modelling, a company's gas load profile alone is not sufficient. The flow temperatures must also be taken into account in order to determine technically and economically suitable renewable heat generation technologies. The temperature requirements, particularly for process heat, are specific to each economic sector.

Ten studies were used to analyse the industry-specific temperature requirements for the process heat demand (Blesl 2014; Fleiter, Steinbach, and Ragwitz 2016; Frisch et al. 2013; Kemmler et al. 2017; Vannoni, Battisti, and Drigo 2008; Pehnt et al. 2010; Werner and Constantinescu 2006; Brückner et al. 2015; Lauterbach, Vajen, and Schmitt 2011; Schmitz and Linckh 2012). Firstly, the process temperature data and process heat quantities specified in the literature sources were assigned to the economic sector classification (WZ).

The final energy consumption for the provision of process heat in the studies examined is presented for each sector in absolute or relative values, which are categorised in individually defined temperature classes.

As an example, 66 % of the final energy consumption for process heat supply is used for process heat in the temperature range between 100 and 200 °C in the economic sector of the Manufacture of Paper and Paper Products (C17), according to (Fleiter, Steinbach, and Ragwitz 2016). The temperature classes vary depending on the literature source in terms of width and the selected temperature minima and maxima.

All final energy consumptions for the provision of process heat were converted into relative values for each temperature class, whereby the sum of the relative energy consumptions of all temperature classes of an economic sector per literature source is 100 %. The relative frequency density is determined by multiplying the relative energy consumption by the respective class width. The relative total frequency is obtained by adding up the relative frequencies per literature source and economic sector. These results are displayed graphically as histograms and sum functions in order to show the relative breakdown of final energy consumption in the provision of process heat depending on the process temperature for each economic sector.

The next step is to create separate temperature classes based on the flow temperatures of renewable heat generation technologies. This allows the suitability of the use of climate-neutral generation technologies to be derived and potential for the use of renewable energies in various sectors to be identified. The data from the literature sources are classified into these newly defined temperature classes for each economic sector. For this purpose, an arithmetic mean is formed from the relative frequencies of the literature sources for each temperature class. If the temperature class of a literature source is broader than the newly defined temperature classes, the relative frequency in the relevant new temperature classes is taken into account proportionally according to the class width. A separate weighting of the relative frequency is not possible, as no information is available on the distribution of final energy quantities in the temperature classes.

4. RESULTS

4.1. Electricity and gas load profiles

4.1.1. Evaluation of synthetic and real load profiles by economic sector

The following overview shows studies which are freely available that have developed electricity and gas load profiles for companies in the tertiary and industrial sector (Table 2).

TABLE 2

Overview of electricity and gas load profiles for the industry sector and trade, commerce and services sector from the literature SMEs: small and medium-sized enterprises; TCS: trade, commerce and services

[Number] Category Source	Resolution	Published load profiles	Methodological approach of the generated load profiles
[1] Meas_ (Seim et al. 2021b)	¼ hour	Electricity load profiles for 32 economic sectors	Regression method taking into account 1100 measured load profiles
[2] Prc+Meas_ (Böckmann et al. 2021; Seim et al. 2021a)	¼ hour	Electricity load profiles for 11 economic sectors	Bottom-up modelling taking into account attendance profiles, technology data, calendar data, weather data and application balances
[3] Meas_, SLP_ (Meinecke et al. 2021; Spalthoff et al. 2019)	¼ hour	Electricity load profiles for 7 commercial types	Comparison of real load profile data with standard electricity load profiles
[4] Meas_ (Huber et al. 2023)	¼ hour	Electricity load profiles for 11 sectors	28 measured load profiles
[5] Meas_ (Braeuer 2020)	¼ hour	Electricity load profiles for various SMEs	50 measured load profiles
[6] Prc_ (Sandhaas, Kim, and Hartmann 2022)	¼ hour	Electricity load profiles for 11 economic sectors	Modelling based on normalised daily load profiles for 8 electrical consumption applications (AGEB industry application balances), supplemented by industry-typical mechanical processes and fluctuation as a stochastic attribute
[7] SLP_ (BDEW 2017)	¼ hour	Electricity load profiles for 7 commercial types	BDEW standard load profiles for electricity, which were developed based on 1209 measured load profiles (617 of which were commercial)
[8] Meas_ (Jesper et al. 2021; Pag, Jesper, and Jordan 2021)	Daily profile	7 generic heat demand profiles for the industry and TCS sector	Clustering of 797 gas load profiles (> 1.5 GWh/a) into 7 generic heat demand profiles
[9] Meas_ (Pezzutto et al. 2019)	Hourly	Generic heat demand profiles for 5 energy-intensive industries	Combination of annual, seasonal, quarterly and monthly consumption data at a country level
[10] Prc_ (Sandhaas et al. 2022)	¼ hour	Heat demand profiles for 14 sectors (26 economic sectors)	Modelling based on normalised daily load profiles, supplemented by industry-typical heat requirements (space heating (depending on outdoor temperature), hot water, process heat) in accordance with the AGEB application balances for industry

TABLE 2

Overview of electricity and gas load profiles for the industry sector and trade, commerce and services sector from the literature SMEs: small and medium-sized enterprises; TCS: trade, commerce and services (continued)

[Number] Category Source	Resolution	Published load profiles	Methodological approach of the generated load profiles
[11] SLP_ (BDEW 2024)	Hourly	Gas load profiles for 11 commercial types	Standard gas load profiles: daily gas quantities determined using real, sporadically recorded consumption, day of the week, outside temperature and business type

It is clear from Table 2 that different methodological approaches were used to develop the synthetic load profiles. The methodological approaches can be summarised in the following overarching categories:

- **Analysis of measurement data (Meas_)**: Real data-based load profiles developed using datasets consisting of measured load profiles of companies and the evaluation of these using statistical methods. There are industry-specific profiles (Gotzens et al. 2020; Seim et al. 2021a; Seim et al. 2021b), also known as industry load profiles, and generic profiles (Jesper et al. 2021), which are assigned to industries with similar characteristics according to those characteristics.
- **Standard load profiles (SLP_)**: Load profiles that reflect the characteristic consumption patterns of different customer groups, such as households, agriculture and commerce (BDEW 2017, 2024). There is an explicit differentiation between winter, the transitional period and summer as well as working days and weekends. According to § 12 paragraph 1 of the Electricity Network Access Ordinance (StromNZV), electricity distribution network operators are required to use standard load profiles for electricity customers who do not have detailed load curve or meter-reading data, particularly for consumers without RLM or smart metering systems (Deutsche Bundesregierung 2005).
- **Process-based (Prc_)**: Load profiles derived based on industry or sector-typical processes. In addition to these end-user applications, attendance profiles, technology data, calendar data or weather data are often taken into account in load profile development (Sandhaas et al. 2022; Sandhaas, Kim, and Hartmann 2022).
- **Process-based, including comparison with measurement data (Prc+Meas_)**: Load profiles developed by combining the procedures in *Prz_* and *Meas_* (Böckmann et al. 2021).

The synthetic profiles of the studies are compared with each other, provided a synthetic profile is available for the same economic sector. Regarding the electricity segment, a comparison is possible for the economic sectors Manufacture of Food Products (C10), Retail Trade (G47) and Engineering Activities (M71). Concerning the gas segment, examples of profiles for the economic sectors Manufacture of Food Products (C10) and Manufacture of Non-metallic Mineral Products (C23) are considered below.

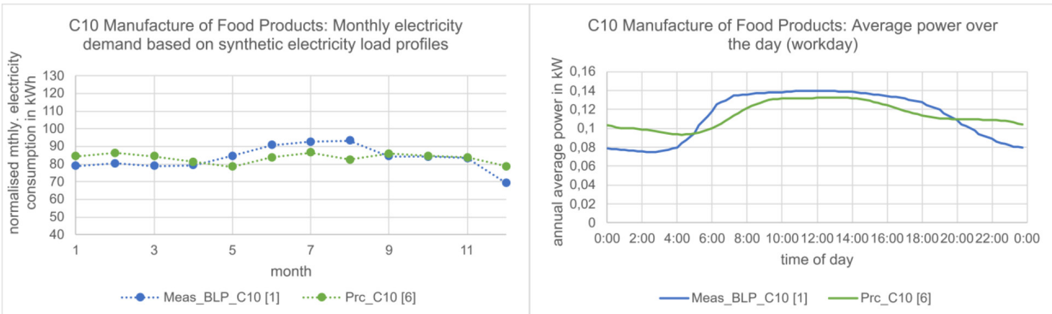
The studies by [1] (Seim et al. 2021b) and [6] (Sandhaas, Kim, and Hartmann 2022) each propose a synthetic electricity load profile for the sector C10 Manufacture of Food Products.

It can be seen in Figure 2 that the monthly electricity requirements are similarly mapped by both studies. The industry load profile (Meas_BLP_C10 [1]) in (Seim et al. 2021b), which is based on 241 measured datasets, shows a slight seasonality in electricity demand, meaning that the electricity demand is slightly higher in summer than winter, while the process-based profile (Prc_C10 [6]) in (Sandhaas, Kim, and Hartmann 2022) assumes a more even monthly electricity demand.

Overall, the maximum fluctuation in the monthly values of the process-based profile is about 9 % between the minimum and maximum monthly electricity demand and that of the industry load profile is about 26 %. The measurement-based electricity demand also shows greater differences (between day and night) than the process-based profile over the course of the day. The industry load profile shows a significant increase in electricity demand between 4 and 6 a.m. and a decrease in electricity demand between 6 and 10 p.m. on average over the course of the day. Electricity demand rises in the morning hours by around 30 % according to the process-based profile, while the industry load profile shows an increase of around 45 %.

FIGURE 2

Comparison of synthetic electricity load profiles – C10 Manufacture of Food Products
Underlying datasets of the real data-based profiles: Meas_BLP_C10: 241 electricity load profiles

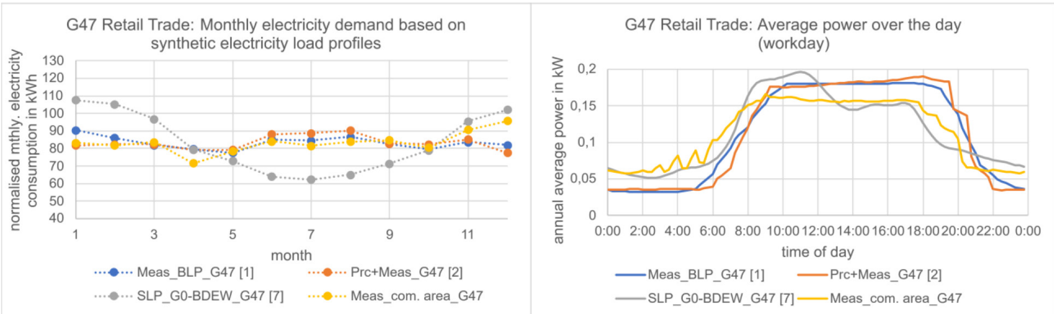


A synthetic profile is proposed for the industry sector G47 Retail Trade (excluding the motor vehicle trade) in the studies by [1] (Seim et al. 2021b), [2] (Seim et al. 2021a) and [7] (BDEW 2017) (Figure 3). The standard load profile in (SLP_G0-BDEW [7]) (BDEW 2017) shows a pronounced seasonality in electricity demand with a fluctuation between minimum and maximum monthly electricity demand of about 42 %, while the industry load profile in (Meas_BLP_G47 [1]) (Seim et al. 2021b) and the process and measurement data-based profile in (Prc+Meas_G47 [2]) (Seim et al. 2021a) show a more even monthly electricity demand with a maximum fluctuation of about 14 % each. Their similar progression is also due to the fact that both profiles are based on the same dataset with 125 measured load profiles. The average electricity demand for all three profiles over the course of the day is significantly higher than at night. Regarding the industry load profile in (Meas_BLP_G47 [1]) (Seim et al. 2021b) and the process and measurement data-based profile in (Prc+Meas_G47 [2]) (Seim et al. 2021a), the electricity demand remains at a constant level after a significant increase between 6 and 8 a.m. and falls again just as significantly between 6 and 10 p.m. By contrast, the standard load profile in (SLP_G0-BDEW [7]) (BDEW 2017) shows a drop in the electricity demand towards midday, which then falls more gently towards the evening.

A real profile (Meas_com. area_G47) from the commercial area under consideration can also be specified for the G47 Retail Trade sector. The profile is a weighted average of four electricity load profiles from four different companies and is standardised to 1,000 kWh/a. The monthly electricity consumption is similar to the industry load profile in (Meas_BLP_G47 [1]) (Seim et al. 2021b) and the process and measurement data-based profile in (Prc+Meas_G47 [2]) (Seim et al. 2021a), with a fluctuation between the minimum and maximum monthly electricity demand of about 25 %. Notably, the increased electricity consumption in December results in a closer approximation to the standard load profile in (SLP_G0-BDEW [7]) (BDEW 2017).

FIGURE 3

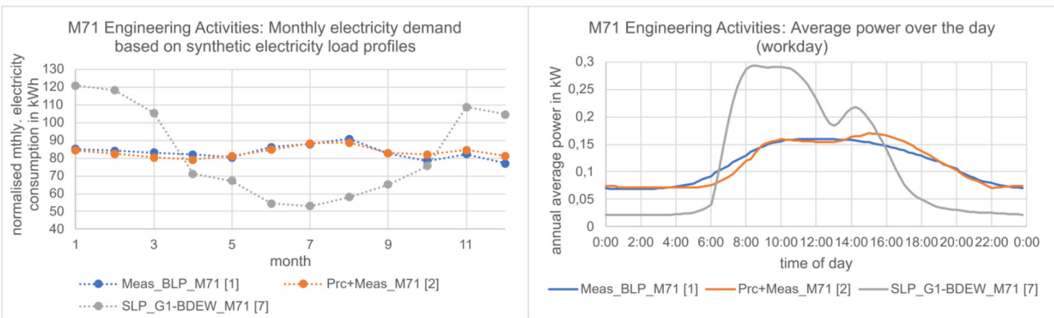
Comparison of synthetic electricity load profiles - G47 Retail Trade.
Underlying datasets of the real data-based profiles: Meas_ BLP_G47: 125 electricity load profiles; Prz+Mess_G47: the same dataset as Mess_BLP_G47; Meas_com. area_G47: 4 electricity load profiles



A synthetic profile is also proposed for the M71 Architectural and Engineering Activities sector in the studies [1] (Seim et al. 2021b), [2] (Seim et al. 2021a) and [7] (BDEW 2017) (Figure 4). Here, the development of the monthly electricity demand over the year is similar to the profiles from the respective Retail Trade studies (G47). The standard load profile in (SLP_G1-BDEW [7]) (BDEW 2017) shows a pronounced seasonality with low electricity demand in the summer, whereas both the industry load profile in (Meas_BLP_M71 [1]) (Seim et al. 2021b) and the process and measurement data-based profile in (Prc+Meas_M71 [2]) (Seim et al. 2021a) behave oppositely, with only a very slight increase in the summer. Their similar

FIGURE 4

Comparison of synthetic electricity load profiles - M71 Engineering Activities.
Underlying datasets of the real data-based profiles: Mess_BLP_M71: 13 electricity load profiles for office operations in general; Prz+Mess_M71: the same dataset as Mess_BLP_M71



progression is due to the fact that both profiles are based on the same dataset with 13 measured load profiles. The average power over the course of the day differs the most between the studies. (Seim et al. 2021b) (Meas_BLP_M71 [1]) and (Seim et al. 2021a) (Prc+Meas_M71 [2]) show a similar average daily curve. The standard load profile shows a significantly higher power requirement in the morning and another small peak in the afternoon.

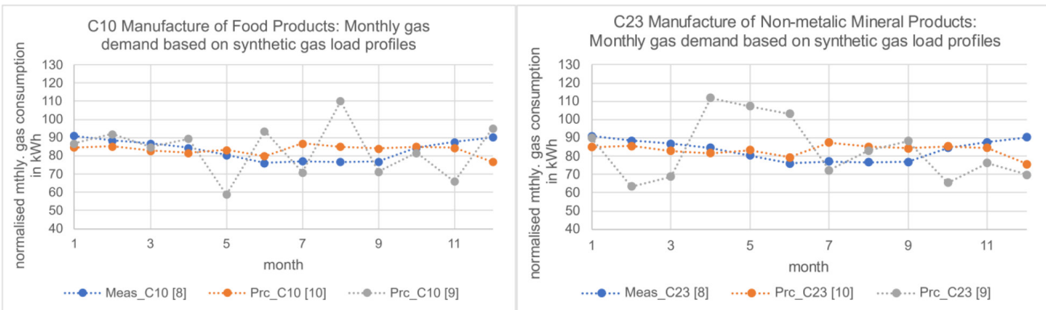
Synthetic gas load profiles are proposed in the studies [8] (Jesper et al. 2021), [10] (Sandhaas et al. 2022) and [9] (Pezzutto et al. 2019) for the economic sector C10 Manufacture of Food Products and for the economic sector C23 Manufacture of Non-metallic Mineral Products. A similar picture emerges for both economic sectors (Figure 5). There are slight deviations between the monthly gas requirements of the generic load profiles in (Meas_ [8]) (Jesper et al. 2021) and the process-based load profiles in (Prc_ [10]) (Sandhaas et al. 2022). Furthermore, there is no seasonality in the gas demand over the year. The deviation in December is notable, as the generic profile increases slightly compared to November, while the process-based profile decreases slightly. Only (Prc_ [9]) (Pezzutto et al. 2019) deviates significantly from the other profiles. No systematic deviation is recognisable here. The daily average power curve cannot be formed for the gas load profiles, as the profiles in [8] (Jesper et al. 2021) are given in daily resolution.

FIGURE 5

Comparison of synthetic gas load profiles – C10 and C23

Underlying datasets of the real data-based profiles:

Meas_C10: 19 gas load profiles, Meas_C23: 6 gas load profiles



The exemplary comparison of synthetic profiles with each other (gray and orange curves), thus, shows that there are sometimes considerable deviations in both the monthly and daily energy consumption curves. By contrast, the synthetic electricity profiles from [1], [2] and [6] (Seim et al. 2021b; Seim et al. 2021a; Sandhaas, Kim, and Hartmann 2022) and the synthetic gas profiles from [8] and [10] (Jesper et al. 2021; Sandhaas et al. 2022) are more similar to each other, despite the authors' different data collection methods (Meas_, Prc_, Meas+Prc_, respectively). The process-based methodology in studies [6] and [10] (Sandhaas, Kim, and Hartmann 2022; Sandhaas et al. 2022) provides more uniform load profiles with no pronounced seasonality at the monthly aggregation level. The similarity between Meas_BLP [1] (Seim et al. 2021b) and Prc+Meas [2] (Seim et al. 2021a) is also due to the fact that the same measurement datasets were used.

A crucial aspect in selecting suitable load profiles is the consideration of heterogeneity within the different economic sectors. In the case of economic sector C10, Manufacture of Food Products, specific factors, such as refrigeration requirements, shift systems or continuous processes, can be a reason for the differences in the synthetic profiles. Seasonal fluctuations, for example, in electricity consumption by companies with high cooling requirements may be the cause. Similar considerations apply to economic sector G47, Retail Trade. This sector is also heterogeneous in terms of its energy requirements. One example of this is that the Retail Trade sector includes both the non-food and food subsectors (e.g. supermarkets). There are cooling requirements in the food sector that generate different consumption patterns than in the non-food sector. Here, the demand for cooling can be a cause for the different seasonality of the synthetic profiles in electricity demand. The daily profiles also vary depending on shift systems and office hours. On the other hand, electricity demand in the M71 sector, Architecture and Engineering activities, is strongly influenced by office hours and the associated attendance times, which is reflected in the daily power peaks. The table below provides an initial overview of possible influencing factors that can lead to differences in the daily or monthly profiles within the individual economic sectors.

TABLE 3
Factors influencing the electricity profiles of economic sectors

Factors influencing daily profiles	Factors influencing seasonality (monthly profiles)
• Office hours or attendance • Shift systems (number of shifts and their periods) • Type of processes (continuous or discontinuous operation)	• Heating requirement • Refrigeration/cooling requirement • Seasonal production

Due to the influencing factors, it remains unclear which load profile is representative of a specific economic sector. Therefore, it is crucial to consider influencing factors such as shift systems, cooling demands and the nature of the processes (continuous or discontinuous operation) of individual companies. A significant challenge is recognising the heterogeneity of economic sectors and the manifestation of key influencing factors. Due to the pronounced heterogeneity within some economic sectors, synthetic load profiles only approximate real consumption patterns, but these can be improved by considering the specific circumstances of individual companies. Economic sectors with less heterogeneity in influencing factors tend to be more suitable for the use of synthetic load profiles.

The overview in Table 2 also shows that none of the studies fully represents all economic sectors. Therefore, when simulating the real load profiles using synthetic profiles, different studies were combined. The following table shows the basis on which the synthetic profiles are created for the companies in the commercial area under consideration.

The coefficient of determination R^2 and the MAPE are calculated for each economic sector by varying the resolution of the profiles. The results from the comparison of the electricity profiles can be found in Table 5. The comparison of the synthetic profiles from the literature with the real profiles of companies from different economic sectors in the commercial area shows that there are large deviations.

Irrespective of the temporal resolution, the coefficient of determination is predominantly so low ($R^2 \leq 0.5$) that no satisfactory estimation is possible using the synthetic load profile for each economic sector. Only the comparison of synthetic annual duration curves with real annual duration curves per economic sector results in an R^2 above 0.8 for 70 % of the electricity and gas annual duration curves and, thus, an acceptable prediction. The formation of

TABLE 4
Breakdown of the synthetic profiles used per economic sector

Economic Sector		Synthetic profile: source, methodology, data basis
Manufacturing	C10	[1], Meas_BLP, 241 datasets
	C25	[1], Meas_BLP, 4 datasets
	C28	[1], Meas_BLP, 15 datasets
	C32	[1], Meas_BLP, 4 datasets
Construction	F41	[1], Meas_BLP, 4 datasets
	F43	[7], SLP
Retail Trade; Repair of Motor Vehicles and Motorcycles	G45	[7], SLP
	G46	[7], Meas_BLP, 10 datasets
	G47	[7], Meas_BLP, 125 datasets
Transportation and Storage	H53	[7], SLP
Accommodation and Food Service Activities	I56	[7], SLP
Engineering Activities	M71	[1], Meas_BLP, 13 datasets (for offices in general)
Arts, Entertainment, Recreation	R93	[1], Meas_BLP, 8 datasets

the MAPE shows that the resolution of the profile influences the average difference between the predicted and the real value. The average deviation decreases with decreasing temporal resolution, so that weekly and monthly profiles can be predicted at least acceptably. The economic sectors C10 Manufacture of Food Products, G47 Retail Trade and M71 Architectural and Engineering activities deserve special mention. Using the real data-based load profiles in (Meas_BLP [1]) (Seim et al. 2021b), the average percentage deviation in monthly electricity consumption is 10 % for C10, between 5 and 22 % for G47, and 9 % for M71. This corresponds to a good to acceptable accuracy of these sector load profiles for mapping the real electricity consumption of the three economic sectors. The MAPE of 189 % for F41 Building Construction is striking, which means that the sector load profile used deviates significantly from the real profile. One explanation for this deviation is that the dataset on the basis of which the sector load profile was determined only contains 4 profiles (Gotzens et al. 2020; Seim et al. 2021b).

4.1.2. Superposition of synthetic load profiles: Evaluation of the load profile of the entire commercial area

Electricity and gas consumption are added together to form an area consumption for electricity and one for gas. In the commercial area under consideration, 84 % of the electricity consumption and 94 % of the gas consumption is recorded continuously by means of RLM. The remaining 16 % of electricity consumption, which is not continuously measured, is synthetically simulated using the synthetic load profile models from [1], [2] and [7] (Seim et al. 2021b; Seim et al. 2021a; Böckmann et al. 2021; BDEW 2017). The entire synthetic electricity area load curve is also derived from these models (Seim et al. 2021b; Seim et al. 2021a; Böckmann et al. 2021; BDEW 2017). The unmeasured 6 % of gas consumption and the synthetic gas area load profile are based the synthetic load profile models from [10] and [11] (Sandhaas et al. 2022; BDEW 2024).

TABLE 5
Assessment of the forecast quality of the synthetic electricity load profiles for economic sectors of the commercial area

		R^2				
Economic Sector		¼ h profile	Daytime (6 h interval)	Calendar week	Month	Duration curve
Manufacturing	C32	0.35	0.33	0.08	0.26	0.95
	C28	0.19	0.22	0.08	0.06	0.84
	C25	0.21	0.11	0.12	0.07	0.54
	C25	0.23	0.12	0.13	0.17	0.64
	C10	0.06	0.05	0.00	0.08	0.70
Construction	F41	0.01	0.00	0.03	0.05	0.87
	F43	0.63	0.33	0.02	0.37	0.99
	F43	0.52	0.26	0.14	0.49	0.94
Retail Trade; Repair of Motor Vehicles and Motorcycles	G45	0.29	0.18	0.01	0.13	0.96
	G46	0.03	0.05	0.00	0.02	0.13
	G47	0.18	0.46	0.00	0.06	0.92
	G47	0.36	0.64	0.06	0.12	0.96
	G47	0.34	0.63	0.04	0.32	0.79
	G47	0.22	0.43	0.04	0.05	0.81
	G46	0.11	0.23	0.03	0.03	0.34
Transportation and Storage	H53	0.03	0.00	0.16	0.40	0.93
Accommodation and Food Service Activities	I56	0.33	0.00	0.46	0.73	0.94
Engineering Activities	M71	0.34	0.50	0.00	0.00	0.95
Arts, Entertainment, Recreation	R93	0.35	0.21	0.54	0.85	0.98

TABLE 5
Assessment of the forecast quality of the synthetic electricity load profiles for economic sectors of the commercial area (continued)

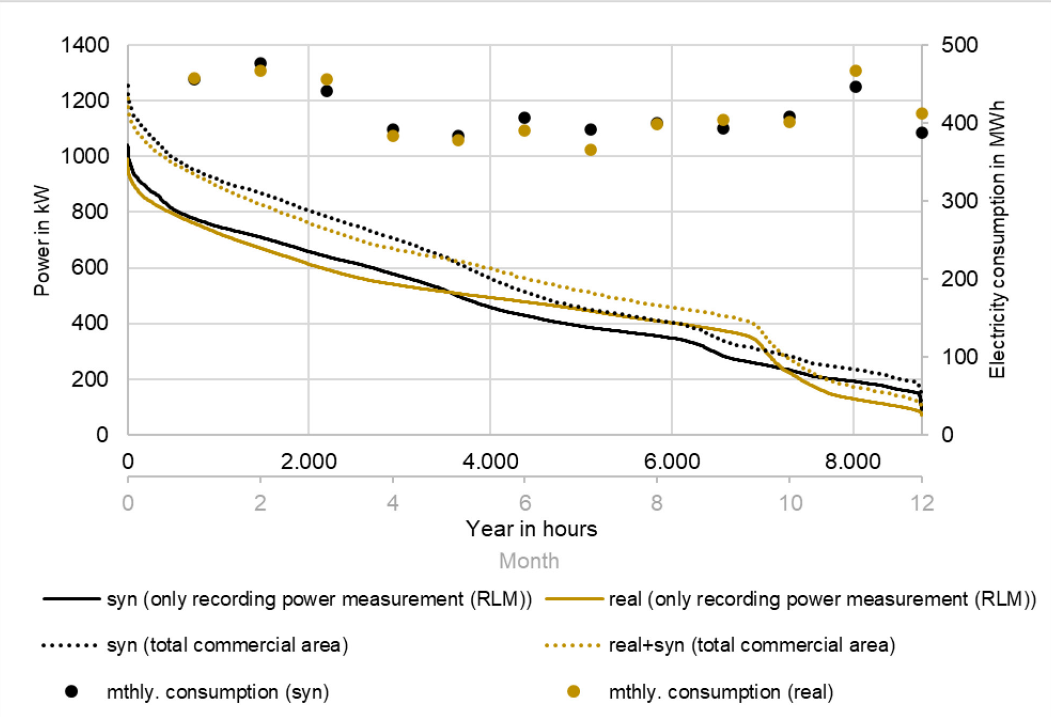
		MAPE				
Economic Sector		1 h profile	Daytime (6 h interval)	Calendar week	Month	Duration curve
Manufacturing	C32	45 %	59 %	28 %	23 %	18 %
	C28	58 %	133 %	42 %	34 %	63 %
	C25	507 %	15604 %	41 %	30 %	8469 %
	C25			28 %	27 %	
	C10	92 %	107 %	11 %	10 %	52 %
Construction	F41	44 %	505 %	113 %	189 %	352 %
	F43	115 %	128 %	30 %	21 %	23 %
	F43		709 %	26 %	19 %	
Retail Trade; Repair of Motor Vehicles and Motorcycles	G45	70 %	96 %	20 %	15 %	54 %
	G46	62 %	357 %	52 %	46 %	222 %
	G47	55 %	41 %	9 %	10 %	40 %
	G47	91 %	83 %	10 %	9 %	66 %
	G47	576 %	409 %	11 %	5 %	479 %
	G47	60 %	50 %	16 %	22 %	26 %
	G46		145 %	24 %	13 %	
Transportation and Storage	H53	187 %	127 %	17 %	15 %	77 %
Accommodation and Food Service Activities	I56	43 %	32 %	31 %	35 %	13 %
Engineering Activities	M71		35 %	8 %	9 %	
Arts, Entertainment, Recreation	R93		109%	24 %	14 %	

Figure 6 and Figure 7 show the total area consumption for electricity and gas as annual duration curves and the monthly cumulative consumption. In addition, the total electricity and gas consumption of all RLM customers in the commercial area is shown.

As the area consumption of electricity and gas is not recorded continuously in full, both the real annual duration curves and the real monthly cumulative consumption for the entire commercial area each contain a synthetic share. By contrast, the annual duration curves for the consumption of RLM customers only contain real consumption data. In addition, the monthly cumulative consumption as well as the total area consumption and the consumption of the RLM customers were determined using the synthetic load profiles, as shown in Figure 6 and Figure 7.

FIGURE 6

Real and synthetically estimated annual duration curves of a commercial area for electricity as an energy source as well as monthly cumulative real and synthetically estimated electricity consumption

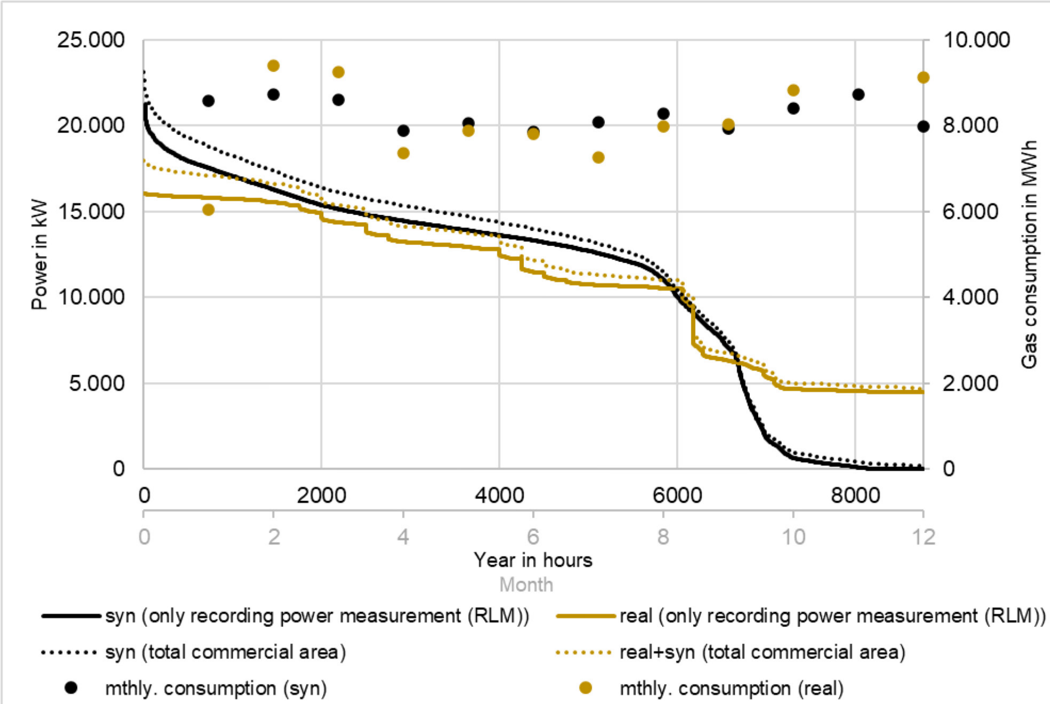


The annual duration curves for the entire area are higher than those for RLM customers, because more companies are taken into account. This is also reflected in the higher peak loads, in both the synthetic and in the mixed (real and synthetic) profiles. The relevant influencing factors were taken into account when selecting the synthetic profiles for companies without RLM data. However, it is not possible to verify with certainty how well the non-continuously measured consumption is reproduced by the synthetic load profiles.

It is clear from Figure 7 that the superposed synthetic profiles do not replicate the characteristics of the real base load. This base load in the gas demand of the commercial area results primarily from the process heat demand of economic sector C, which dominates gas consumption in the area. These specific characteristics of the load profiles cannot be fully covered

FIGURE 7

Real and synthetically estimated annual duration curves of a commercial area for the energy source gas as well as monthly cumulative real and synthetically estimated gas consumption



by the synthetic models. This example illustrates that more information about the respective companies is required than just the absolute annual energy consumption and the affiliation to an economic sector in order to precisely simulate individual load profiles. Depending on the dominance of an economic sector in the total energy consumption of a commercial area, this has a considerable influence on the estimation of the load profile for the entire area.

Table 6 shows the results of the analysis of the forecast quality for the area profiles as a function of the time resolution. The comparison between the synthetic and real area annual duration curves results in an R^2 of 0.96 for electricity and 0.95 for gas. The coefficient of determination decreases as the profile resolution is varied. Higher coefficients of determination are achieved for the electricity area profile than for the gas area profile. The exclusive consideration of the RLM shows similar results.

The greatest difference between electricity and gas can be seen in the monthly resolution, as the electricity area profile with an R^2 of 0.82 is predicted with sufficient accuracy by the synthetic load profiles, while the gas area profile with an R^2 of 0.07 cannot be predicted by the synthetic load profiles. By contrast, the MAPE shows that the average deviation between the real and synthetic area profile and the RLM sum profile at monthly resolution for electricity and gas is < 10 %, which can be interpreted as a high level of accuracy. Figure 7 shows that the average percentage deviation in monthly gas consumption of 9 % is caused particularly by the deviations in the winter months. Good forecasting accuracy can also be seen in the weekly resolution for electricity and gas consumption and the RLM sum profile (electricity and gas). The real gas area profiles and the RLM sum profiles are not sufficiently represented by the

TABLE 6
Evaluation of the forecast quality of the synthetic electricity and gas load profiles for the commercial area

	Annual duration curve	¼ h or 1 h profile	Daytime (6 h interval)	Calendar week	Month
	Electricity profile (total commercial area)				
MAPE	12 %	45 %	42 %	5 %	3 %
R^2	0.96	0.40	0.39	0.64	0.82
	Electricity profile (only recording power measurement)				
MAPE	15 %	70 %	46 %	7 %	4 %
R^2	0.95	0.22	0.35	0.31	0.62
	Gas profile (total commercial area)				
MAPE	26 %	223 %	200 %	11 %	9 %
R^2	0.95	0.15	0.17	0.15	0.07
	Gas profile (only recording power measurement)				
MAPE	28 %	3429 %	5322 %	12 %	10 %
R^2	0.95	0.14	0.16	0.08	0.02

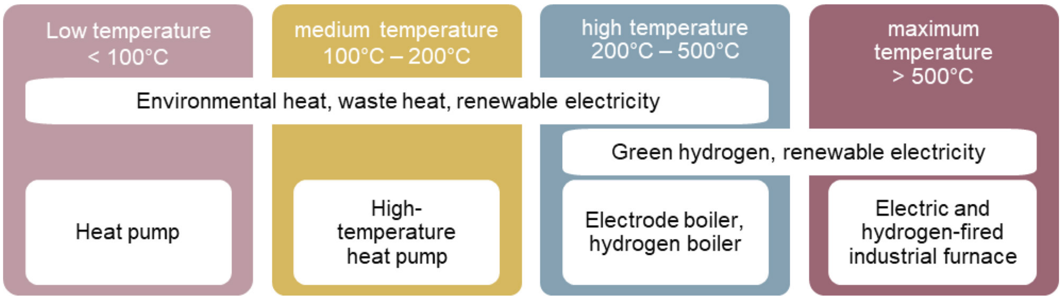
TABLE 7
Technology overview by temperature level

Technology	Temperature range	Data basis of the study
Solar heat and heat pump Biomass and electrification via heating elements, hydrogen, electrode boilers and heat pump Fuel-powered boilers, such as hydrogen boiler and electric furnace	< 100 °C 100 – 500 °C > 500 °C	Fraunhofer ISE: Analysis of the development of the German energy system with the goal of climate neutrality by 2050, model calculations using the energy system model REMod (Sterchele et al. 2020)
Solar heat and heat pump Heat pump Hydrogen, electrode boiler Hydrogen	< 100 °C 100 – 200 °C 100 – 500 °C > 500 °C	Agora Energiewende: Evaluation of heat generation technologies for different temperature levels based on their efficiency (ratio between electricity input and heat output) (Agora Industrie and FutureCamp 2022)
Conventional heat pump High-temperature heat pump Maximum temperature heat pump Electrode boiler Electrode boiler with superheater Hydrogen boiler Electrification (various electrical and electrothermal processes)	< 80 °C 80 – 100 °C 90 – 165 °C 100 – 350 °C 100 – 500 °C 100 – 400 °C > 1000 °C	German Federal Environment Agency: Investigation of 13 sectors and 34 exemplary applications in the metal and mineral industry as well as in the cross-sectional technology of steam generation to identify heat generation technologies that are suitable for CO_2-neutral heat supply from a technical, economic and ecological point of view (Fleiter et al. 2023)

Source: Our own representation based on (Sterchele et al. 2020), (Agora Industrie and FutureCamp 2022) and (Fleiter et al. 2023)

FIGURE 8

Requirements for process heat: temperature classes, energy sources and technologies



synthetic gas profiles (MAPE > 100 %) for the resolution by time of day and the resolution by hour. It can be seen for the electricity area profiles and the RLM sum profiles (electricity) that the synthetic electricity profiles have an acceptable accuracy at a ¼-hourly and 6-hourly resolution (MAPE < 50 %).

In summary, the results of this analysis should be limited to the specific conditions of the economic area under consideration and generalisations should be treated with caution.

4.2. Temperature levels of heat supply with renewable energies

4.2.1. Technologies for heat generation

The choice of heat supply technology in the future will depend largely on the temperature level of the industrial process required. Three studies, (Sterchele et al. 2020), (Agora Industrie and FutureCamp 2022) and (Fleiter et al. 2023), were considered which present heat supply technologies for different process temperatures (Table 7). The results are summarised in Figure 8.

Based on this, the temperature classes are selected for the following analyses in such a way that technological trends for climate-neutral heat generation are taken into account. The temperature ranges reflect the technology application potential, in that the temperature classes are based on the maximum heat generation temperature of the technologies.

Heat pumps and waste heat recovery are suitable in the low temperature range (< 100 °C), high-temperature heat pumps are recommended in the medium range (100 – 200 °C) and electric boilers in the high temperature range (200 – 500 °C). The use of hydrogen is economical in some applications. Fuel-based technologies, such as green hydrogen, offer potential above 500 °C. Figure 8 summarises the breakdown of the temperature levels of process heat into temperature classes and shows which technologies and energy sources are suitable in these classes:

4.2.2. Usual temperature levels of the economic sectors

The heat consumption is derived from the gas consumption, whereby the temperature level is decisive for the use of climate-friendly technologies. The process heat demand is particularly high in the economic sector C Manufacture, often exceeding the requirements for space heating. Based on a literature analysis, the sector-specific process temperature of the process heat demand was determined and evaluated. The results are presented as normalised frequency

FIGURE 9
Frequency distribution of temperature requirements using the example of C10 - Manufacture of Food Products

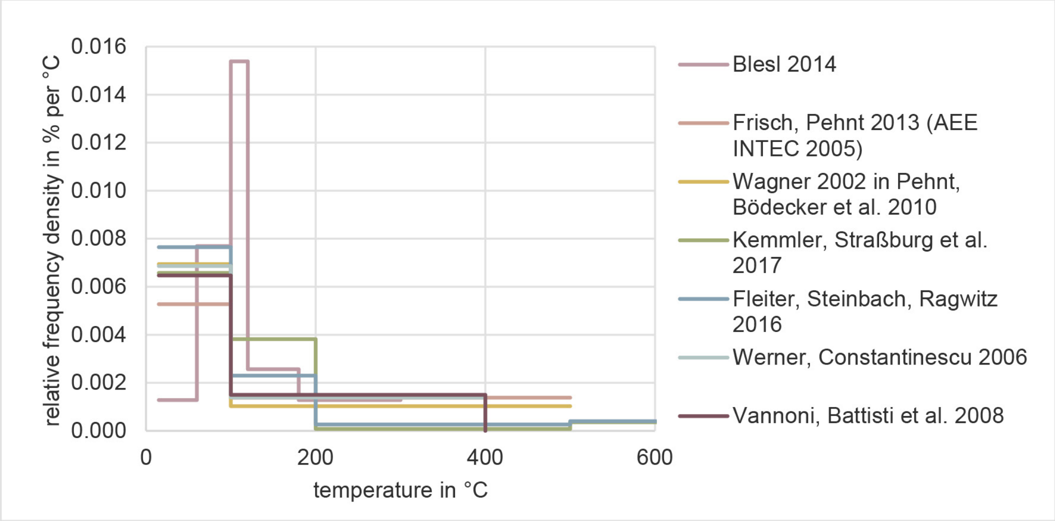
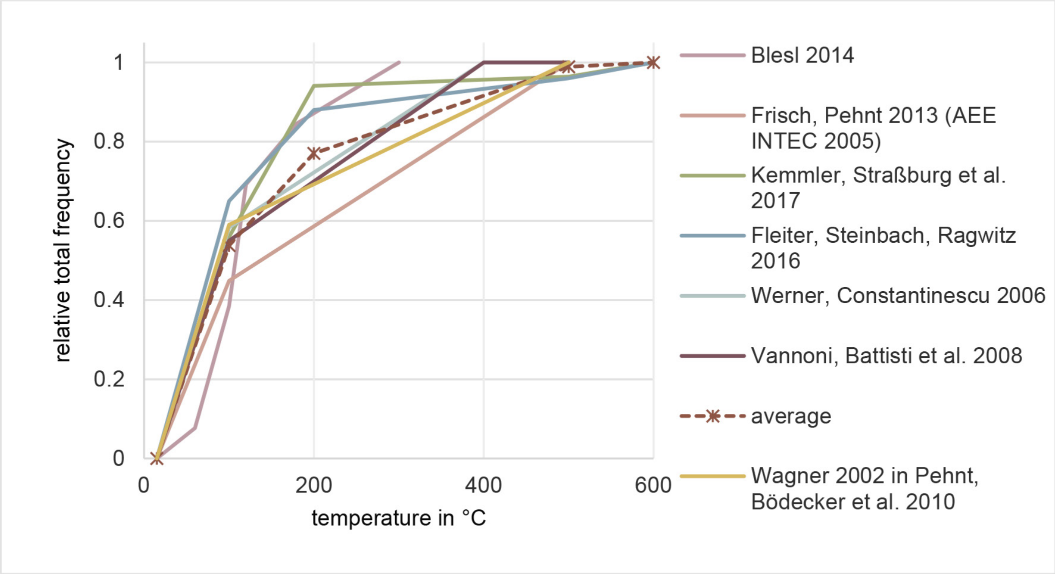


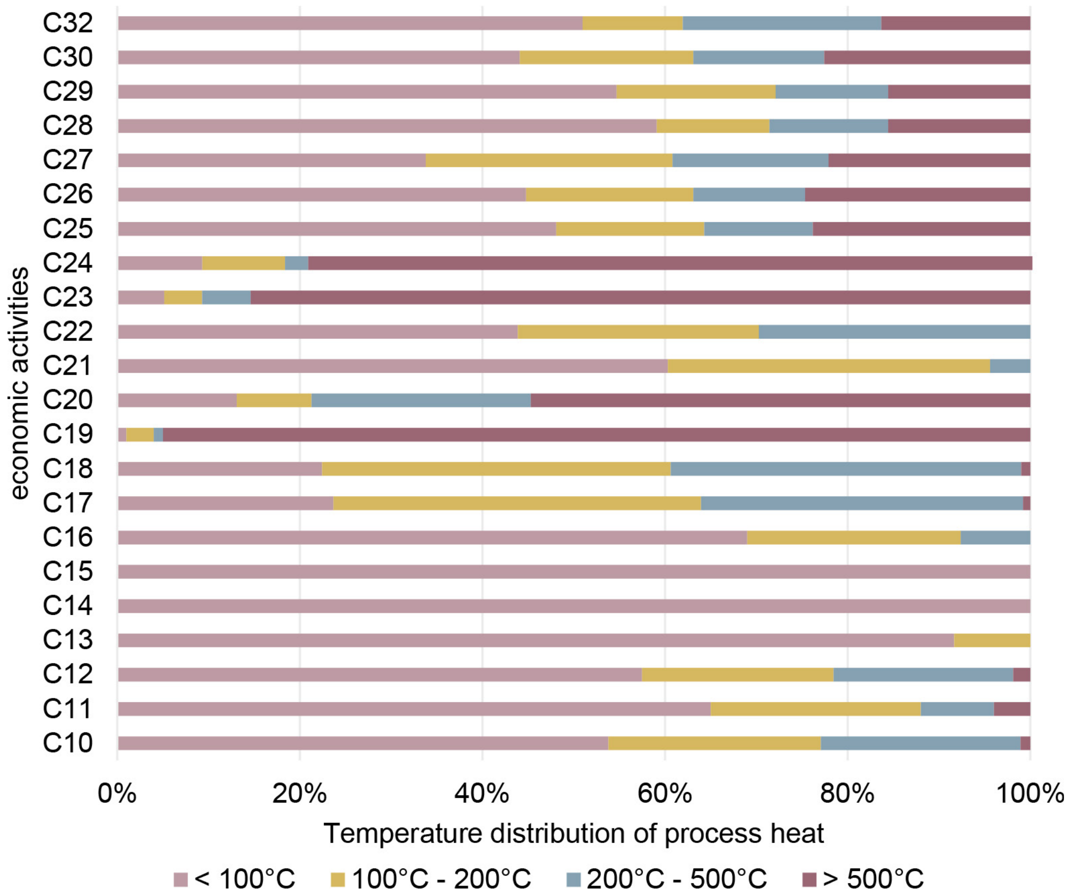
FIGURE 10
Cumulative curve of the temperature requirement using the example of C10 - Manufacture of Food Products



distributions (percentage of heat demand per °C) and as an integral of the heat demand over the process temperature for the various economic sectors.

Figure 9 shows an example of the frequency distribution determined from seven different studies for the economic sector Manufacture of Food Products (C10). Figure 10 shows the cumulative curves derived from this and an averaged cumulative curve that shows the relative breakdown of the average heat demand by temperature level. The data basis for the studies comes from the statistical surveys AGEB (Blesl 2014), IEA (Vannoni, Battisti, and Drigo

FIGURE 11
Typical temperature levels of process heat in economic sector Manufacture (C)



2008) and AGFW (Werner and Constantinescu 2006), as well as the energy balance of BMWi (Frisch et al. 2013).

It can be seen that just under 80 % of final energy consumption in the provision of process heat is at temperatures below 200 °C. Almost 55 % of this is below 100 °C. Accordingly, conventional heat pump technologies for generating process heat in economic sector C10 Manufacture of Food Products are well-suited to providing a large proportion of the process heat required.

Figure 11 shows the resulting average relative temperature distribution of process heat for the economic sector C Manufacture. This temperature distribution is used as the basis for the energy system modelling in order to substitute the known gas consumption of the companies with suitable energy sources.

Temperatures below 200 °C predominate. About 48 % of the process heat demand has temperature requirements below 100 °C. Heat supply technologies such as conventional heat pumps and high-temperature heat pumps in combination with environmental and waste heat as well as renewable electricity are suitable for providing process heat in a climate-neutral way in the future if the process temperature requirements are taken into account exclusively.

The economic sectors, particularly of *Manufacture of coke and refined petroleum products* (C19), *Manufacture of chemicals and chemical products* (C20), *Manufacture of non-metallic mineral products* (C23) and *Manufacture of basic metals* (C24) are characterised by process heat requirements at temperatures above 200 °C, with temperatures above 500 °C dominating. In the future, electric hydrogen boilers and electrified or hydrogen-based industrial furnaces could be the heat generation technologies for climate-neutral process heat, provided that renewable electricity or green hydrogen is used.

5. CONCLUSION AND OUTLOOK

Synthetic load profiles for electricity and gas were identified from the literature and compared in this analysis. The profiles were compared with measured data of load profiles of companies in a commercial area in Germany with a gas consumption of 100 GWh/a. In addition, temperature levels were defined to enable a more detailed analysis of the heating requirements of companies in different economic sectors.

The comparison of synthetic profiles of an economic sector shows differences in the course of the day and seasonality depending on their underlying datasets and data collection methods. One approach to explaining the deviations within an economic sector are influencing factors, such as shift systems in production, energy requirements of the production processes or heating/cooling requirements, which cause different load profiles of individual companies within this sector.

The comparison of synthetic profiles from the literature with the real profiles of the companies in various industry sectors within the commercial area shows that these profiles exhibit significant deviations from the measurements. Therefore, as expected, the synthetic profiles are not directly usable to predict profiles of individual companies. However, it must be noted, that the comparison of synthetic with real profiles was based on a very small dataset of real data. A possible explanation for the deviations is that industry sectors have heterogeneous energy requirements, and synthetic profiles cannot capture this heterogeneity. Additionally, the dataset of real data used does not adequately reflect the heterogeneity of energy demand within the individual economic sectors. It is, therefore, to be expected that sectors that tend to have particularly heterogeneous requirements have influenced the assessment of the forecast quality. Synthetic load profiles are only an approximation of real consumption patterns, which can be improved by considering the specific circumstances of individual companies. Economic sectors with less heterogeneity in influencing factors tend to be more suitable for the use of synthetic load profiles. In principle, it should be noted that a synthetic load profile cannot be used to infer the load profiles of individual companies with sufficient accuracy.

The energy consumption of a commercial area was simulated by superposition of the synthetic individual profiles. On an aggregated level, from a weekly basis, acceptable matches are obtained (electricity MAPE = 5 %, gas MAPE = 10 %), which improve further on a monthly basis (electricity MAPE = 3 %, gas MAPE = 9 %). Annual duration curves offer the most precise matches when both indicators MAPE and R^2 (MAPE: electricity 12 %/gas 26 %; R^2: electricity 0.96/gas 0.95) are considered in combination. Superposed load profiles can be useful for large commercial areas if many different companies are represented and the temporal resolution is sufficiently low. Validation using other commercial areas is still pending.

In addition, temperature levels were determined to identify applicable technologies, that are able to provide temperatures at the same level without burning gas and without causing CO_2 emissions. Temperature classes were formed based on the heat provision temperatures of innovative heat producers (particularly heat pumps). The meta-studies consulted show consensus in the assessment of heat generation for specific temperature levels in German industry. Typical temperature distributions for each economic sector were determined by superposition of process temperature distributions. No weighting of the underlying temperature distributions was applied, which does not rule out the possibility of result distortion. An additional aspect for future investigations is the influence of seasons on the typical temperature distributions determined. A weighting is required here in order to take appropriate account of seasonal fluctuations.

The results of this analysis underscore that synthetic consumption profiles play an important role in compensating for missing data, even though they cannot accurately represent the real energy needs of individual companies. The temporal simultaneity of heat demands and waste heat potentials of neighboring companies is crucial, particularly when analysing decarbonisation strategies, such as the formation of energy communities. This requires the detailed mapping of load profiles on an hourly, daily and weekly basis, as annual load duration curves alone have too little explanatory power to adequately assess the potential of energy communities. However, a high temporal resolution is a weakness of synthetic load profiles, because their agreement with real profiles decreases as the temporal resolution increases.

The industry-specific temperature requirements, together with the consumption profiles, form the basis for modelling local energy communities for decarbonisation. Further investigation is necessary to evaluate the impact of synthetic load profiles on energy system models, particularly regarding decarbonisation strategies for commercial areas.

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