Generation of Industrial Electricity and Heat Demand Profiles for Energy System Analysis

by

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Abstract

To achieve Germany's climate targets, the industrial sector, among others, must be transformed. The decarbonization of industry through the electrification of heating processes is a promising option. In order to investigate this transformation in energy system models, high-resolution temporal demand profiles of the heat and electricity applications for different industries are required. This paper presents a method for generating synthetic electricity and heat load profiles for 14 industry types. Using this methodology, annual profiles with a 15-minute resolution can be generated for both energy demands. First, daily profiles for the electricity demand were generated for 4 different production days. These daily profiles are additionally subdivided into eight end-use application categories. Finally, white noise is applied to the profile of the mechanical drives. The heat profile is similar to the electrical but is subdivided into four temperature ranges and the two applications hot water and space heating. The space heating application is additionally adjusted to the average monthly outdoor temperature. Both time series were generated for the analysis of an electrification of industrial heat application in energy system modelling.

1 Introduction

Today, the industrial sector accounts for 42 % of primary energy consumption and is responsible for energy-related greenhouse gas emissions of around 19 % [1]. For many industrial companies, the question arises as to how their energy supply and emissions can be reconciled in the medium and long term with the decarbonization targets up to 2045 [2] and to what extent sector coupling measures, including in particular electrification measures for the use of renewable electricity, can be realized today and in the future. Energy-intensive as well as heat-intensive processes are still mainly supplied with fossil fuels today [3]. In the IND-E project, the very heterogeneous conditions of individual industrial sectors with exemplary different energy demands are to be examined for their electrification potential and processed for energy system analysis. Specifically, high-resolution time series for the industrial energy demand are to be supplied for this purpose. This task is particularly challenging because although industrial companies continuously measure their energy consumption, this data is usually not publicly available for data protection reasons. In this conference paper, a methodology is presented for modeling electricity and heat demand profiles (15 min interval for one year) for 14 different industry types covering the entire German industrial sector. This methodology combines data from different sources, including the analysis of real electricity load data within the project and profiles from other models and making assumptions where data are not available.

2 Methodology

Electrical and thermal heat load profiles were generated for different industry branches. For this work, the entire German industry was divided into 14 industry types (Table 1). This classification is in line with the AGEB[1]. The corresponding code of the German classification WZ08 [4] is given in the second column of Table 1.

Table 1: The 14 types of industry synthetic energy demand profiles are generated for.

Number	WZ08 Code	Name of Industry Type
1	8	Extraction of stones and earths
2	10, 11, 12	Food and tobacco
3	17	Paper industry
4	20.1	Basic chemicals
5	20, 21 without 20.1	Other chemical industry
6	22	Rubber and plastic products

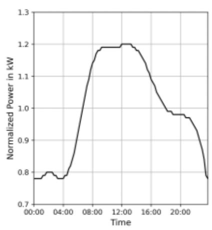
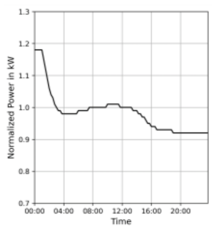
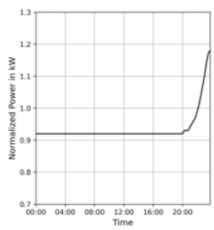
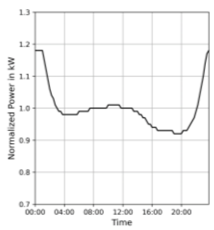
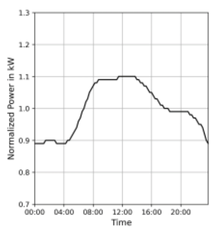
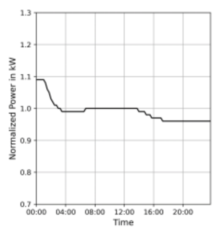
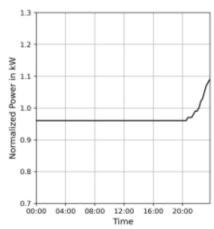
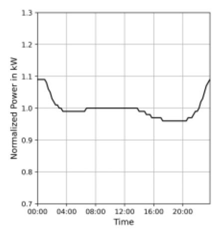
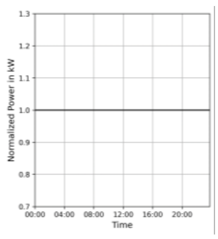
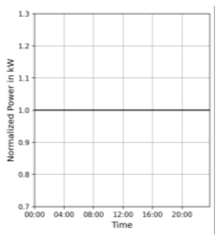
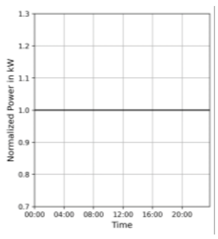
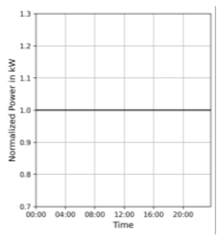
[1] Arbeitsgemeinschaft Energiebilanzen (AGEB) - An association mainly concerned with the scientific evaluation of statistics relating to the energy industry. As part of its activities, it publishes the annual energy balances for Germany.

7	23.1, 23.2, 23.3	Glass and ceramics
8	23 without 23.1, 23.2, 23.3	Processing of stones and earths
9	24.1	Metal production
10	24.4, 24.5	Non-ferrous metals and foundries
11	24.2, 24.3, 25	Metalworking
12	28	Machinery
13	29, 30	Vehicle construction
14	13, 14, 15, 16, 18, 26, 27, 31, 32, 33	Other industries

2.1 Generation of Electrical Load Profiles

All electrically operated devices in industrial plants can be classified to one of the eight following end-use applications: process heat, mechanical drive, space heating, hot water, space cooling, lighting, ICT and process cooling. It is assumed that the basic profile of the end-use applications is the same for each industry type. Therefore, each of these categories was first assigned to one of three normalized daily load profiles for production day "weekday" (Table 2).

Table 2: Normalized daily profiles for the eight end-use applications for four different production days.

End-use applications	**Weekday**	**Saturday**	**Sunday**	**Holiday**
• Process heat • Mechanical drive				
• Space heating • Hot water • Space cooling • Lighting • ICT				
• Process cooling				

Building on our published method for the generation of electricity load profiles for a working day [5], this article includes additional end-use application profiles for three other types of production days "Saturday, "Sunday", and "holiday". These additional profiles were adapted from the “Weekend” profiles of the EPRI load shape library [6]. All profiles are given as time series with 15 min intervals and normalized to a daily average consumption of 1. Table 2 shows the course of the three profiles respectively for the four different days and the assignment of the eight end-use applications. In addition to the energy balances, AGEB publishes the annual shares of the eight end-use applications per industry type, which are shown in Figure 1.

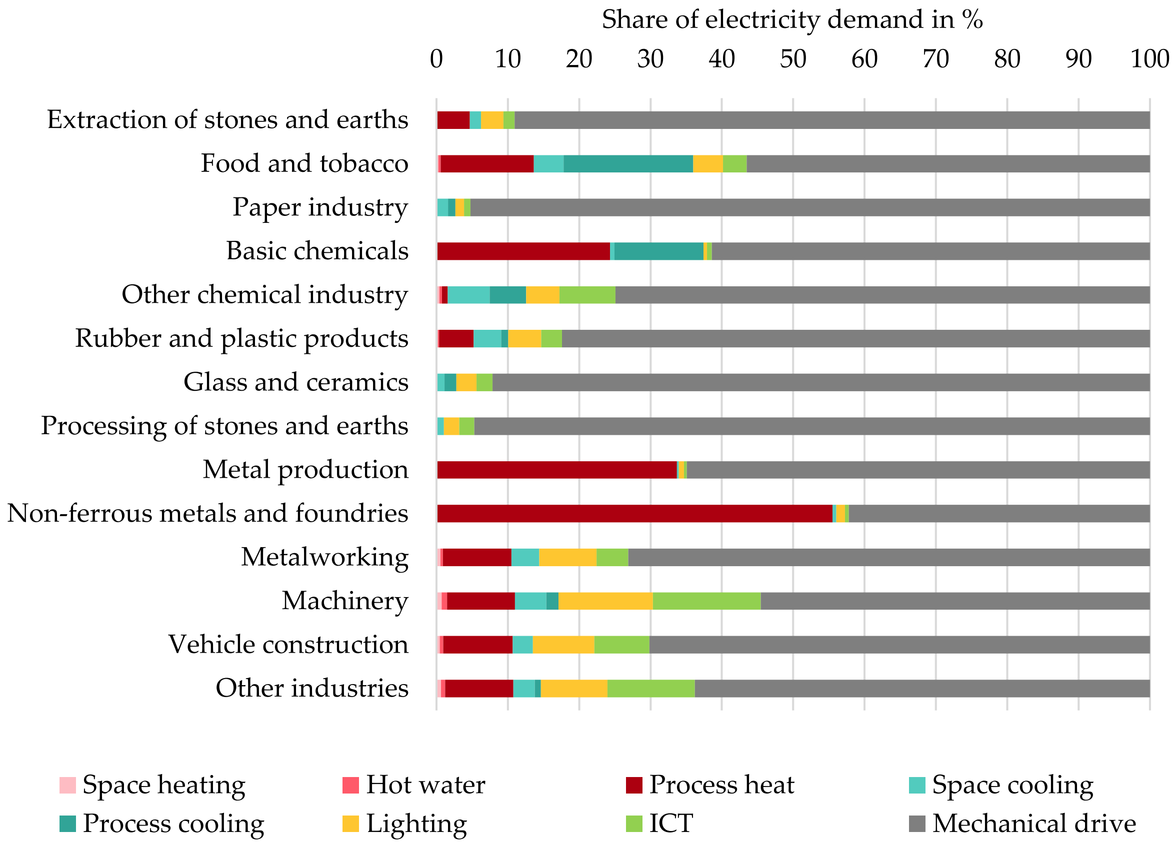


Figure 1: Distribution of yearly electricity demand per industry type and end-use application [7].

In order to model the daily profiles for one industry type, first, the time series of the end-use application profiles (Table 2) are each multiplied with the percentage of the respective application (Figure 1). The eight resulting profiles are stacked on top of each other to form the overall profile, which is automatically normalized to an average value of 100. The unit kW is added. This procedure is performed successively for the four production days. Figure 2 shows the profiles of the exemplary industry type machinery.

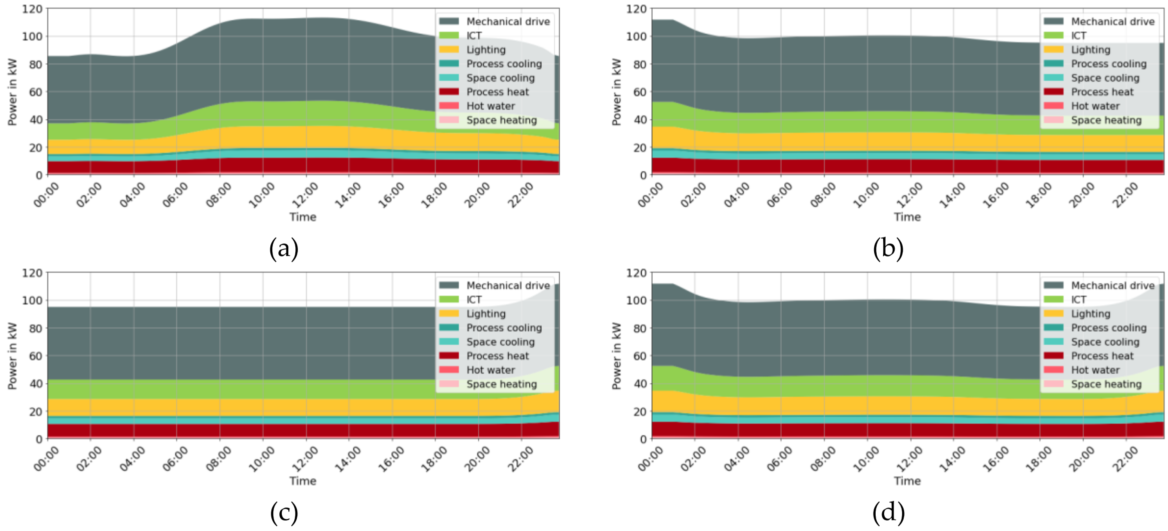


Figure 2: Normalized electrical daily load profiles for the industry type machinery for different production days: (a) Weekday, (b) Saturday, (c) Sunday and (d) holiday.

The resulting load profile for a working day (weekday) in Figure 2a) shows a ratio of 1.32 between peak and base level. The analysis of real load data, however, shows that plants whose main processes are shut down overnight have a much higher gap between these two levels. For this reason, 30 existing real load data out of eleven industry types were analyzed. First the weekly profiles of one year are normalized to an average consumption of 100 kW, in order to protect the confidentiality of the case, and the profile is smoothed according to [5] (frac=1). Figure 3 shows the weekly electricity load of a machinery company for one year. $\overline{p_{day}}$ is the median of the maximum values and $\overline{b_{night}}$ the median of all minimum values of the five weekly working days. $\overline{b_{weekend}}$ is the median of the minimum values of the 52 weekends.

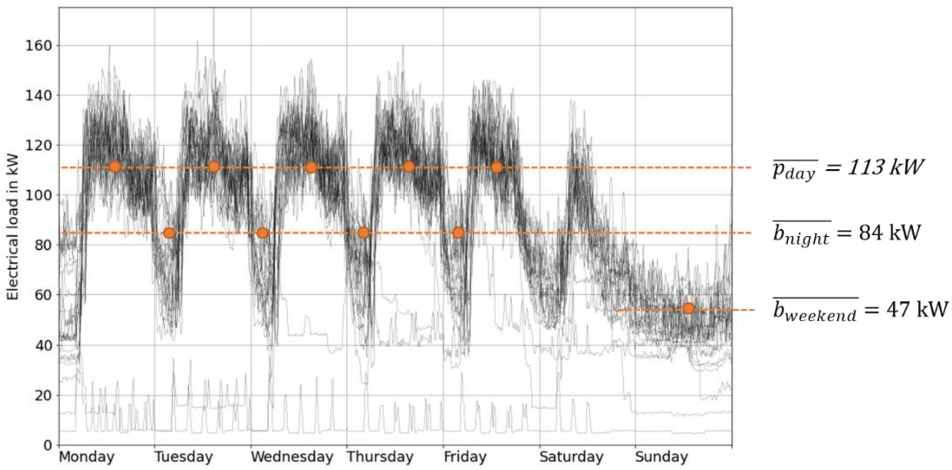


Figure 3: Weekly electricity load of a machinery company for one year.

Then the factors f_{peak} between peak load p_{day} and base load at night b_{night} on the one hand and f_{base} between base load at night b_{night} and base load at the weekend $b_{weekend}$ on the other hand were calculated according to Equations (1) and (2):

$$f_{peak} = \frac{\overline{p_{day}}}{\overline{b_{night}}} \tag{1}$$

$$f_{base} = \frac{\overline{b_{night}}}{\overline{b_{weekend}}} \tag{2}$$

These two factors were used to stretch or compress the normalized profiles in the vertical direction (Figure 4). The peak factor f_{peak} is used to adjust the weekday profile. The base factor f_{base} is used to adjust the Saturday, Sunday and holiday profiles. Finally, they-axis is rescaled respectively, so starting point (value at 0 a.m.) for weekday, Saturday and holiday and end point for the Sunday profile (values at 12 p.m.) are fixed to b_{night} = 100 kW. In this way, smooth transitions between different profiles at midnight are achieved when they are composed to represent a longer period of time.

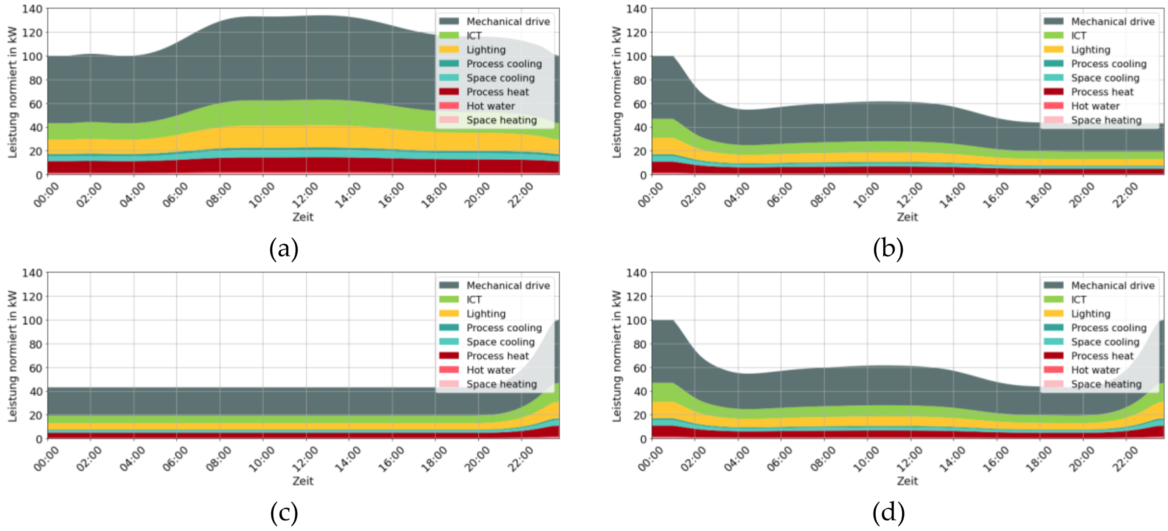


Figure 4: Normalized electrical daily load profiles for the industry type machinery for different days: (a) Weekday, (b) Saturday, (c) Sunday and (d) holiday. The profiles were adjusted vertically using stretch factors determined from real data.

For the assembling of the profiles to any calendar year, first, each day of this year is identified as working day, Saturday, Sunday, bank holiday or bridging day. Then each day is assigned to one of the four profiles according to the following conditions:

- Profile weekday: working days, which are no holidays or bridging days
- Profile Saturday: Saturdays or the first day of a multi-day production break
- Profile Sunday: Sundays or the last day of a multi-day production break
- Profile holiday: bank holidays that fall on a Wednesday (if a bank holiday falls on a Tuesday or Thursday, the previous Monday respectively the following Friday is a bridging day)
- For a period of multi-day holiday, the days within (except first and last) have a constant demand at the value of $b_{weekend} = \frac{100\ kW}{f_{base}}$.

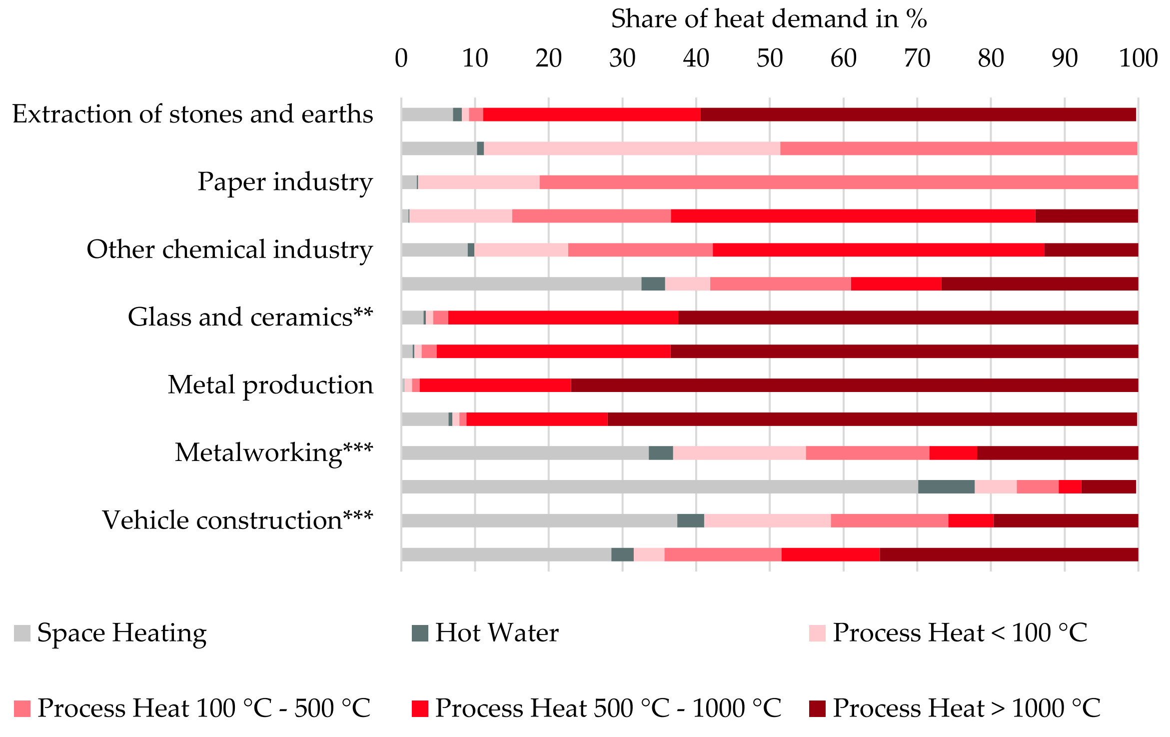
Then, the 365 profiles are put together in the correct order to form an annual profile, which results in a time series with 15-minute resolution. As the total consumption will always be different for different years, the generated annual profile is scaled to a total consumption of 1000 MWh.

In the last step, a fluctuation is imposed on the profile, as real electricity demands are rarely smooth, but fluctuate strongly as can be seen in Figure 3. The fluctuation rates for the individual industry types were first calculated from the 30 real loads (see annex Table 3) and imposed on the end-use application mechanical drives as white noise according to our recently published method [5].

2.2 Generation of Heat Load Profiles

In order to generate heat load profiles, unfortunately, no real load data is available, nor could any information on the profile of heat demand be found in the literature. For this reason, it was assumed that the temporal profile of the process heat applications and the electricity applications depends mainly on the production schedule (e.g. the shift schedule) and that both these time series have similar daily profiles [8, 9]. Therefore, for the presentation of the heat demand, the overall profile of the electrical (the smooth profile before the application of the fluctuation) was assumed as a basis.

Similar to the electrical profile, the thermal profile is also divided into application areas. The thermal applications in industry can be roughly divided into the three end-use applications space heating, hot water and process heat. For these three, the percentage distribution was taken from [7]. Since process heat has the highest energy demand, it is further divided into four temperature ranges: < 100 °C, 100 °C - 500 °C, 500 °C - 1000 °C and > 1000 °C according to Naegler et al. [10]. Naegler's cluster of industries is slightly different from ours or AGEB's. For industry types for which there is no data, the process heat distribution was taken from the one industry type that most resembles it. The final shares are shown in Figure 5.



** Process heat shares same as Other industries. ** Process heat shares same as Extraction of stones and earths. *** Process heat shares same as machinery.*

Figure 5: Percentage distribution of process heat for the fourteen industry types.

Using these shares, the total annual profile was divided evenly into the different categories. Compared to the other heat end uses, space heating is highly dependent on the outdoor temperature. For this purpose, monthly factors f_i for the months i (i = 1,…,12) are first calculated, which result from the difference between the target room temperature of 20 °C and the average monthly temperature T_i of the last ten years [11] in Germany (see annex Table 4) and are scaled to an average of 1 according to Equation (3).

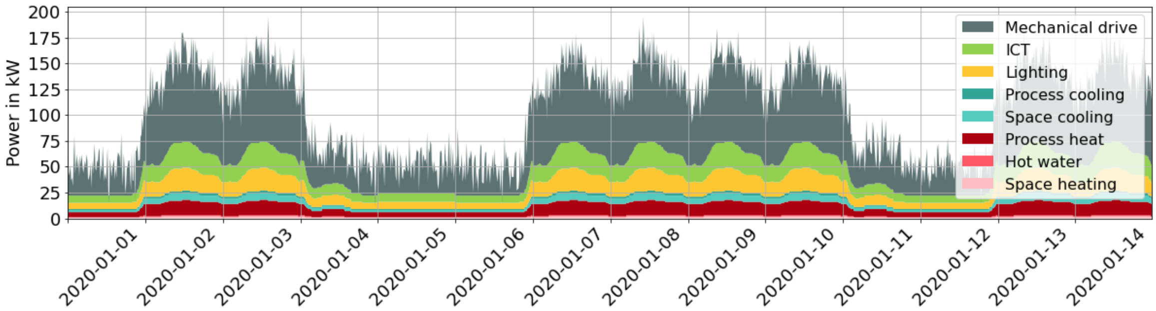
$$f_i = \frac{T_i - 20\,°C}{\frac{1}{12}\sum_{i=1}^{12}(T_i - 20\,°C)} \tag{3}$$

The space heating load of each day is multiplied by the corresponding monthly factor. Since each month has a different number of days, working days and holidays, the annual space heating load must then be adjusted to the previous consumption.

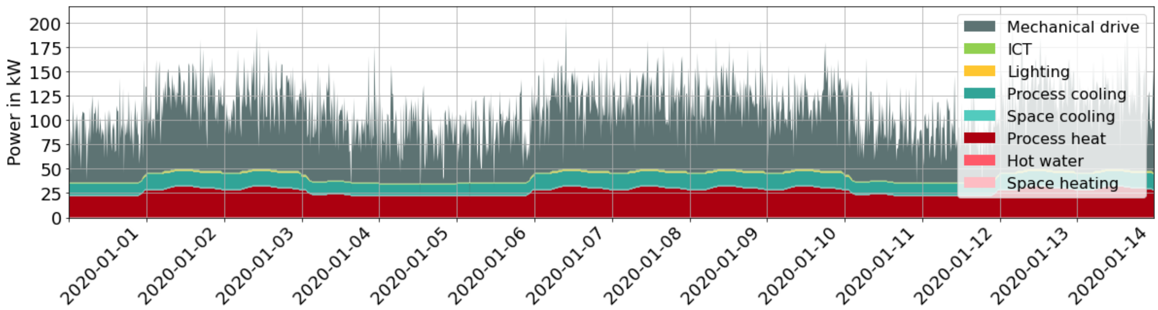
3 Results and Discussion

3.1 Synthetic Electricity Demand Profiles for Different Industry Types

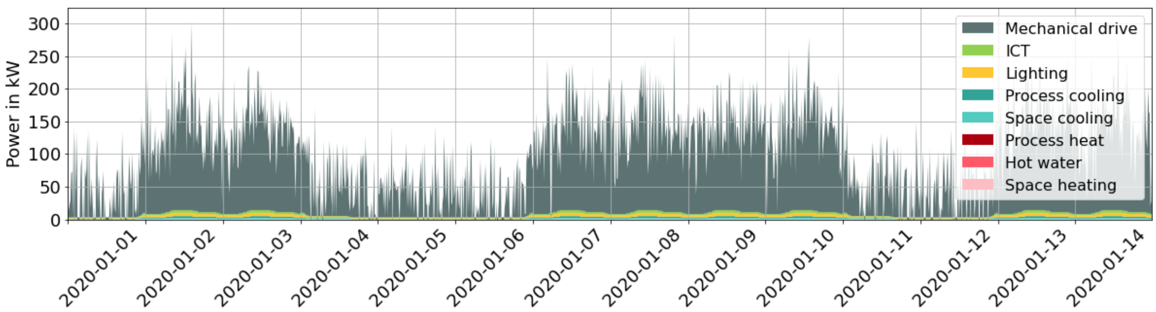
Figure 6 shows the synthetic electricity load profiles exemplary for the industry type machinery, basic chemicals and glass and ceramics. The first two weeks of the year 2020 are plotted for each case. As the profiles are divided into the different application categories, it is possible to see at a glance for which application the electricity is used in the respective industry. These three industries have different baseline and peak levels and a white noise different in heights was applied on the electricity demand of the mechanical drive.



(a)



(b)

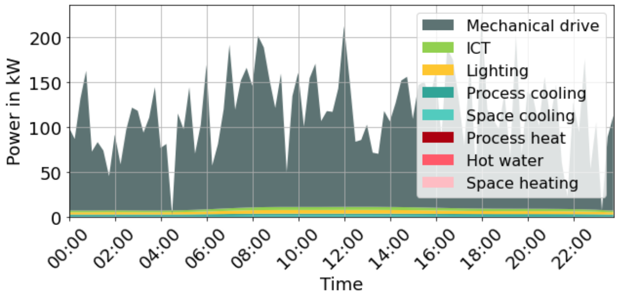


(c)

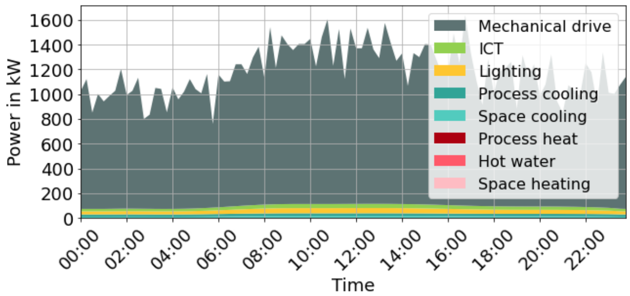
Figure 6: Synthetic load profile for industry type (a) machinery, (b) basic chemicals and (c) glass and ceramics.

The height of the fluctuation has a non-linear relationship to the amount of power consumption. If electricity consumption increases by a factor of 2, the relative fluctuation level grows by the square root of 2. This means that large industries or regions have a smoother demand profile compared to small ones, which is taken into account by our model.

Figure 7 shows a weekday profile for the glass and ceramics industry for different quantities of electricity demand. The relative smoothing at higher power consumption levels can be seen clearly. A major advantage of mapping fluctuations using random numbers is that, each time the demand of the same type of industry is modeled, a different profile is created and thus a stochastic component is included in the modeling and, on the other hand, when an aggregated electricity demand of a region is generated, in which the individual profiles of different industrial sectors are summed up, smoothing is automatically performed.



(a)



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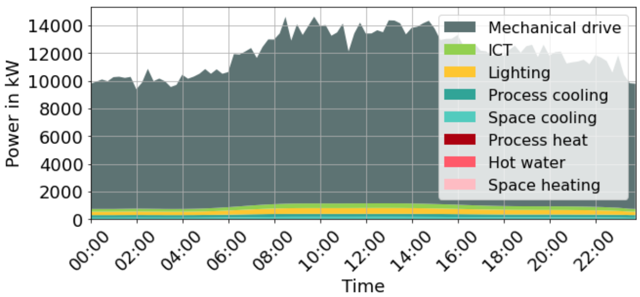
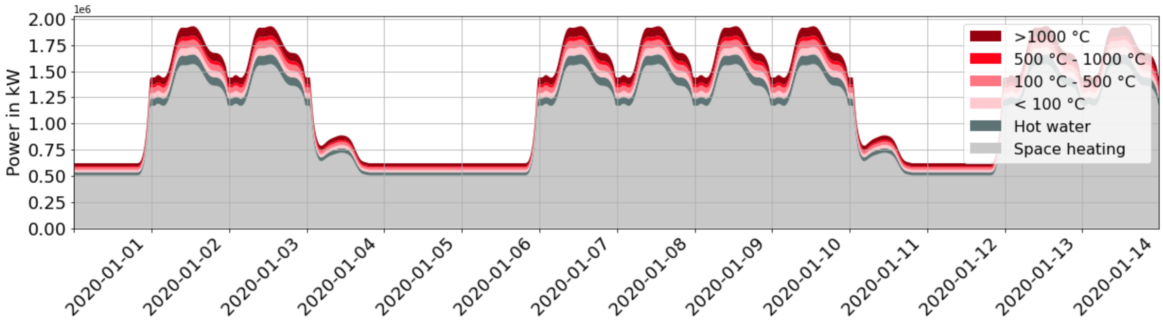


(c)

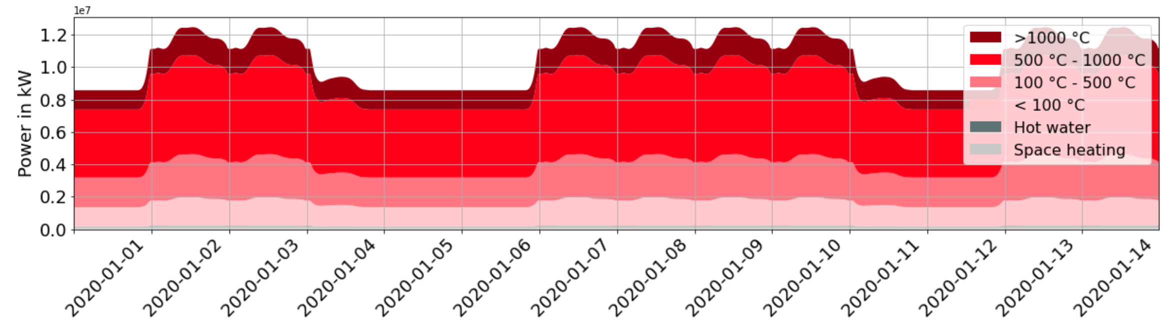
Figure 7: Synthetic load profiles for industry type Glass and Ceramics with (a) the single, (b) the tenfold and (c) the hundredfold power consumption.

3.2 Synthetic Thermal Demand Profiles for Different Industry Types

Figure 8 shows the synthetic heat load profiles exemplary for the industry types machinery, basic chemicals and glass and ceramics. The first two weeks of the year 2020 are plotted in each case. The profile is identical to the smooth electrical profile. Like the electrical profiles, the division into heat applications makes it clear what the heat energy is used for.



(a)



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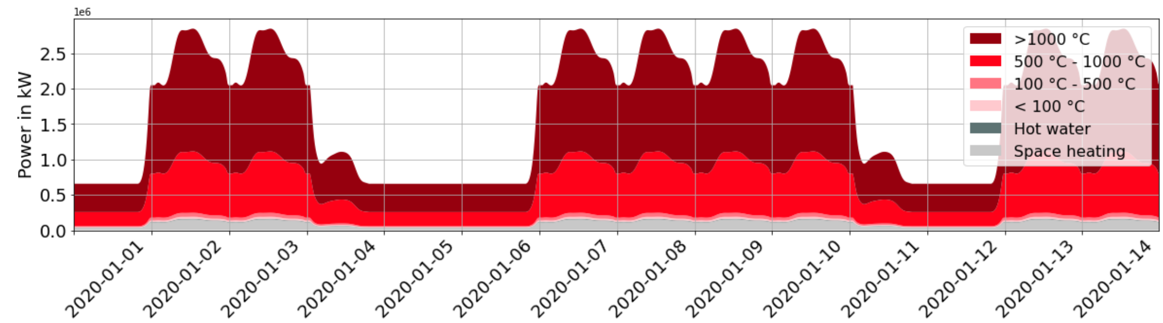

(c)

Figure 8: Synthetic load profiles for industry type (a) machinery, (b) basic chemicals and (c) glass and ceramics.

Since the space heat for each month was scaled based on the average temperature, the overall profile changes accordingly along with it. In Figure 9, four weekday profiles of the four seasons for the machinery sector are plotted for comparison purposes. In the cold months of February (a) and November (d), obviously more energy is needed for space heating than in August (c).

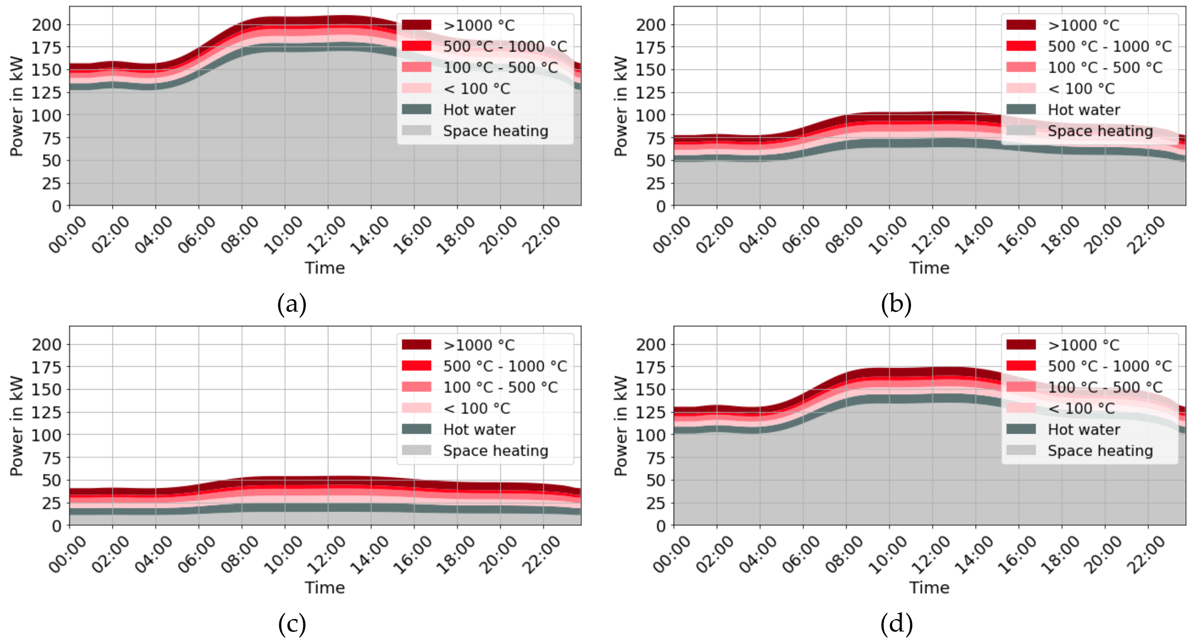

Figure 9: Synthetic heat load profiles for industry type machinery for (a) February, (b) May, (c) August and (d) November.

3.3 Benefits and Limits of the Methodology

The modeling of the synthetic load profiles for electricity and heat was successfully completed despite difficult data conditions. Both time series for electricity and heat were generated for the analysis of an electrification of industrial heat application in energy system modeling. In the generation of both profiles, in addition to the time series for total demand, the individual time series for the end-use applications are also generated. Therefore, if in one scenario a thermal application within one temperature range is electrified, its share can be transferred from the heat profile to the process heat application of the electricity profile.

The applied fluctuation made the electrical profiles more realistic, and short-time flexibility modeling could be realized in an energy system analysis [5]. Two major advantages of mapping fluctuations using random values are, first, that each time the demand of the same industry is modeled, a different profile emerges and thus a stochastic component is included in the modeling, and second, that when an aggregate electricity demand of a region is created by summing the individual profiles of different industries, smoothing is automatically performed.

One drawback is that the method cannot be validated with real data for the simple reason that there is no freely available load data and few project internal data have been included in the modeling itself. For some industries only one load curve was available and for three none at all. If no additional real data is available in the future, the profiles could be supplemented by the typical shift times practiced per industry type. Some load generators already use this top-down approach [8, 12]. However, for a better statistical evaluation and to validate the results, it would be helpful if industrial companies published their energy data anonymously in the future.

The method is written in python and available open source.

4 Annex

Table 3: Fluctuation heights for the different industry types

Industry Types	Fluctuation Height in %
Extraction of stones and earths	19*
Food and tobacco	32
Paper industry	28
Basic chemicals	21
Other Chemical industry	15
Rubber and plastic products	16
Glass and Ceramics	35
Processing of stones and earths	34
Metal production	19*
Non-ferrous metals and foundries	18
Metalworking	14
Machinery	11
Vehicle construction	20
Other industries	19*

* *For these industry, no real load data was available. The 19 % fluctuation height is the average from all 30 electrical loads.*

Table 4: Average temperature of the last ten years in Germany and calculated monthly factor for the modeling of the space heat profiles.

Month i	**Average Temperature T_i of last ten years (2011-2020) of Germany** in °C	**Monthly Factors f_i (normalized to average of 1)** -
January	1.41	1.82
February	1.60	1.80
March	4.95	1.47
April	9.50	1.03
May	13.10	0.68
June	16.87	0.31
July	18.50	0.15
August	18.44	0.15
September	14.36	0.55
October	10.04	0.98
November	5.40	1.43
December	3.38	1.63

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Data Availability Statement: The model can be accessed under https://github.com/asandhaa/ElectricalAndHeatProfiles (accessed on 6 July 2022).

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Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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