Analysis of heating load diversity and application in a district heating system

Claudia Weissmann[1], Patrick Wörner[1], Tianzhen Hong[2]
[1]Institute of Concrete and Masonry Structures, Technische Universität Darmstadt, Darmstadt, Germany
[2]Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, Berkeley CA, United States

Abstract

In Germany, district heating systems for the heat supply of residential districts have become more important in recent years. Still, their efficiency and costs heavily depend on the installed capacity of the central plant, which is designed to be capable of covering the district's maximum requested heating load at any time. A high diversity of energy demand profiles in the district may balance the impact of individual peak loads and consequently lower the installed capacity. That is why *load diversity* has already been the focus of previous studies, particularly regarding the electricity demand. However, the influence of single building and occupant related characteristics on diversity respectively the residential district's overall heat demand profile has not been under further investigation.

In order to measure diversity, this paper introduces a *peak load ratio (PLR)* index that gives the percentage reduction in the district's peak load compared to the aggregated peak loads of all individual buildings. Based on a definition of building and occupant related boundary conditions, 144 distinct load profiles are created using IDA ICE, a dynamic building simulation software. After that, the PLR index is employed on a fictional test district consisting of these profiles. The example shows that especially after adding buildings with a different occupant behavior the PLR goes up to 15%.

In the second part of this paper, the results of the PLR analysis are applied to a district heating simulation model in order to trade off the described benefit of reduced installed capacities against the practical disadvantage of heat distribution losses. Likewise, the influence of load density and the district's building profile is analyzed. The outcomes show that most notably districts with high load density including buildings constructed according to the latest building energy standards have the potential to take the advantage of load diversity.

Introduction

In a conventional energy system, residential buildings are independent entities with separate facilities to generate heat, although depending on external energy sources. As the role of buildings shifts from a stand-alone perspective to a more urban view, i.e. as part of a city block or neighborhood, energy systems with one central plant to provide a whole district emerge, giving the chance to unlock advantages in energy and cost efficiency.

From a technical perspective, such concepts enable a minimization of the heat source's installed capacity, which depends on the maximum requested heating load in one particular time step. In German residential buildings, one boiler typically produces the heat demand for both space heating and domestic hot water (DHW). That is why either space heating or hot water demand influence the maximum heating load. In a district with a multitude of different buildings, the time step in which this maximum load appears is usually not the same. Consequently, if one central plant is designed to supply a group of buildings, the maximum heat demand of this group (central supply peak load) is expected to be lower than the aggregated individual supply peak load of all buildings (see Figure 1).

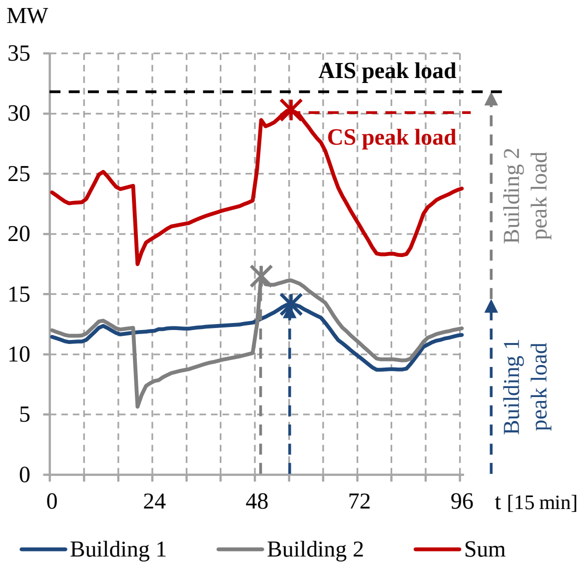

Figure 1: Aggregated individual supply (AIS) peak load and central supply (CS) peak load

This benefit heavily depends on the variability of heat demand profiles for residential buildings, in the following labeled as *load diversity*. For instance, better-insulated buildings have certainly increased the load diversity in the last years, therefore extending the impact of the occupant's hot water demand on the total heat demand profile. This paper aims to identify those building and occupant related characteristics that influence the heat demand profiles of residential buildings, thus being able to establish the advantages described above.

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District heating systems, distributing the heat produced in a central plant within a residential district, are an established technology in Germany. Moreover, reduced installed capacities lead directly to lower investment costs. Maintaining only one central plant decreases the overall operating costs for the whole district, too. Furthermore, the space usually reserved for decentral plants may be used for another purpose in the individual buildings. District heat also qualifies for exemptions from charges, because the German Renewable Energies Heat Act (EEWärmeG 2015) considers district heat equal to heat from renewable energy sources under specific prerequisites. Apart from that, additional systems such as solar thermal power plants and geothermal storages are able to reduce carbon emissions in order to achieve national and global climate goals (Bauer et al. 2010).

On the downside, distribution heat losses depending on pipe length, insulation, and supply temperature may increase the minimum installed capacity of the central plant. Likewise, high-pressure losses require over-designed pumps, consequently increasing electricity consumption. Therefore, a further objective of this paper is to confront the benefit of load diversity and the presented advantages of a central heat supply system with the practical disadvantage concerning the heat distribution.

Methodology

The quantitative analysis in this paper is based on different coefficients from previous studies (Weissmann et al., 2017). Winter et al. (2001) compared the district peak load of two district heating systems in Austria with the corresponding aggregated individual building peak loads using a “simultaneity factor” (Winter et al., 2001; Rehau, 2012). Following up on this approach, Guan et al. (2016) measured electricity and heating load as well as water supply of a university campus. Their “coincidence factor” describes the total maximum load of the campus divided by the aggregated individual building load maxima. In a similar manner, Yarbrough et al. (2015) applied the coincidence factor to investigate the relationship between total campus peak load and individual building peak loads. In this paper, the basic principles of the methodology used in these studies will be adopted to quantify load diversity and to directly draw conclusions regarding the minimization of installed capacity.

For this purpose, two cases need to be compared: one district in which every building is supplied with heat individually and one with a central heating supply system. The key figure for the first situation is the *aggregated individual supply (AIS)* peak load written as:

$$Q_{AIS\ peak\ load} = \sum_{i=1}^{n} Q_{max,i} \qquad (1)$$

In a district with n individually supplied buildings, the AIS peak load describes the overall installed capacity as the sum of the maximum heat demand Q_{max} of all buildings. Each of these peaks occurs within a particular time step during the day, but varying from building to building.

In order to derive the minimum installed capacity for the second case, the specific demand profile of the district $Q_{D,n}(t)$ must be determined first. The profile is a function over time aggregating each single demand profile of all n buildings:

$$Q_{D,n}(t) = \sum_{i=1}^{n} Q_i(t) \qquad (2)$$

The *central supply (CS)* peak load, which is the minimum installed capacity in the second situation, is simply the peak value of this function:

$$Q_{CS\ peak\ load} = max\big(Q_{D,n}(t)\big) \qquad (3)$$

Most likely, the individual peak demands $Q_{max,i}$ will not all coincide with the maximum of $Q_{D,n}(t)$. Consequently follows $Q_{CS\ peak\ load} \leq Q_{AIS\ peak\ load}$.

In order to summarize the results and to show the reduction of minimum installed capacity, the *peak load ratio (PLR)* index is defined as follows:

$$PLR = \frac{Q_{AIS\ peak\ load} - Q_{CS\ peak\ load}}{Q_{AIS\ peak\ load}} \qquad (4)$$

The PLR index returns values between 0 and 1, which may also be interpreted as a percentage. A high PLR index implicates high load diversity, whereas a value of zero indicates no diversity at all. Admittedly, the latter is only a theoretical case implying that the peak loads of all buildings in the district would occur at the same time.

Simulation

Development of representative heating load profiles

As mentioned before, one plant usually produces the heat for both domestic hot water and space heating. Therefore, heating load profiles must contain the DHW demand and the required heating demand to obtain a desired indoor temperature. Various load profiles exist based on real gas consumption data for German residential buildings. They all depict a typical trend with a high demand peak in the early morning due to a temperature setback at night and associated high hot water consumption. During the day, the heat demand decreases because of higher outdoor temperatures and times when occupants are out but rises again in the evening when they come home. In the end, the demand falls again because of the nightly setback.

These profiles just represent the heat demand of a multitude of buildings neglecting the influence of single building and occupant related characteristics. However, this level of detail is vital for the present research project. Fischer et al. (2016) addressed these deficiencies by combining the physical building model with a behavioral model to simulate individual heat demand profiles for space heating and hot water demand. Their work resulted in profiles that are more diverse because they also considered different internal loads, heating set points (including a nightly setback program) and the orientation of the building. Consequently, the upcoming analysis in this paper needs to consider at least these parameters.

Table 1 summarizes all building and occupant related characteristics that have a general influence on heating load profiles, thus being subject to variation in order to create distinct profiles.

Table 1: Building and occupant related characteristics

Characteristic	Variation
Building type	Single-family house (SFH) Multi-family house (MFH)
Year of construction	1960s 2016
Orientation	North/South East/West
Occupancy	2 people per household 3 people per household 4 people per household
Internal loads	Varying density and schedule
Comfort temperature	20 °C 22 °C
Temperature control during night hours	No heating setback 2 °C heating setback 3 °C heating setback

The test district in the following part of this paper will contain either single-family houses (SFH) or multi-family houses (MFH) with six apartments each. They were built in 2016 or in the 1960s, therefore featuring different energy efficiencies. While all new constructions meet the requirements of the current German Energy Saving Ordinance (EnEV 2014), the building envelope of the older buildings is designed according to the German residential building typology (Loga et al., 2012). Table 2 outlines several parameters that reflect the energy standard of both construction years. They all have a decisive impact on heat losses and convective heat gains as well as surface temperatures. By entering this data into the simulation model, analyses on how structures of different age influence the heating load profiles are possible.

Representing the German building stock, the building envelope mainly consists of massive materials such as concrete or brickwork (Loga et al., 2012). In order to assess the influence of solar radiation, the gable end of the buildings is either facing north respectively south or east respectively west.

Table 2: Year of construction related input parameters

	1960s	2016 (EnEV)
Thermal transmittance • Wall • Roof • Floor • Window	 1.20 W/m²K 0.58 W/m²K 1.59 W/m²K 2.90 W/m²K	 0.31 W/m²K 0.23 W/m²K 0.24 W/m²K 1.10 W/m²K
Infiltration	0.420 ACH	0.105 ACH
Thermal bridges	0.10 W/mK	0.05 W/mK
Heating system	Radiator, 70 °C supply temp.	Radiator, 50 °C supply temp.
Boiler efficiency	0.73	0.95

According to the average size of a German household, single-family houses provide space for four people, while in an average multi-family house of the chosen size three people share one apartment (Statistisches Bundesamt, 2011). Internal loads describe the total heat gains from people, lights, and appliances that might vary among different occupants and over time. According to DIN V 18599, the desired indoor air temperature in heating mode is 20 °C. Still, some people perceive higher temperatures as more comfortable, so the following analyses will consider an alternate indoor climate of 22 °C, too. It is adequate to investigate two temperature levels to be able to deduce implications for the influence of other indoor air temperatures. Moreover, the influence of a temperature setback during night hours is analyzed. An optional temperature setback between 11 PM and 6 AM is described in DIN V 18599, typically leading to a temperature decrease of about 2 to 3 °C. Therefore, these two alternate control cases will be investigated.

In order to create diverse load profiles, user profiles U1-U4 link the building type to some of the occupant related characteristics. Table 3 determines fixed values for occupancy and internal loads in each user profile. The average household sizes are used in the user profiles U1 and U2 representing a base case scenario for single- (U1) and multi-family houses (U2-B). Internal loads are set to be constant throughout the day in accordance with DIN V 18599. However, because both household size and occupancy schedule may differ in reality, alternate user profiles were created. That is why user profiles U3 and U4 represent households with varying internal loads reflecting the fact that occupants may be out on weekdays (for work etc.). These occupants are absent between

Table 3: User profile related input parameters

User profile		Occupancy [PPH]	Building type	Internal loads [Wh/(m²d)]	Schedule internal loads	Schedule temp. setback
U1		4	SFH	45	Always on	11 PM – 6 AM
U2	-A	3	SFH	34	Always on	11 PM – 6 AM
	-B		MFH	90		
U3	-A	3	SFH	34	Off weekdays 7 AM – 6 PM	11 PM – 5 AM
	-B		MFH	90		
U4		2	MFH	60	Off weekdays 7 AM – 6 PM	11 PM – 5 AM

Table 4: Possible alterations within one user profile

	1	2	3	4	5	6	7	8	9	10	11	12
Orientation	North/ South	North/ South	North/ South	East/ West	East/ West	East/ West	North/ South	North/ South	North/ South	East/ West	East/ West	East/ West
Comfort temperature	20 °C	20 °C	20 °C	20 °C	20 °C	20 °C	22 °C	22 °C	22 °C	22 °C	22 °C	22 °C
Temperature setback	None	2 °C	3 °C	None	2 °C	3 °C	None	2 °C	3 °C	None	2 °C	3 °C

7 AM and 6 PM. Furthermore, they get up an hour earlier than in the base cases, which is relevant if the temperature control during night hours is active. Beyond that, orientation, comfort temperature, and temperature setback are variable enabling further modification (see Table 4). By combining the variations from Table 4 to the six user profiles for both construction years, 144 distinct heating load profiles can be simulated.

Simulation of heating load profiles in IDA ICE

Heating load profiles were developed using the dynamic building simulation software *IDA ICE* (version 4.7) based on the previously defined conditions. IDA ICE facilitates the creation of multi-zone models to compute the heating or cooling demand of buildings. The software consists of a library with components written in the equation-based language *Neutral Model Format* (EQUA AB, 2013). Through a graphical interface, the user can arrange these modules by connecting variables to create the zone model and the desired plant system. The software has been validated according to ASHRAE 140, IEA TASK 34 (Annex 43), EN 15255 and 15265 as well as EN 13791 (EQUA AB, 2004). The underlying climate file is "TRY 04 Potsdam" as this dataset is also required for calculations according to EnEV 2016 (BBSR, 2016). It should be stressed that this data is used for all buildings in the simulation despite their year of construction.

Figure 2 shows one SFH (above) and one MFH (below) as modeled in IDA ICE. Cubature and orientation of the buildings are chosen according to Klauß & Maas (2010) who developed representative prototype buildings for the German building stock.

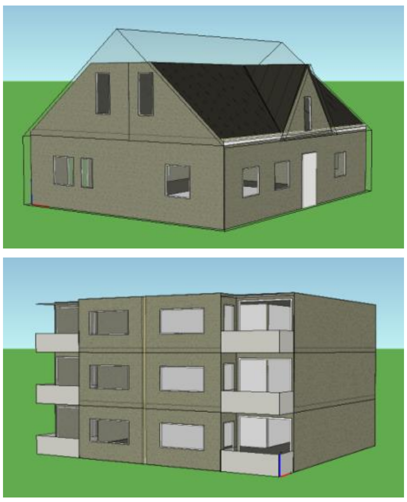

Figure 2: SFH and MFH models represented in IDA ICE

The standard plant model of IDA ICE generates heat for both space heating and hot water demand in one boiler. Its design-installed capacity can be determined according to DIN EN 12831. In the model, hot water is stored in a tank at a temperature level of 70 or 60 °C. The tank is connected to all supply pipes for DHW and the space heating system. Thus, hot water is mixed with cold potable water (10 °C) and the return flow of the space heating system, hence providing domestic hot water at 50 °C while the supply temperature of the room heating system is 70 or 50 °C (as required due to the specifications in Table 2). The tank's small volume of approximately 1 liter prevents that the heat demand profile decouples from the heat production profile of the boiler.

As it is common practice in building simulation, IDA ICE uses a static schedule to model the domestic hot water demand. However, this simplification does not represent the complexity of occupant behavior (Yan et al, 2015). Therefore, a hot water demand profile for an average German household was created with the software tool *DHWcalc* and connected to the plant model in IDA ICE. The tool allows setting different hot water drawing types such as larger amounts for taking a shower or smaller for washing hands. The German Passive House Institute defined average hot water consumption profiles for bathtub, shower, sink and other small draw-offs, summing up to a total average daily consumption of 35 liters per occupant (Passivhaus Institut, 2008). After having implemented this data into DHWcalc, the tool determines the probability of a hot water draw at time step *t* as follows (Jordan & Vajen, 2005):

$$p(t) = p_{day}(t) \cdot p_{weekday}(t) \cdot p_{season}(t) \cdot p_{holiday}(t) \quad (5)$$

The resulting mass flow dataset is able to reflect the varying daily user behavior much better than a simple static schedule. As a matter of course, the calculations consider the user profiles to ensure that during those times when occupants are absent no water draw appears.

After having fed the simulation model with all necessary data, heating load profiles for all 144 cases are simulated on 15-minute time steps ($t \in \{1 \ldots 672\}$). The simulation is conducted for the first week of January because in this specific week the selected climate file contains the time steps with the lowest outside air temperature of the year (time step 336 and 417) and the time step for which DHWcalc calculated an over-average hot water draw. Consequently, the influence of climate-driven as well as DHW-driven peaks can be analyzed.

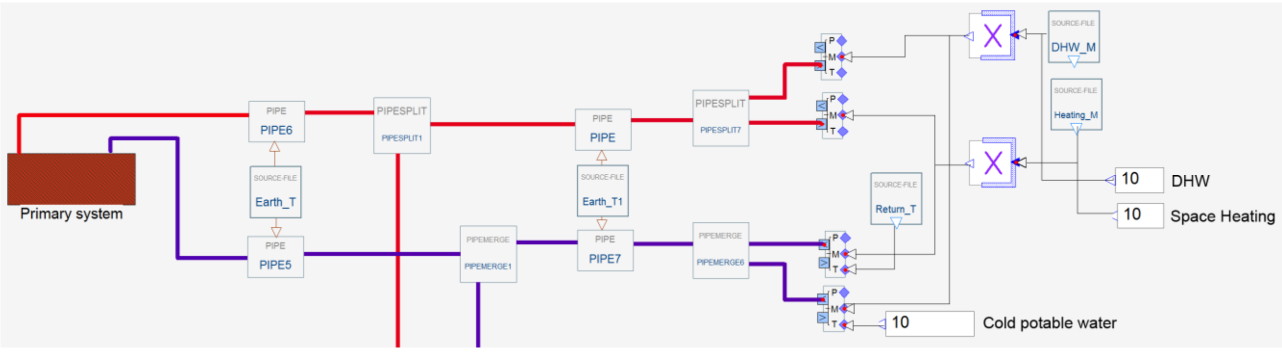

Figure 3: Screenshot of the district heating system model in IDA ICE

Simulation of the district heating system in IDA ICE

For the second part of the analysis, a district heating system is modeled in IDA ICE. For this purpose, the ESBO Plant model, an extension of the standard plant model, is expanded by several components on the software's advanced level mode. All components in Figure 3 are connected with variables for describing mass flow, fluid temperature, and pressure.

Each single building load profile is implemented in form of three source files describing the mass flows for space heating and domestic hot water as well as the return temperature of the space heating system. In addition, a constant describes the temperature of the cold potable water (10 °C according to DIN V 18599). The mass flows can be upscaled by constant multipliers to describe the number of buildings with the same profile in the district (see exemplary factor 10 in Figure 3). The different water flows are separated or added up by the "pipesplit" and "pipemerge" blocks. In order to calculate distribution losses properly, the pipe blocks are connected to a source file which contains a dataset describing the ground temperature based on measurements in the climate zone Potsdam (PIK, 2016). The measurements were conducted on a monthly basis, so the earth temperature stays constant during the simulated period of one week.

The primary system contains a central heating plant designed in the ESBO plant model. This central plant is connected to the district by one main supply and one main return pipe. Eventually, the district heating load is calculated as follows:

$$Q_{D,n}(t) = \dot{m}(t) \cdot c_p \cdot \Delta T(t) \qquad (6)$$

In this formula, $\dot{m}(t)$ stands for the water mass flow, c_p for the specific heat capacity of water and ΔT for the difference between supply and return temperature.

Results

Analysis of the heating demand of single buildings

Figure 4 displays exemplary heating loads as output of the performed IDA ICE simulations. The total heating loads are split into space heating and DHW for a single-family house (left) with user profile U1 and a multi-family house (right) with profile U2-B. The blue line indicates buildings from the 1960s, the gray line stands for buildings according to the EnEV 2016 standard. In all buildings, the temperature is set back during night hours by 2 °C.

It is eye-catching that the space heating peak load of the 1960s SFH tops the domestic hot water peak about four times whereas this difference is not that significant

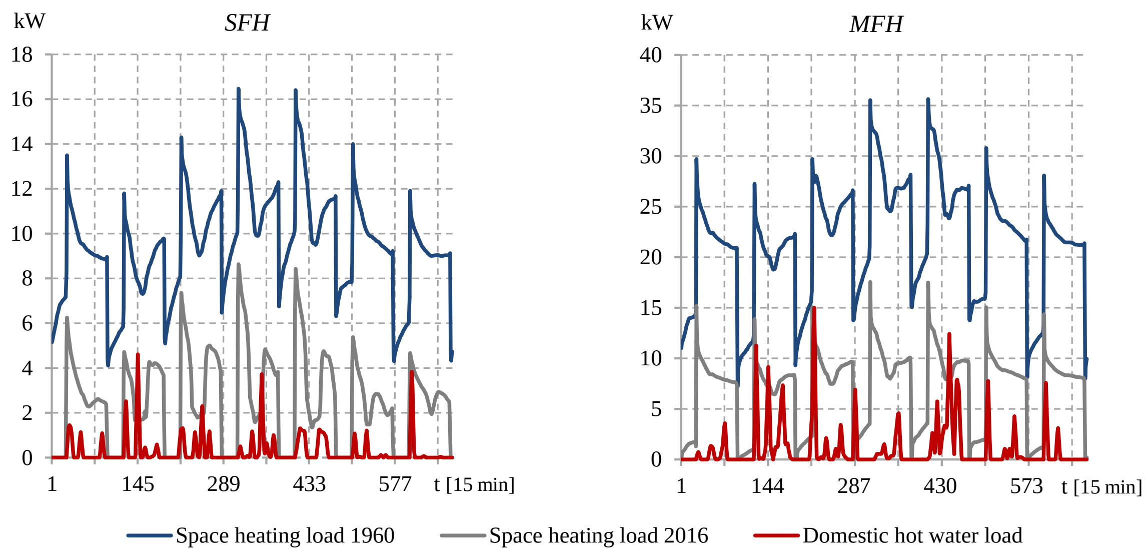

Figure 4: Load profiles for space heating and domestic hot water in exemplary buildings

regarding the MFH case. Figure 4 also shows that in the case of a newly built and better-insulated building from 2016, the DHW load partly exceeds the space heating load. Moreover, the influence of thermal mass on the space heating load profile can be seen especially in the SFH case. As the building envelope of the older buildings contains more massive materials, heat can be stored longer. That is why on some days the heating load of the 1960s SFHs does not rise in the evening, while the contrary can be observed in the newer buildings every evening (see Figure 4, left).

Theoretical analysis of PLR growth on a district level

All 144 simulated heating load profiles can now be utilized to investigate the PLR. At first, the PLR of two test districts consisting of only SFHs or MFHs is calculated. The first district consists of a base case SFH (user profile U1) and the second neighborhood of a base case MFH (U2-B). Both were constructed in the 1960s, have a desired indoor temperature of 20 °C without temperature control and are oriented north/south. Table 5 shows the PLR index for both districts if another SFH or MFH is added to the district with only one changed feature compared to the base cases.

Table 5: Influence of single features on the PLR index

	Pre-existing building	
Changed feature of the second building	**Base case SFH (U1), 1960**	**Base case MFH (U2-B), 1960**
Year of construction	**3.19 %**	0.88 %
User profile U2-A	0.89 %	–
User profile U3	5.69 %	**12.09 %**
User profile U4	–	**9.34 %**
Comfort temp. 22 °C	0.00 %	0.00 %
Orientation east-west	0.00 %	0.00 %
Heating setback 2 °C	1.16 %	0.67 %
Heating setback 3 °C	2.42 %	0.00 %

Table 5 shows that certain features lead to higher diversity ratios than others depending on the pre-existing building in the district. Looking at the MFH case, the addition of one building with a different user profile leads to the highest diversity due to higher occupant density, extending the influence of hot water demand on load diversity. The impact of occupant behavior in the SFH case is minor whereas energy optimization of the building envelope (as implied by the year of construction) entails the highest diversity within this two-buildings-district. This comes down to the fact that SFHs are more affected by the outdoor temperature.

After this initial observation, all individual heat demand profiles are aggregated to a single heating load profile representing the heating demand of an urban district with 144 buildings. Figure 5 illustrates this *adding process* and the associated PLR. The test district's setup starts with building 1 which is a base case SFH as described before in Table 5. After that, the district is extended with 71 more SFHs. Including the first building, one half has been built in the 1960s and the other in 2016. Beginning with building 73, solely MFHs complement the district.

All buildings can be combined with the respective user profile (U1, U2-A and U3-A for SFHs, U2-B, U3-B and U4 for MFHs, see Table 3). In Figure 5, bold gray lines mark the change of a user profile.

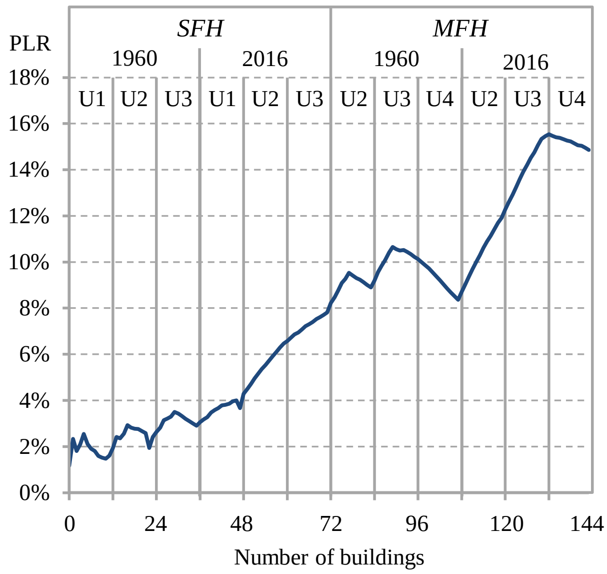

Figure 5: PLR growth analysis

More variations take place within each user profile by modifying the setting for orientation, comfort temperature, and temperature setback (see Table 4). For instance, building 49 is the first added SFH with a construction year of 2016 and user profile U2-A. According to Table 4, this building is orientated north/south and comfort temperature is set at 20 °C without any temperature setback. Compared to that, building 50, which is added afterward, features all the same characteristics like number 49 but with a temperature setback of 2 °C between 11 PM and 6 AM.

Figure 5 demonstrates that the chosen test district achieves a PLR index of around 15% after aggregating all buildings. Especially the addition of recently constructed buildings involves growing diversity. This is the result of the already investigated higher influence of hot water demand on the maximum peak load in the case of better-insulated buildings.

While adding the 36 SFHs from the 1960s, whose heating loads are more climate-driven, PLR decreases occur regularly during the addition of buildings with a desired comfort temperature of 22 °C (each second half of the buildings within one user profile). A higher indoor climate does not affect the shape of the individual load profile but causes a shift along the y-axis. Because of that, the load profiles are not very diverse, therefore inducing no increase in PLR.

Buildings with temperature setback control either increase or decrease the PLR depending on the time step when the warm-up process starts in the morning. The PLR will only increase if this time step is very different from other buildings in the district.

There is almost no effect on PLR growth due to building orientation. That is because solar radiation influences the

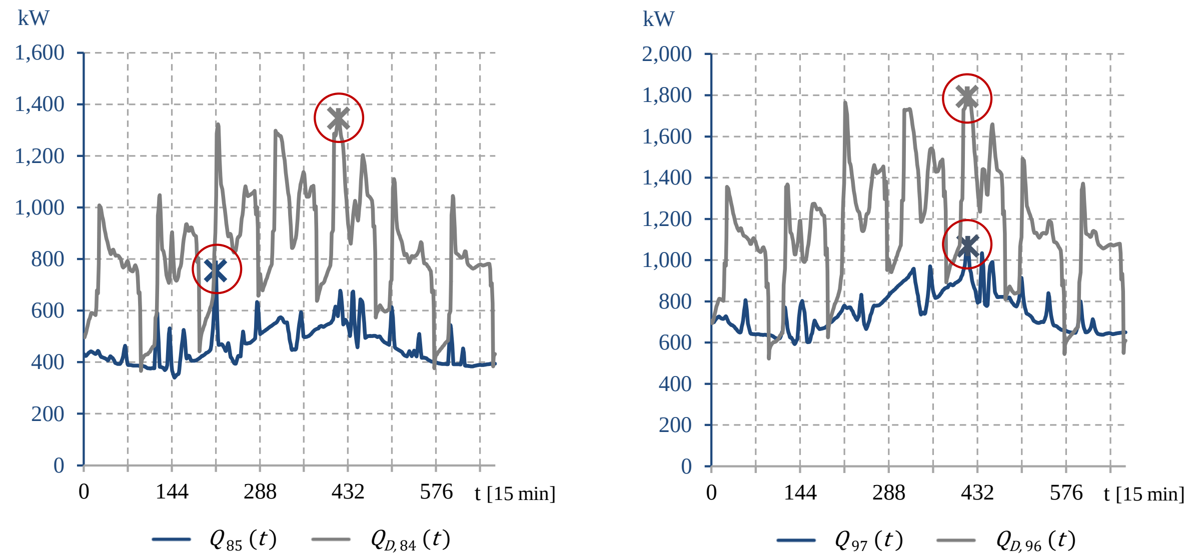

Figure 6: Comparison of up-scaled U3 (left) and U4 load profiles (right) to the temporary district load profile shape

heating load profiles mostly around noon while the peak load always appears in the early morning during the warm-up process. In Figure 5 the interval borders between user profiles highlight that diversity increases as soon as buildings with a distinct user profile join the district (time step 13, 25, 37, etc.). The only exception to this rule is the addition of buildings with user profile U4 (time step 97 and 133).

Figure 6 shows up-scaled load profiles for exemplary MFHs (blue lines) with user profile U3 (left) and U4 (right) as well as temporary district profiles that correspond to the respective step of the adding process. The peak in the U4 case and the district's peak load coincide in time step (432), while the maximum in the U3 case appears at another time step (216). Hence, the addition of user profile U3 tends to increase the PLR index due to more diverse profiles. However, it is worth saying that the district's profile $Q_{D,84}(t)$ has another slightly lower peak in time step 216. Therefore, adding more U3 buildings with a dominant peak in this time step would finally lead to a declining PLR. Again, this confirms that the impact of single building characteristics on the load diversity in a district always depends on the characteristics of all pre-existing buildings.

Consequently, the first part of the analysis in this paper leads to the following statements:

- PLR increases if buildings in accordance with the EnEV 2016 standard are added to a test district with older buildings from the 1960s
- PLR increases if MFHs join a district of SFHs
- PLR increases in most cases if buildings with different user profiles are added
- PLR increases if buildings with temperature control are added to buildings without any setback
- PLR does not necessarily grow with a higher number of buildings within the district

Figure 7 shows the demand profile of the test district containing all 144 buildings. The typical peak loads in the morning throughout the simulated week can be seen very clearly. The temperature setback has a strong impact on the maximum peak load and thus the minimum installed capacity. In buildings without temperature setback, the simulation returns a maximum peak load that is about 27% lower, particularly in the older buildings. However, one needs to keep in mind that such a setting also increases the yearly energy consumption

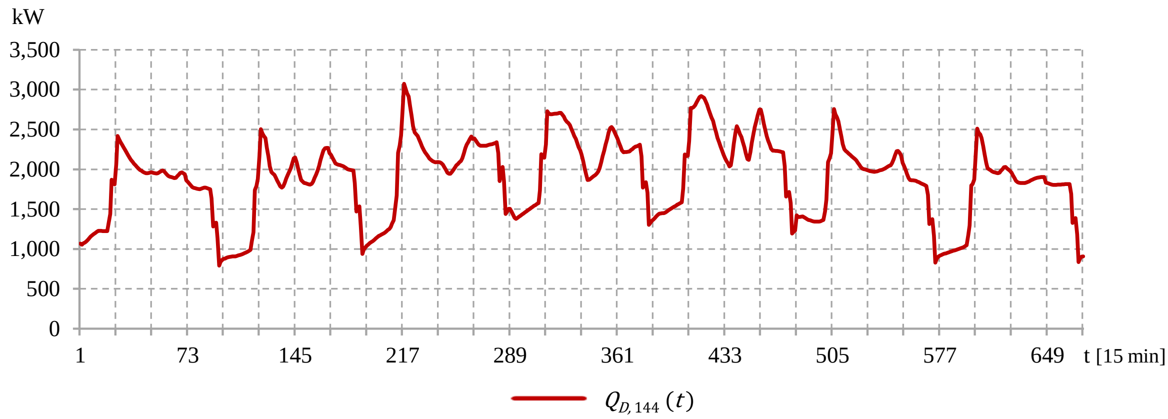

Figure 7: Total test district heating load profile

by 8%. On the other hand, modern homes allow heating throughout the night without wasting too much energy because of the better-insulated building envelope (see Figure 4).

Evaluation of results regarding distribution losses

The investigations in the previous part point out that benefits from heating load diversity can arise in a certain district composition. Adding up diverse load profiles leads to a reduced installed capacity of central plant. However, this is just a theoretical, ideal view as distribution losses have been neglected so far. In order to provide a required heat level to the single recipients within the district, the supply temperature has to be increased. Hence, the central plant has to produce more heat than the ideal CS peak load. Therefore, the following case study trades off the benefit from load diversity against the disadvantage of distribution losses.

In order to emphasize the diversity effect, the district in this case study contains six building types with very diverse load profiles according to the PLR calculation before. The corresponding growth in PLR is depicted in Figure 8. The first three buildings are SFHs and three more MFHs complement the test district. Each of the six buildings is connected to one of the distinct user profiles covering all six profiles (see Table 4). They were all built in 2016, are oriented north/south and have a desired comfort temperature of 20 °C with a setback during night hours by 2 °C. It is crucial for a district heating system that every building is supplied at the same temperature level. Figure 8 shows that the PLR index continues to grow with every building added to the district.

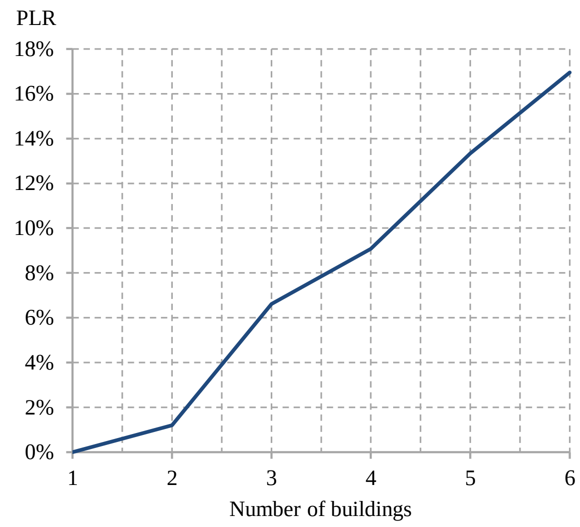

Figure 8: PLR growth of selected heating load profiles

Distribution losses strongly depend on the length of the piping network. Therefore, *load density* as another coefficient is introduced. In the context of electrical engineering, this ratio is defined as the aggregated total load per area (Heuck et al., 2010). A high load density implicates that buildings stand closer together, so more heat can be distributed with reduced losses. In order to investigate the impact of density, a “City” and a “Rural” scenario have been created resembling the building distances of district type ST 1 and ST 8 referring to the district typology by Zukowska et al. (2013). Apart from an assumed average pressure loss of 100 Pa/m, the pipe lengths for each scenario are chosen according to Dötsch et al. (1998) (see Table 6).

Table 6: Pipe lengths according to Dötsch et al. (1998)

	City scenario	**Rural scenario**
Supply pipe length SFH	14 m per building	25 m per building
Supply pipe length MFH	2 m per apartment	6 m per apartment

The constant ground and supply temperatures imply that distribution losses can be mainly concluded from the heating load profile in terms of water mass flow. Above that, the supply temperature strongly influences the distribution losses which is why both scenarios are simulated first with 2016 buildings operating at 50 °C supply temperature and second with 1960s buildings requiring 70 °C for space heating.

Table 7 summarizes the input parameters for both scenarios. As buildings stand closer together in the “City” scenario, it is assumed that the area contains twice as many buildings in this case. Just like the PLR analysis, the simulation of the district heating model is performed for the first week of January in 15-minute time steps.

Table 7: Input parameters for the scenario analysis

	City scenario 1960s/2016	**Rural scenario 1960s/2016**
No. of buildings	10 of each type, 60 in total	5 of each type, 30 in total
Total pipe length	780 m	915 m
Supply temperature	70 °C (1960s) 50 °C (2016)	

The results show that distribution losses implicate an increasing district supply temperature by 2 °C in the City scenarios and by 3 °C in the Rural scenarios compared to individual supply. Figure 9 depicts the resulting *district heating (DH)* peak load in relation to the corresponding AIS and CS peak load as defined before.

Regarding the 2016 scenarios, Figure 9 shows that the DH peak load lies between the theoretical AIS and CS peak load figures. Therefore, some of the identified diversity benefits still occur in these scenarios. The City 2016 scenario’s DH peak load is closer to the ideal CS peak load due to lower distribution losses compared to the corresponding Rural scenario. However, the DH peak is almost twice as high as the AIS peak load in the 1960s scenarios. Firstly, this can be traced back to previous studies by Rezaie & Rosen (2012) showing that district heating systems are much less efficient if operating at higher temperatures. The supply temperature in the 1960s cases is 70 °C compared to

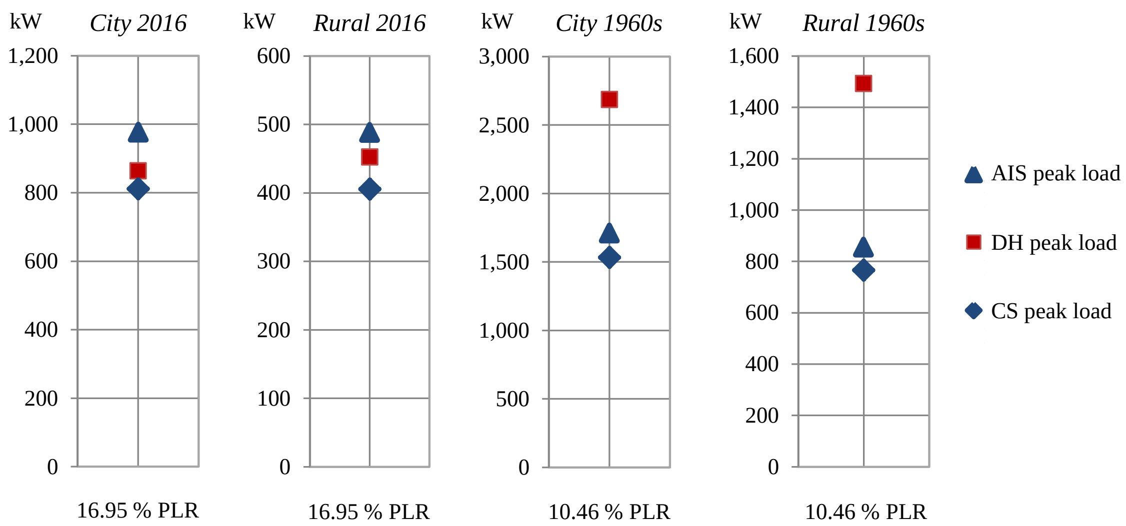

Figure 9: Results of the scenario analysis

50 °C in the 2016 scenarios. Secondly, the supply temperature is higher than the hot water temperature of 50 °C. While in an individually supplied building a boiler can be set up to address both demands, the hot water in a district system needs to be heated up to unnecessary 70 °C leading to further inefficiency. As a consequence, the original benefit of a reduced CS peak load from a theoretical perspective gets completely eliminated by the unfavorable distribution losses in a system with a high supply temperature. Additional investigations regarding the City 2016 scenario show that the smallest difference between DH peak load and CS peak load appears if the applied load profiles are represented equally within the district (Weissmann et al., 2017).

Conclusion

This paper introduces a peak load ratio (PLR) index to quantify the impact of building and occupant related characteristics on the heating load diversity within a prototype German residential district. The theoretical analysis about effects of single building characteristics shows that particularly a combination of buildings with different construction years, temperature controls and user profiles can increase load diversity. Moreover, the conducted study reveals that the domestic hot water demand has a strong influence on the PLR. The second part of the study confronts the benefits from diversity with the disadvantages of heat distribution in a district heating system. The performed case study demonstrates that especially in scenarios with high load density and low supply temperature the diversity benefit leads to a minimized installed capacity of the central plant.

However, the analysis has some weaknesses which are mainly linked to simplifications in the simulation model. For instance, the hot water demand profiles are still constant within each user profile and should be based on a stochastic occupant behavior model in future research to achieve higher PLR indices (Hong et al., 2016). Further investigations should also take a look at district systems serving buildings with mixed use involving the commercial sector. A combination with non-residential buildings might result in a much higher load diversity as peak heating loads of residential buildings likely appear at different times compared to commercial buildings. Moreover, the current district heating model could be expanded by storages and top-up boilers in the single buildings to decouple individual demand peaks from the central system. In this context, decentralized electrical hot water generation should be taken into account, too, in order to tackle inefficiencies of hot water generation in the summer season. Finally, future simulation models should include elements such as solar thermal plants, wind turbines or heat pumps to represent the increasing share of renewable energies in the heat supply of buildings. In combination with seasonal storages, such systems might also lead to reduced installed capacities.

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Nomenclature

ACH = Air changes per hour
AIS = Aggregated individual supply
CS = Central supply
DH = District heating
MFH = Multi-family house
PLR = Peak load ratio
PPH = People per household
SFH = Single-family house

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