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Analysis of heating load diversity in German residential districts and implications for the application in district heating systems

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Abbreviations[1]

Abstract

In recent years, the application of district heating systems for the heat supply of residential districts has been increasing in Germany. Central supply systems can be very efficient due to diverse energy demand profiles which may lead to reduced installed equipment capacity. Load diversity in buildings has been investigated in former studies, especially for the electricity demand. However, little is known about the influence of single building characteristics (such as building envelope or hot water demand) on the overall heating peak load of a residential district. For measuring the diversity, the peak load ratio (PLR) index is used to represent the percentage reduction of peak load of a district system from a simple sum of individual peak loads of buildings. A total of 144 residential building load profiles have been created with the dynamic building simulation software IDA ICE for a theoretical analysis in which the PLR reaches

[1] PLR = Peak load ratio
SFH = Single-family house
MFH = Multi-family house
PPH = People per household
AIS = Aggregated individual supply
CS = Central supply
DH = District Heating

15%. Within this study, certain district features are identified which lead to higher diversity. Furthermore, these results are used in a district heating simulation model which confronts the possible advantage of reduced installed capacity with the practical disadvantage of heat distribution losses. Likewise, the influence of load density and the district´s building structure can be analyzed. This study shows that especially in districts with high load density, which consist of newly constructed buildings with low supply temperature and high influence of the hot water demand, the advantages of load diversity can be exploited.

Keywords

Load diversity; peak load; heat supply; space heating; domestic hot water; residential district; district heating; dynamic building simulation

1. Introduction

Traditionally, energy supply systems for residential buildings are being designed individually, treating each building as a stand-alone system. However, as buildings are integrated into an urban context, such as a district or a neighborhood, designing the energy supply on the district scale with one central plant may lead to advantages in energy efficiency as well as economic benefits.

From the technical perspective, a major advantage can be achieved concerning the design installed capacity. Regarding heat supply of buildings, the installed capacity of the heat source depends on the maximum requested heat load in one time step. In German residential buildings, heat for space heating and hot water is traditionally produced by the same boiler. Likewise, the maximum heat load is influenced either by the space heating demand or the hot water demand. It is assumed that the time step in which this maximum load appears varies within a certain range for different buildings. Consequently, if one central plant is designed for several buildings, the maximum heat demand of the supplied group is likely to be less than the sum of the individual building peak load (Fig.1).

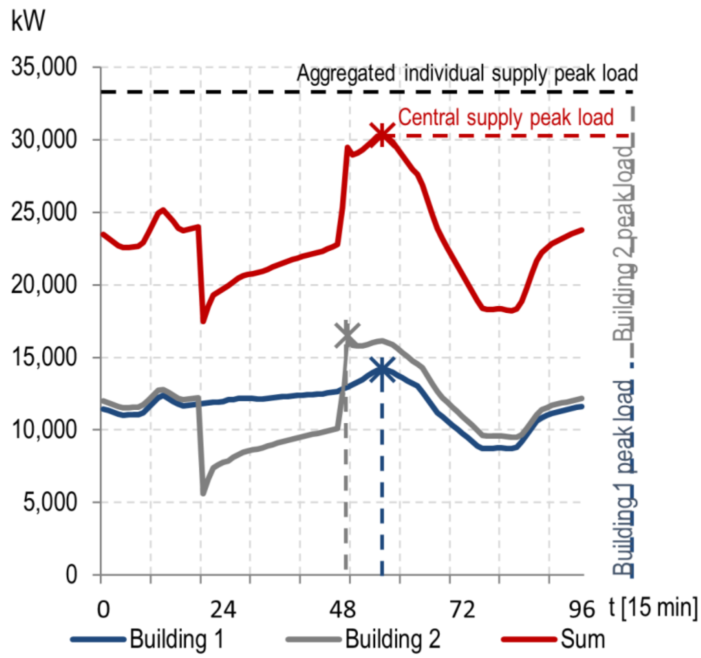

Fig. 1. Aggregated individual supply (AIS) peak load and central supply (CS) peak load

This benefit is dependent on the variability of residential building heat demand profiles, in the following designated as load diversity. It is assumed, that the diversity of heat demand profiles for residential buildings has increased in recent years as buildings are better insulated which extends the influence of the occupant´s hot water demand on the total heat demand profile. The aim of this paper is to identify building and occupant related characteristics that influence the heat demand profile of residential buildings and to quantify their influence on the heating load diversity within a residential district.

The heat produced by a central plant can be distributed to the district´s buildings via a district heating system. District heating systems are an established technology for the heat supply of residential districts in Germany. Moreover, innovative systems that include solar thermal power plants and geothermal storages and likewise reduce carbon emissions have been tested [1]. According to the German Renewable Energy Heat Act (EEWärmeG), district heat is considered equal to heat from a renewable energy source if at least 50% of the total heat outcome is gained from industrial waste heat or produced by a combined heat and power plant [2]. Hence, there is a lot of potential for the further establishment of district heating systems in Germany in the context of the turnaround in the national energy policy [3]. Apart from that, the reduction in installed capacity leads to smaller investment costs. At the same time, the overall operating costs of the whole district might be reduced as only one central plant has to be maintained and individual buildings can save the plant room space for another usage. Furthermore, due to scaling effects, the economic benefit is enhanced with an increasing amount of supplied buildings by the central plant.

However, disadvantages appear regarding the distribution of heat from the central plant to the final recipient. Depending on the pipe length, insulation, and supply temperature, distribution heat losses may increase the minimum installed capacity of the central plant. Likewise, high-pressure losses cause additional electricity consumption because of the pump power. Therefore, a further objective of this paper is to confront identified diversity advantages of central heat supply systems with their practical disadvantage regarding heat distribution.

1.1 Existing diversity studies related to energy supply

In energy research, the term “diversity” is used for different purposes and applications. Former studies refer to energy diversity for describing optional energy sources (coal, gas, biomass) or a variety of energy suppliers for energy portfolios in the context of energy supply security. Stirling lists several indices for describing energy diversity in the form of variety, balance or disparity such as the Shannon, Simpson, Herfindahl-Hirschman, Solow-Polasky or Weitzman index and illustrates that these are also applicable in the context of energy transition and sustainability [4]. Furthermore, Skea analyzed how political incentives may increase the diversity of an energy system in this context [5].

In the framework of ASHRAE RP-1093, ”diversity factors” have been developed to create various individual load profiles based on measured data that can be applied in energy simulations [6]. Yang et al. analyzed the influence of diversity in occupancy behavior on the energy efficiency of HVAC systems by using the Minkowski distance for occupancy profile clustering [7]. Likewise, Zhou et al. aimed to increase the efficiency of centralized HVAC systems by identifying differences of load curves in separate zones with the Gini coefficient [8].

Instead of analyzing the whole load profile other studies focused simply on peak loads for detecting diversity effects. The “diversity factor” in the context of electrical engineering is defined as “the ratio of the sum of the maximum power demands of the subdivisions of any electric power system to the maximum demand of the whole system measured at the point of supply” [9]. Guan et al. apply this definition of diversity not only for assessing electricity load but also the heating load and water supply of a university campus. They define a “coincidence factor” which is the total maximum load of the campus divided by the sum of the individual building load maxima. Moreover, they measured the contribution of each singular building to the maximum campus load peak [10]. Yarbrough et al. also focused on the relationship between total campus peak load and individual building peak load by applying the coincidence factor. For this purpose, they also developed a pivot table tool for visualizing the loads of all buildings [11].

Based on the same principle, Winter et al. defined a “simultaneity factor” for comparing the district peak load with the aggregated individual building peak load for two district heating systems with overall 558 buildings in Austria. They furthermore developed a formula for estimating the simultaneity depending on the number of buildings in the district [12, 13].

In this paper, the basic principle of the peak load methodology used in the campus studies and by Winter will be adopted for measuring diversity as it leads to direct conclusions regarding the reduction of minimum installed capacity.

1.2 Definition of the peak load ratio (PLR) index

In a district in which every building is supplied with heat individually, the overall installed capacity is described by the aggregated individual supply (AIS) peak load $Q_{AIS\ peak\ load}$.(see Fig. 2)

$$Q_{\mathrm{AIS\ peak\ load}} = \sum_{i=1}^{n} Q_{max,i} \tag{1}$$

With $Q_{max,i}$ as the maximum heat demand of a single building i *at* a certain time step within the investigated period.

In a district with a central heating supply system, the minimum installed capacity is only defined after aggregating the demand profiles of all n single buildings to one time step specific district demand profile $Q_{D(n),t}$ (see Fig. 2).

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

After describing the district demand profile $Q_{D(n),t}$ the central supply peak load $Q_{CS\ peak\ load}$ can be determined as:

$$Q_{CS\ peak\ load} = Max\left(Q_{D(n),t}\right) \quad (3)$$

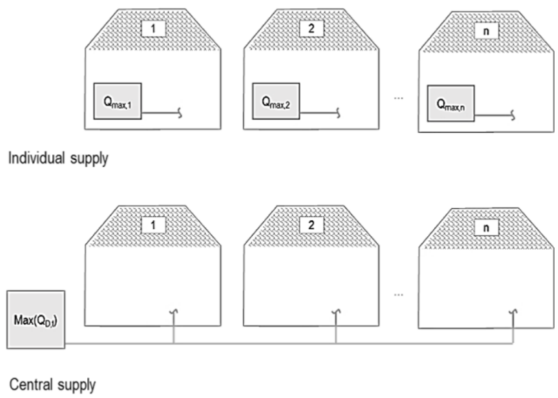

Fig. 2. Illustration of individual supply and the central supply system

Most likely, the individual peak demands $Q_{max,i}$ of all *n* buildings will not appear within the same time step *t* . Consequently $Q_{CS\ peak\ load} \leq Q_{AIS\ peak\ load}$.

For measuring this advantage in reduced installed capacity, the peak load ratio (PLR) index is defined as follows:

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

PLR is the inverse of the metrics defined by Guan and Weber and varies between 0 and 1, hence it can also be expressed as a percentage. The larger the PLR, the larger the load diversity; a value of zero indicates no diversity at all (as if the peak loads of all buildings in the district would occur at the same time step which is only a theoretical case). In the following, the influence of single building and occupant related characteristics on PLR is investigated.

2. Theoretical analysis of the influence of building and occupant related characteristics on residential district diversity

2.1 Existing heating load profiles in Germany

Before measuring the heating load diversity in a residential district, heating load profiles of individual residential buildings have to be created. It is assumed that domestic hot water and the heat for the space heating system are generated by the same plant. Hence, the heating load profile contains the domestic hot water demand as well as the heating demand for achieving the desired indoor temperature. Representative heating load profiles based on real consumption measurements for single-family and multi-family houses in Germany have previously been published in the framework of VDI 4655 [14]. Furthermore, synthetic gas load profiles, which describe the total heat consumption of buildings in the form of an hourly percentage of the total daily heat consumption, have been developed by Hellwig based on gas monitoring data. The shapes of these profiles can be adapted to certain outdoor air temperature levels [15] (see Fig. 3).

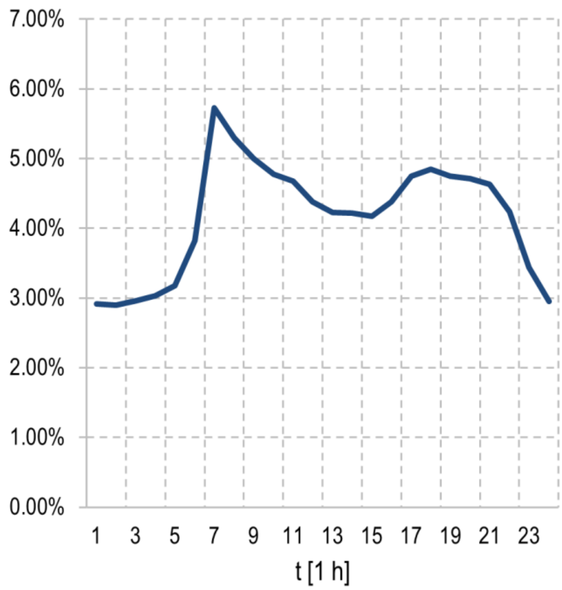

Fig. 3. Synthetic gas load profile, single-family house, outdoor air temperature level: -15 °C to -10 °C, (1 h time step) [15], [16]

Fig. 3 shows a high demand peak in the early morning due to the morning warm up at the end of space heating night setback and a high hot water consumption during this time. As the outdoor air temperature increases during the day and the occupant may be absent, the heat demand reduces. It rises again in the colder night when occupants are at home before it falls down due to the night setback. This profile shape is to be considered highly representative for the German building stock as it is applied by a large number of energy suppliers in Germany [16]. However, as these synthetic profiles represent the heat demand of a multitude of buildings, the influences of single building related characteristics are smoothed out, especially occupant related influences cannot be recognized. Therefore, a load profile representing a single building would look very different because of its individual characteristics, but the sum of a large number of individual profiles would resemble the trend of the profile in Fig. 3. Addressing these deficits, Fischer et al. combined a behavioral model with the physical model to simulate individual heat demand profiles for space heating and hot water demand. They varied the internal loads, heating setpoints (including a night setback program) and the building orientation for creating more diverse profiles [17]. Consequently, these features are to be considered in the following development of load profiles for the diversity analysis.

2.2 Development of heating load profiles for German residential buildings

Table 1 summarizes variations of building and occupant related characteristics that are used to create the diverse heating load profiles.

Table 1 Building and occupant related features with influence on the heating load profile

Building type	Year of construction	User profile	Orientation	Comfort Temperature	Temperature control
Single-family house (SFH) Multi-family house (MFH)	1960 2016	U1 U2 U3 U4	North-South East-West	20 °C 22 °C	No control 2 °C setback 3 °C setback

All reasonable combinations of these characteristics lead to a total of 144 different heating load profiles. The profiles have been created with the dynamic building simulation software IDA ICE (version 4.7).

In IDA ICE, multi-zone models can be designed for calculating the heating or cooling demand of buildings. The software consists of a library with components that are written in the equation-based language Neutral Model Format [18]. The user can arrange these modules on a graphical interface by connecting variables for creating the zone model as same as the desired plant systems. IDA ICE has been validated according to ASHRAE 140, IEA TASK 34 (Annex 43), EN 15255 and 15265 as well as EN 13791 [19].

As described in Table 1, the buildings within the test district are either single-family houses or multi-family houses with six apartments. First, a zone model of these buildings has to be created in IDA ICE 4.7. The cubature and orientation of these buildings are chosen according to Klauß et al. [20] who developed representative prototype buildings for the German building stock (Fig. 4).

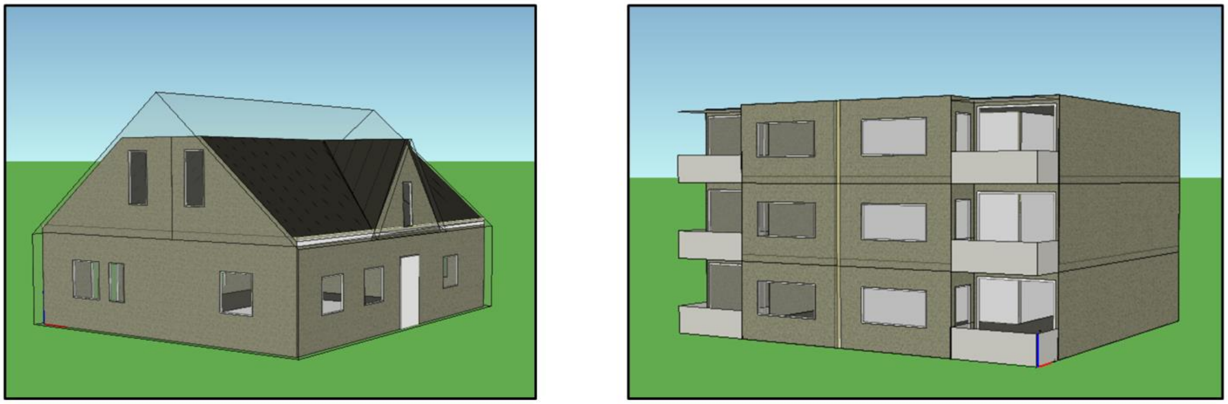

Fig. 4. Single-family House and Multi-family House models represented in IDA ICE 4.7

The district contains newly built buildings as well as old buildings built in the 1960s. The envelope of the newly constructed buildings is designed according to the current German Energy Saving Ordinance (EnEV 2016) [21]. The features of the 1960s buildings´envelope are selected according to the German residential building typology [22, 23].

Table 2 Construction year related input parameters

1960	2016 (EnEV)
-U-value: Wall 1.2 W/m^{2}K Roof 0.58 W/m^{2}K; Floor 1.59 W/m^{2}K Windows 2.9 W/m^{2}K -Infiltration: 0.42 ACH -Thermal bridge: 0.1 W/mK -Heating system: Radiator, 70 °C supply temperature -Boiler efficiency: 0.73	-U-value: Wall 0.31 W/m^{2}K Roof 0.23 W/m^{2}K; Floor 0.24 W/m^{2}K Windows 1.1 W/m^{2}K -Infiltration: 0.105 ACH -Thermal bridge: 0.05 W/mK -Heating system: Radiator, 50 °C supply temperature -Boiler efficiency: 0.95

The envelope model also contains detailed parameters for describing features of building materials (e.g., thermal conductivity and specific heat capacity). These parameters influence the conduction heat losses as well as the wall surface temperature and likewise the convective heat gains. Hence, the influence of different structures on the heating load profile can be assessed. The envelope mainly consists of massive materials such as concrete or masonry, representing the German building stock [22, 23].

Regarding the technical systems, it is assumed that the heat for hot water and the space heating system is provided by the same gas boiler. The design installed capacity of this boiler has been determined according to DIN EN 12831 [24].

In IDA ICE, the domestic hot water demand can be modeled with a static schedule which is common practice in building simulation. However, this does not represent properly the complexity of occupant behavior [25]. Therefore, the hot water demand profile of an average German household has been created with DHWcalc. In this software tool, different hot water drawing types can be defined (such as larger amounts for a shower or smaller amounts for washing hands). For this purpose, the average hot water consumption profiles for the bathtub, shower, sink and other small draw-offs, that were defined by the German Passive House Institute, have been implemented into DHWcalc. The average daily consumption is 35 l/occupant [26]. DHWcalc determines the probability of a hot water draw at time step t as follows [27]:

$$p(t) = p_{day}(t) \times p_{weekday}(t) \times p_{season}(t) \times p_{holiday}(t) \tag{5}$$

The resulting mass flow dataset represents the daily varying user behavior better than a simple static schedule. This dataset has been connected to the standard plant model in IDA ICE. In this model, heat is generated by the boiler and stored in a tank at a temperature level of 70 °C or 60 °C. Within this tank, the hot water mixes with cold potable water (10 °C) and the space heating system return flow. All supply pipes for domestic hot water and the space heating system are also connected to this tank model. Domestic hot water is delivered at 50 °C while the supply temperature of the room heating system is 70 °C or 50 °C (see Table 2) [28]. The volume of the tank is assumed to be very small (approximately 1 liter) as the storage should not decouple the heat demand profile from the boiler heat production profile.

The desired indoor air temperature according to DIN V 18599 is 20 °C. However, as for some people, temperatures up to 24 °C are comfortable, an alternate desired indoor climate of 22 °C is considered

(Table 1). By analyzing the influence of higher indoor air temperature on diversity, implications for the influence of lower indoor air temperature can be deduced too. This is why it is not necessary to include another profile with a lower temperature in the analysis. Furthermore, the group of people who prefer lower indoor air temperature is represented in profiles with temperature setback. DIN V 18599 describes an optional turn-off of the heating system or a setback of the desired indoor temperature between 11 PM and 6 AM. In reality, this typically leads to a temperature decrease of about 2 to 3 °C. Likewise, these two alternate control cases have been modeled.

According to the average household size per square meter of living area in Germany, the single-family house has four people per household (PPH). In an average multi-family house of the chosen size, three people share one apartment [29]. These average household sizes are used for the user profiles U1 and U2 which represent a base case SFH (U1) and MFH (U2-B). Internal loads of 45 Wh/(m^2·d) in the base case SFH and 90 Wh/(m^2·d) in the base case MFH are modeled as to be constant over 24 hours according to DIN V 18599-10 [28]. However, as both household size and occupancy schedule may differ in reality, alternate user profiles have been created (see Table 3).

Table 3 User profile related input parameters

User profile		PPH	Building type	Internal load	Schedule internal loads	Schedule temperature setback
U1		4	SFH	45 Wh/(m^2·d)	Always on	11 PM - 6 AM
U2	A B	3	SFH MFH	34 Wh/(m^2·d) 90 Wh/(m^2·d)	Always on	11 PM - 6 AM
U3	A B	3	SFH MFH	34 Wh/(m^2·d) 90 Wh/(m^2·d)	Off weekdays 7 AM – 6 PM	11 PM - 5 AM
U4		2	MFH	60 Wh/(m^2·d)	Off weekdays 7 AM – 6 PM	11 PM - 5 AM

The user profiles U3 and U4 represent households with varying internal loads because occupants may be absent during the week (for work etc.). These occupants get up an hour earlier than in the base cases and stay away from the house between 7 AM and 6 PM. Also, the simulation settings of DHWcalc have been adapted accordingly to ensure that no water draw appears during this period of absence. For SFHs as well as MFHs a household size of three people is very common. For this reason, two versions (A and B) of U2 and U3 with adapted internal loads have been created.

The resulting heating load profile is simulated for the first week of January on a 15 minute time step ($t \in \{1 \dots 672\}$). Therefore, the TRY 04 Potsdam climate file is selected as required by EnEV 2016 [30]. In this specific week, the selected climate file contains the time step with the lowest yearly outside air temperature as well as the time step for which DHWcalc calculated an over-average hot water draw. Hence, the influence of climate driven peaks as well as hot water driven peaks can be investigated.

Fig. 5 shows resulting exemplary heating loads, divided into space heating load and domestic hot water load for a single-family house (left) with user profile U1, 2 °C heating setback, built in 1960 (blue) or in 2016 (grey) and a multi-family house (right) with user profile U2, 2 °C heating setback, built in 1960 (blue) or in 2016 (grey).

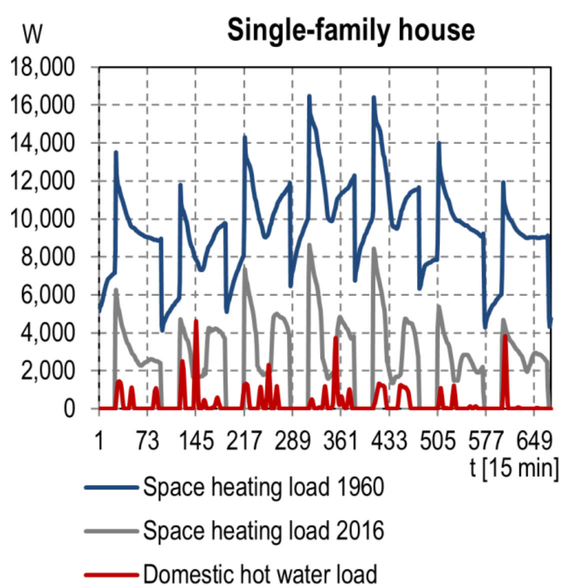

Fig. 5. Space heating load profiles and domestic hot water load profiles for exemplary buildings

The peak of the space heating load of the 1960s single-family house is about four times as high as the domestic hot water peak, while this difference is not as extreme regarding the 1960s multi-family house. Fig. 5 also demonstrates that in the case of a newly built 2016 building the domestic hot water load is even higher than the space heating load in certain time steps because these buildings are highly insulated. Furthermore, especially the case of the single-family house shows the influence of thermal mass on the space heating load profile. As the envelope of the 1960s buildings contains more massive materials, the heat can be stored longer. Therefore, the heating load of the 1960s single-family house does not rise again in the evening on some days of the simulated winter week, while this is happening in the 2016 buildings every evening (see Fig. 5, left).

2.3 Analysis of PLR growth in a German residential district

After simulating the 144 different heating load profiles, PLR can be analyzed. At first, the PLR of only two buildings is calculated. These buildings are either the base case SFH or the base case MFH and a second building with only one changed feature. The base case building was built in the 1960s, contains the base case user profiles (U1 SFH, U2-B MFH), has a desired indoor temperature of 20 °C without setback and is oriented north-south. Table 4 reveals the diversity rates that can be achieved with only one changed feature:

Table 4 Influence of single features on PLR

	Changed feature						
	Built 2016	U2	U3	22 °C	East-West	2 °C setback	3 °C setback
Base case SFH	3.19%	0.89%	5.69%	0.00%	0.00%	1.16%	2.42%

	Built 2016	U3	U4	22 °C	East-West	2 °C setback	3 °C setback
Base case MFH	0.88%	12.09%	9.34%	0.00%	0.00%	0.67%	0.00%

Table 4 illustrates that certain features may lead to higher diversity than others. Regarding the MFHs, in which the hot water demand has a higher influence (because of a higher occupant density), a different user profile leads to a higher diversity while for the more climate dependent SFHs a modified envelope construction with a different insulation level results in higher diversity.

In the next step, all individual 144 heat demand loads are aggregated to a singular heating load profile which represents the heating demand of the urban district. This “adding process” is conducted one at a time, to analyze the growth of PLR (see Fig. 5). The following order has been chosen: Building 1 is the base case SFH. The 72 buildings firstly added are all single-family buildings of which 36 have been built in 1960 (building 1-36) and 36 in 2016 (building 37-72). Starting with building 73, all MFH profiles are added to the district. The parameter settings for building type ("SFH" or "MFH") and build year ("1960" or "2016") can be combined with the simulation parameters for describing three different load profiles (U1-U3 for SFHs and U2-U4 for MFHs, see Table 3). A change of the user profile is marked with intervals in Fig. 6. Furthermore, there are 12 possible feature combinations regarding orientation, comfort temperature and temperature setback control within each user profile (Table 5).

Table 5 Possible feature combinations 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 control	None	2 °C	3 °C	None	2 °C	3 °C	None	2 °C	3 °C	None	2°C	2 °C

For example, in Fig. 6 building 49 is a single-family house built in 2016. Its occupants behave according to user profile U2 (see Table 3). The building is orientated North-South, the comfort temperature is 20 °C, and there is no temperature setback control (see Table 5). For simulating Building 50 afterward, the only change in simulation parameters is the activation of a temperature setback control of 2 °C.

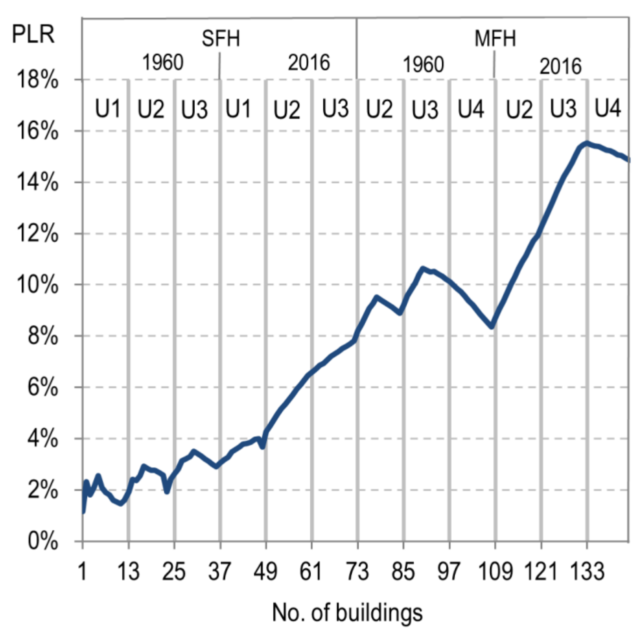

Fig. 6 PLR growth analysis

Fig. 6 shows that for the chosen test district a PLR of approximately 15% can be reached after the aggregation all buildings. However, PLR decreases appear during the adding process, too. The addition of buildings constructed in 2016 leads mostly to a growth of PLR. The reason for this is a stronger influence of the hot water demand on the maximum peak load in newly constructed, better-insulated buildings (see Fig. 5). While adding the first more climate driven heating loads of the 1960s SFHs, PLR decreases appear regularly when the loads of the buildings 7-12 of one user profile (see Table 5) are added to the district. This can be explained by the changed comfort temperature compared to buildings 1-6. A raise of the comfort temperature doesn´t change the shape of the load profile but shifts it up along the y-axis. Hence, the maximum climate driven peak of buildings 7-12 appears in the same time step as the peak of buildings 1-6. Buildings with temperature setback control either increase or decrease the PLR depending on the time step in which the heating-up process starts in the morning. If this time step, which usually contains the daily peak load, is different from the other buildings in the district, the PLR will increase. The building orientation does not contribute to PLR growth as the influence of solar radiation on the heating load profile mainly appears around noon whereas the maximum peak load always turns up in the early morning. In Fig. 6 the user profile related interval borders reveal that PLR increases if buildings with a different user profile are added to the district (time step 13, time step 25, time step 37, etc.). The only exception is the addition of buildings with user profile U4 (time step 97 and time step 133).

Fig. 7 shows the shapes of the up-scaled load profiles of exemplary MFHs with user profile U4 (left) or user profile U3 (right). The peak in the U4 case appears in the same time step (432) as the district´s heating load peak, while the peak in the U3 case appears at a different time step (216). As PLR increases if peaks appear in different time steps, the addition of U3 buildings leads to an increased PLR whereas the addition of U4 buildings leads to a lower PLR.

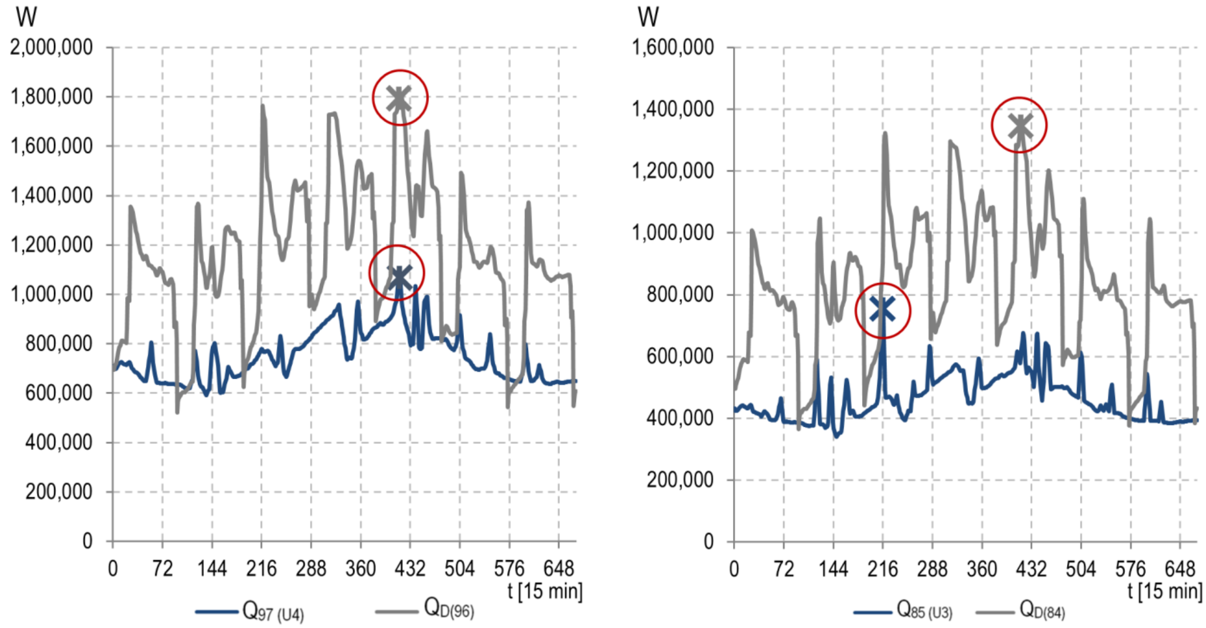

Fig. 7. Comparison of U4 load profile shape (left) and U3 load profile shape (right) to the temporary district load profile shape (15 minutes time step)

However, it should be noticed that $Q_{D(84)}$ also has a peak in time step 216 which is slightly below the peak in 432 (Fig. 7, right). Therefore, including only a few more U3 buildings with a dominant peak in time step 216 to the district would shift the maximum peak load of the district from time step 432 to time step 216. Likewise, the further addition of U3 buildings would lead to a decrease of the PLR. This confirms that the influence of single building characteristics on district diversity is always dependent on the characteristics of all other buildings within this district.

Consequently, the conducted analysis leads to the following statements:

- PLR increases if 2016 buildings are added to a test district with 1960s buildings
- PLR increases if MFHs are added to a district with SFHs
- PLR increases if buildings with temperature setback control are added to buildings without temperature setback control
- PLR increases in most cases if buildings with different user profiles are added
- PLR does not necessarily grow if more buildings (beyond a certain point) are added to the district

These statements can be further explained considering the shape of the demand profile of the test district containing all 144 buildings (see Fig. 8).

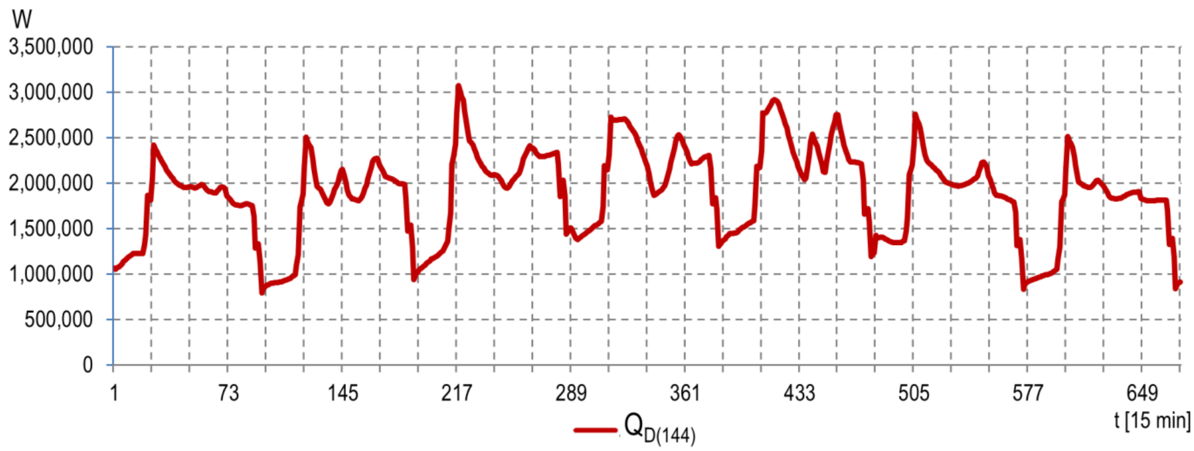

Fig. 8. Total test district heating load profile (15 minutes time step)

Fig. 8 illustrates that the typical morning peak load appears on all days of the simulated week. Therefore, one can conclude that the temperature setback control has a strong influence on the maximum peak load. Without temperature setback, the maximum peak load is lower, especially in the 1960s buildings (about 27% lower). However, without temperature setback the yearly energy consumption in kWh is increased by 8% in the 1960s buildings. This effect is weaker in the 2016 buildings because lower heating loads are needed for the heating-up process (see Fig. 5).

The shape of the district´s heating load profile in Fig. 8 resembles the average daily profile shown in Fig. 3. However, compared to the profile shape in Fig. 3, Fig. 8 also shows several smaller peaks. This can be explained by the stronger influence of domestic hot water in the created profiles. Mainly climate driven peaks appear slightly broader than hot water driven peaks as the outdoor air temperature usually remains at a certain temperature level for several hours (see time step 301 and 415). In the chosen climate file, the lowest outdoor air temperature peaks appear in time steps 336 and 417. Moreover, in this example, the time steps 301 and 415 appear on weekend days with less hot water consumption in the early hours. The peak in time step 217 is mainly hot water driven, although it also spans several time steps. This indicates that the hot water peak of the involved singular building loads varies around a certain time step leading to a broader peak in the aggregated profile. The variation of the hot water peak can be explained by the diverse occupant behavior which has been simulated in DHWcalc. In contrast to that, if the peak is climate driven it appears at exactly the same time step for all buildings with the same insulation level. Moreover, this is the reason for less diversity in districts with climate driven peak load (mostly old 1960s buildings) than in districts with hot water driven peak load (mostly newly built, highly insulated 2016 buildings). The analysis of the 144 heating load profiles has shown that the maximum peaks appeared exclusively next to time step 217 or 415. Consequently, the heating load diversity is generally limited.

3. Application of the diversity analysis results in a district heating simulation model

The former study has illustrated that benefits from the heating load diversity can be achieved in a certain district structure. Hence, a central plant would require a smaller installed capacity. A real technological concept that consists of only one heat source for several buildings is a district heating system. Because of distribution losses, the central plant has to produce more heat than the aggregated heat production of individual plants in the same buildings, though. Therefore, it is crucial to analyze whether the benefit from diversity effects outweighs the disadvantage of distribution losses. Another constraint is the supply water temperature, which has to be equal for every connected building (assuming no local equipment is available to raise the supply temperature). This excludes some of the identified beneficial load profile combinations from the previous analysis.

In order to analyze diversity in the context of district heating, a district with a very diverse load profile mix has to be created to emphasize the diversity effects. The following six different heating load profiles (see Table 6) have been selected from the former analysis as they are very diverse to each other according to the PLR calculation (see Fig. 9).

Table 6 Selected heating load profiles for scenario analysis

Profile abbreviation	User profile	Orientation	Comfort Temperature	Temperature control, setback
SFH 1	U1	North-South	20 °C	2 °C
SFH 2	U2	North-South	20 °C	2 °C

SFH 3	U3	North-South	20 °C	2 °C
MFH 1	U2	North-South	20 °C	2 °C
MFH 2	U3	North-South	20 °C	2 °C
MFH 3	U4	North-South	20 °C	2 °C

Fig. 9 shows that with every added building load profile (described in Table 6) PLR increases further. Moreover, the chosen buildings can be supplied at the same temperature level which is crucial for the district heating system.

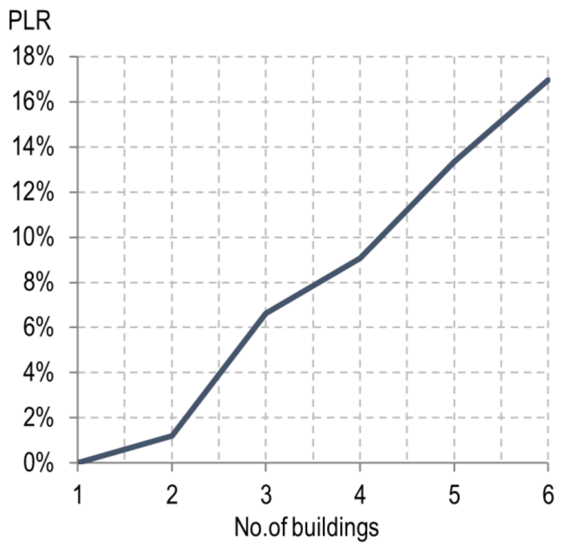

Fig. 9. PLR of selected high diverse heating load profiles

Distribution losses are strongly dependent on the piping grid length. For this reason, a second factor, the load density, is introduced. In the context of electrical engineering the load density is defined as the aggregated total load per area [31]. Likewise, a high load density implies that more heat can be delivered to the buildings with reduced distribution losses per building as these buildings stand closer together.

The pipe lengths for the scenario analysis are chosen according to Dötsch [31] (Table 7).

Table 7 Supply pipe lengths - District heating model [31]

	Rural Scenario	City Scenario
Supply pipe length SFH	25 m/building	14 m/building
Supply pipe length MFH	6 m/apartment	2 m/apartment

Apart from that, an average pressure loss of 100 Pa/m is assumed [32]. The earth temperature is described based on measurements in the climate zone Potsdam. These measurements were conducted on a monthly basis. Thus, in the simulation model the earth temperature is constant during the analyzed week in January [33]. Furthermore, this implies that the distribution losses will be mainly influenced by the heating load profile expressed by the water mass flow, as the supply temperature is constant in the simulation model.

In order to analyze the effects of density a “City” and a “Rural” scenario for a given area have been modeled that resemble the building distances of district type ST 1 and ST 8 in the district typology defined by Erhorn et al. [34, 35] (Fig. 10).

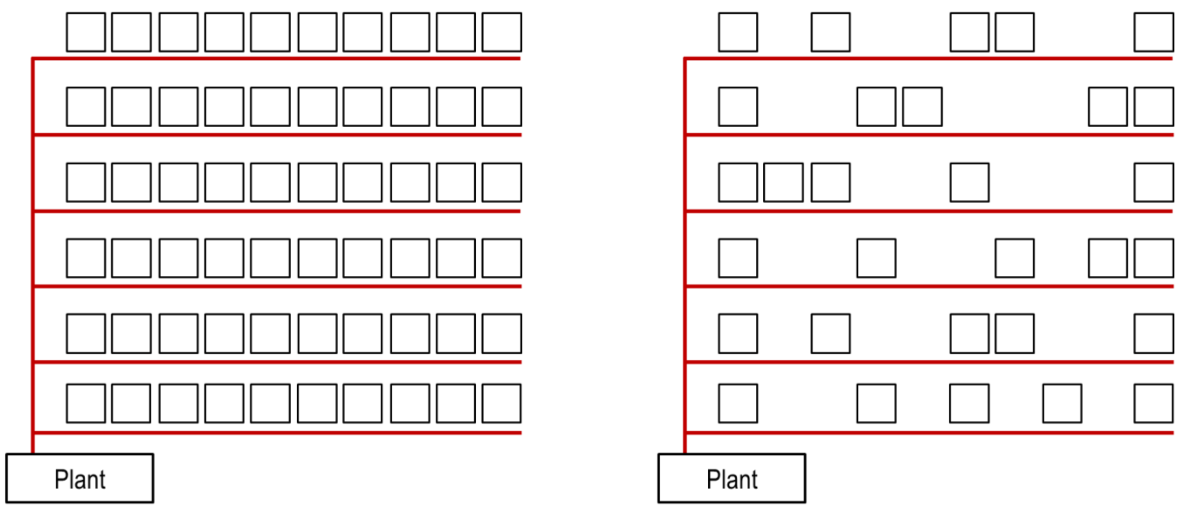

Fig. 10. Structure of the “City” (left) and “Rural” (right) district type

Moreover, the supply temperature has a high influence on the distribution losses. For this reason, both district types are simulated at first only with buildings built in 2016 that require 50 °C supply temperature [36] and secondly exclusively with 1960s buildings that are operated with a supply temperature of 70 °C for space heating.

The district heating system is modeled in IDA ICE to calculate the minimum peak load considering distribution losses. Table 8 summarizes the input parameters for the defined scenarios. As same as in the PLR analysis, the simulation is conducted for the first week of January in a 15 minutes time step.

Table 8 Input parameters, scenario analysis City/Rural, 1960s/2016

	City 2016	Rural 2016	City 1960	Rural 1960
Supply temperature	50 °C	50 °C	70 °C	70 °C
Total pipe length	780 m	915 m	780 m	915 m
No. of SFH 1	10	5	10	5
No. of SFH 2	10	5	10	5
No. of SFH 3	10	5	10	5
No. of MFH 1	10	5	10	5
No. of MFH 2	10	5	10	5
No. of MFH 3	10	5	10	5

The simulation reveals that distribution losses require an increase of the district supply temperature by 2 °C in the city scenarios and by 3 °C in the rural scenarios compared to individual supply. The resulting district heating (DH) peak load is shown in relation to the corresponding AIS peak load and CS peak load in Fig. 11.

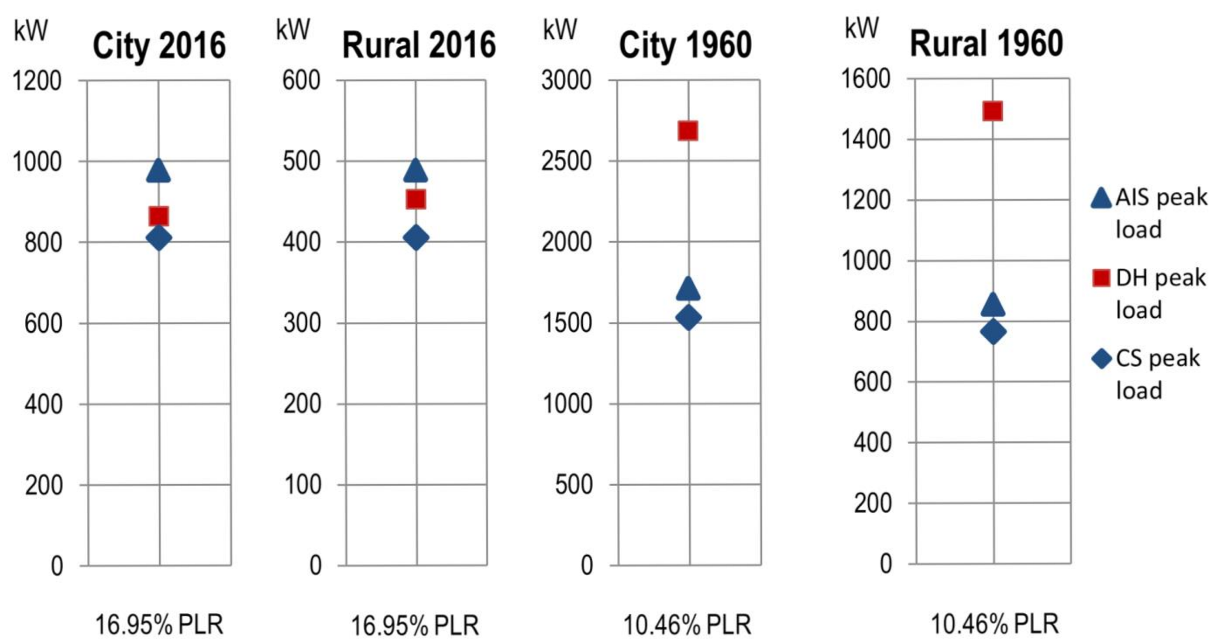

Fig. 11. Results: Scenario analysis City/Rural, 1960s/2016

Fig. 11 shows that the simulation of the 2016 scenarios leads to a DH peak load between the two theoretical figures AIS peak load and CS peak load (see chapter 1.2). Hence, at least parts of the identified diversity effects occur in these cases. In the City 2016 scenario, the DH peak load is closer to the ideal CS peak load as the distribution losses are smaller than in the corresponding Rural 2016 scenario. In the 1960s scenarios, DH peak load is almost twice as high as the AIS peak load. One explanation for that is the higher supply temperature of 70 °C required for space heating. Former research has shown, that district heating systems operated on higher temperatures are much less efficient [37]. Moreover, in this scenario the supply temperature is higher than the hot water temperature (50 °C). While in an individually supplied building both demands can be addressed separately by the boiler, the mass flow for hot water is unnecessarily heated up to 70 °C in the created district heating model, which leads to further inefficiency. Hence, the benefit of a reduced peak load in a central plant system is completely eliminated by the disadvantageous distribution losses in a system with high supply temperature.

The broader distance between the AIS peak load and the CS peak load in the 2016 scenarios, which corresponds to the numerator of the PLR fraction, indicates the greater diversity visually. The PLR remains constant within the same build year group as it does not consider distribution losses (see formula 4). The higher PLR in the 2016 scenarios can be explained by the higher influence of the hot water demand on the total heat demand. Fig. 12 shows that the mainly hot water driven peak (time step 217) is crucial for the CS peak load in the 2016 scenarios while the mainly climate driven time step 415 determines CS peak load in the 1960s scenarios.

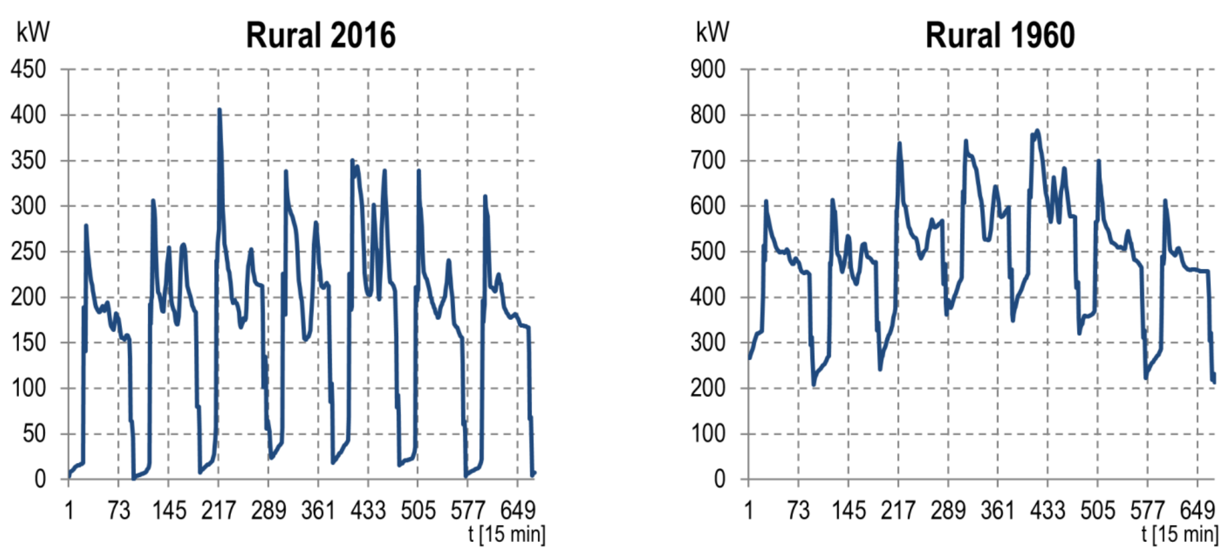

Fig. 12. Visualization: $Q_{D,Rural\ 2016}$ (left) and $Q_{D,Rural\ 1960}$ (right), (15 minutes time step)

Further simulation results are presented in Table 9.

Table 9 Scenario analysis: Distribution losses, Pump electricity

	City 2016	Rural 2016	City 1960	Rural 1960
Total distribution losses [kWh]	1,350	2,415	2,581	3,424
Distribution losses per building [kWh]	22.5	80.5	43.0	114.1
Total pump electricity [kWh]	227	132	1,230	722
Pump electricity per building [kWh]	3.8	4.4	20.5	24.1

The peak loads of the City scenarios in Fig. 11 are almost twice as high as those in the Rural scenarios because these scenarios contain twice as many buildings. For the same reason, the pump has a higher electricity consumption in the City scenarios as a larger mass flow has to be conveyed. The distribution losses are strongly dependent on the pipe length. As the overall Rural pipe length is longer than in the City scenarios, the distribution losses increase, too. The higher distribution losses in the 1960s scenarios can be explained by the higher mass flows and the higher supply temperature as the pipe lengths stay constant.

According to Fig. 11, DH peak load is closest to the CS peak load in the City 2016 scenario. For this reason, a case study with varying shares of each building type is conducted for this scenario in order to gain further perceptions (Table 10). First, the ratio between SFHs and MFHs is changed. Second, the occupant density is modified by raising the share of buildings with an either higher or lower number of people per household.

Table 10 Input parameters for the "City 2016" case study

	75% MFH	75% SFH	High occupant density	Low occupant density
No. of SFH 1	5	15	20	5
No. of SFH 2	5	15	5	5
No. of SFH 3	5	15	5	20
No. of MFH 1	15	5	20	5
No. of MFH 2	15	5	5	5
No. of MFH 3	15	5	5	20

The parametric study shows that the PLR in the 75% MFH case is higher than in the 75% SFH case (Fig. 13) which can be explained by the higher influence of hot water demand.

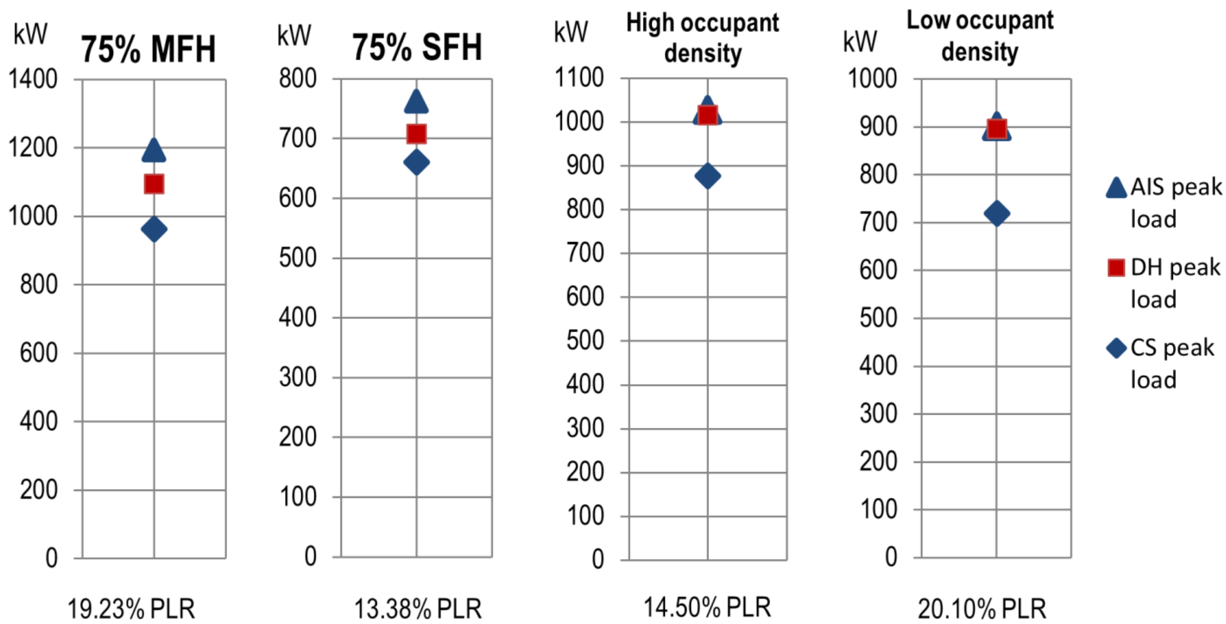

Fig. 13. Results: Case study, City 2016 scenario

In the "high occupant density" case, the variability of the time step in which the main hot water peak appears decreases as one user profile is dominant, while the influence of hot water on the total heat demand generally increases as more occupants live in the district. This leads to a high peak in almost a single time step which decreases the diversity (Fig. 14, left). In the "low occupant density" case, the influence of hot water demand is reduced leading to a former hot water driven peak (time step 217) at the same level as the climate driven peak in time step 415 (Fig. 14 right). This combination increases the diversity.

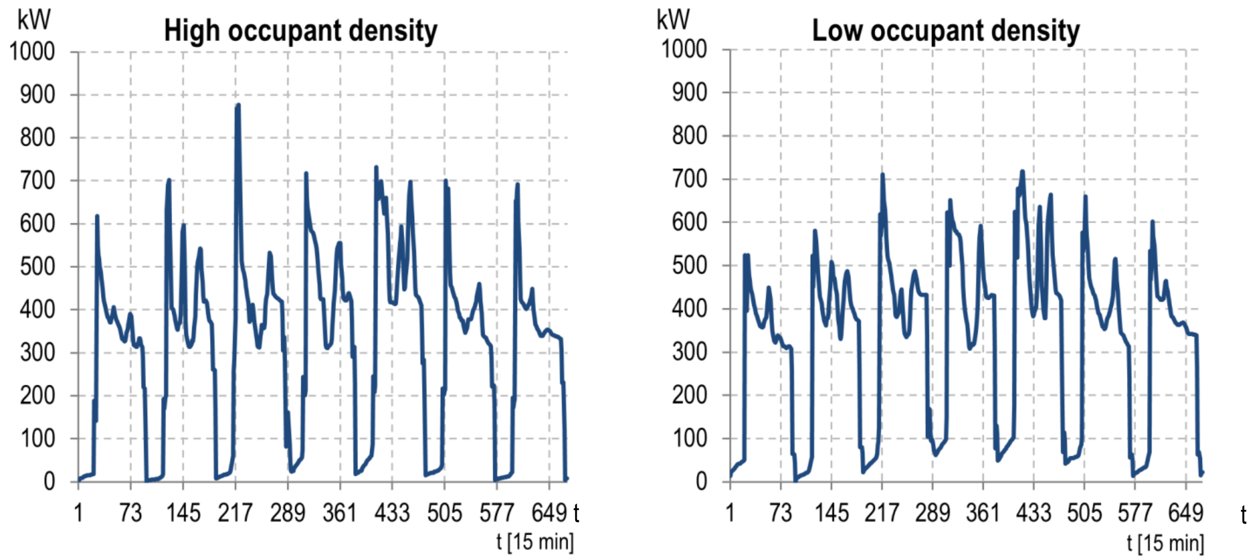

Fig. 14 Visualization: $Q_{D(60)}$ high occupant density case (left), $Q_{D(60)}$ low occupant density case (right), (15 minutes time step)

In all four cases, the difference between the CS peak load and the DH peak load is greater than in the original "City 2016" scenario (see Fig. 11). In this previous scenario, each of the six load profile types defined in Table 6 appears ten times in the modeled district (see Table 8), while in the case study (Fig. 13) the number of each profile is modified (see Table 10). This illustrates that most of the diversity benefit can be used in districts in which different heating load profiles are represented equally.

The conducted studies have shown that the PLR index can be used for analyzing heating load diversity. However, the approach still contains some limitations. One weakness is the application of static hot water demand profiles that lack diverse and stochastic occupant behavior in hot water use. In further research, this simplification should be addressed by embedding an occupant behavior model in IDA ICE [38] as a higher PLR might be achieved. Further research can also look at district systems serving mixed-use buildings, such as residential and commercial buildings. This combination may have a much higher PLR because residential buildings tend to have peak heat loads in the early morning while these occur in commercial buildings at a different time. Moreover, the current district heating model could be extended by adding storages and top-up boilers to the single buildings in order to decouple single building demand peaks from the central system. In this context, a concept with decentralized electrical hot water generation should be analyzed too as the current system with central hot water generation is usually not efficient during the summer season. Finally, district heating systems with innovative elements such as solar thermal plants and seasonal storages should be investigated as they might lead to a further reduction in installed capacity.

4. Conclusion

This study employs a peak load ratio (PLR) index to quantify the influence of identified building and occupant related characteristics on the heating load diversity within a residential district in Germany. By applying the developed methodology, the analysis leads to the following findings. The theoretical analysis about the influence of singular building characteristics on residential district diversity shows that especially the combination of buildings with different construction years, different temperature setback controls and different user profiles may increase the PLR. In the second part of the study, a district heating system is modeled to confront the diversity benefit with the disadvantages of heat distribution. The scenario analysis finds that especially in district heating systems with high density and low supply temperature the diversity benefit leads to a smaller minimum installed capacity regarding the central plant. Furthermore, the conducted study reveals that the domestic hot water demand has a high influence on the PLR. In future research, the application of the PLR will be extended to additional building types and technical systems in order to gain further insights about heating load diversity in urban districts.

Acknowledgment

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