Mitigation and adaptation in multifamily housing: overheating and climate justice

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Abstract
Can thermal retrofit measures also enhance summer heat resilience and climate justice? Two common building types of multifamily dwellings in Central Europe are investigated: the ‘Gründerzeit’ and post-war large-panel construction along with their different inhabitant demographics. Thermal simulations and demographic surveys were undertaken for dwellings in both building types to evaluate the effectiveness of retrofit measures in reducing winter heat demand and to understand the impacts on summer overheating. Results indicate that standard retrofitting measures can reduce the overheating risks. The high summer temperatures on the top floor can be significantly lowered to values comparable with the ground floor. The remaining overheating in highly exposed rooms is reduced by additional selective adaptation measures. Adaptation requires more than technical interventions. Demographic surveys conducted for both building types show that different social groups are affected. The economics of retrofit requires policy clarity to avoid placing additional burdens on economically disadvantaged people. Inhabitants’ active involvement in night-time ventilation are vital for avoiding overheating. Appropriate affordances and a clear guidance for manual window opening/closing can reduce overheating. However, inhabitants who are unable to act (e.g., the elderly, immobile or those with chronic diseases) will be increasingly vulnerable and disadvantaged by increased exposure to overheating.

Practice relevance
The existing approaches for reducing heating demand and their impacts on overheating are examined for two common building types in Central Europe: the Gründerzeit and post-war large-panel multifamily housing. The evidence of physical effects and social interdependencies provides a basis both for decision-makers to select suitable measures, and for inhabitants to apply appropriate behavioural practices. Thermal retrofitting strategies for reducing winter heating demand can lead to enhanced resilience to hot summer weather, but also entail inhabitants’ active involvement. Additional technical measures are needed to ensure reduced levels of overheating. Inhabitants’ practices have a significant influence on resilience and the reduction of overheating. Therefore, technical interventions must be accompanied by clear strategies to empower inhabitants to control internal temperatures using natural ventilation. Elderly or ill inhabitants may not be able to perform these practices and, therefore, remain vulnerable. Increased rents caused by retrofits may displace socially disadvantaged inhabitants.

Keywords: adaptation; building stock; climate justice; housing; inhabitants; mitigation; overheating; resilience; retrofit

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1. Introduction
1.1. Background
The worldwide building sector accounts for 25% of global fossil fuel-related greenhouse gas (GHG) emissions, mainly used for space heating and cooling (Fosas et al. 2018). Particularly in the European Union (EU), dwellings are responsible for more than one-quarter of the total primary energy demand (Fabi, Andersen, Corgnati, & Olesen 2012). As existing buildings in the EU and other developed countries are expected to form 70–80% of the whole built stock in 2050 (Vellei et al. 2016), the retrofitting of existing buildings to reduce their fossil fuel-related GHG emissions is a prime objective. In this context, an increasing overheating risk due to improved insulation and airtightness is predicted (Mavrogianni et al. 2015; Mulville & Stravoravdis 2016). The frequency and severity of heatwave events is projected to increase in future (IPCC 2014). Hence, overheating risk analysis of such retrofitted buildings is essential.

Two factors are of great importance in adapting residential buildings to climate change (CC):

- **CC mitigation** by reducing further GHG emissions of the building operation sector.
- **CC adaptation** of buildings to cope with the incremental impacts of CC, especially the risk of overheating.

For moderate and cold climates, GHG emissions can be reduced by improving the insulation of buildings and by shifting to heat generation with low CO\textsubscript{2} emissions. However, CC adaptation of buildings entails reducing the overheating risk for residents during warm weather. This must avoid the use of mechanical cooling in order to comply with mitigation strategies.

One of the central challenges is to implement such changes without exacerbating social injustice. It is essential not to affect adversely social disadvantaged groups such as elderly or low-income households or by creating differences in quality of life.

1.2. Study aims and objectives
This study investigates the complex interactions of CC mitigation and adaptation measures for residential buildings focusing on aspects of overheating and climate justice. The reasons for this focus on representative multifamily houses (MFH) are as follows:

- By the mid-21st century, 66% of the world population is projected to live in cities (UN DESA 2015) and, thus, typically in MFH.
- The high degree of sealed surfaces and solar absorption in large cities leads to an additional heat burden of MFH inhabitants by the urban heat islands (Oke 1988) within the city.
- The residents of MFH have limited possibilities to transform their dwelling into a CC mitigated and adapted home in comparison with owners of detached houses.
- With respect to the issue to climate justice, residents of MFH are strongly dependent on the actions of the building owner. Additionally, residents of these dwellings, especially tenants, usually have a lower income compared with those living in detached houses. However, from a CC mitigated and adapted MFH, numerous residents can benefit as a group.

The specific focus of this investigation is two regionally prevalent housing types in the context of Central European climate conditions. The setting in central Germany is a representative European climate with a high heating demand in winter, and passive cooling measures are usually sufficient to provide adequate heat protection in summer (without the need of cooling devices).

Two different building types were investigated, one from the turn of the 20th century, the so-called *Gründerzeithaus* (GZH) and the other from the 1960s–90s, the large-panel construction (LPC) MFH to understand how CC mitigation measures interact with CC adaptation measures to reduce overheating for residents. The impacts of the chosen measures are analysed using thermal building simulations for both buildings to identify the most effective and efficient forms of retrofitting.

The choice of the two building types is also grounded on the different social structures of the residents in the LPC and the GZH. While the LPC is often inhabited by socially disadvantaged groups (residents with lower incomes and a higher percentage of elderly people; see section 0), the GZH is a typical dwelling for residents with an average income and better distributed age structure.

A key question is whether the thermal comfort and building operation costs, as measured by the heating and cooling demand, differs in the non-retrofitted versus the retrofitted buildings. The objective is to determine how CC mitigation and adaptation measures change residents’ well-being.

The research is structured as follows. First, an architectural analysis of the two MFH to create realistic building simulation models of the whole buildings and resident structure in both MFH is determined. Building simulation models are validated using temperature and CO\textsubscript{2} measurements in dwellings conducted on different floors during summer 2019 and 2018. The non-retrofitted actual state of both MFH to gain information on heating demand and
overheating risk is simulated. Individual CC-mitigation measures to the buildings to reduce heating demand and proof of possible changes in overheating is implemented along with individual CC adaptation measures to the buildings to reduce overheating.

Different studies have addressed the question of how retrofitting affects overheating risk (Fosas et al. 2018; Mavrogianni et al. 2012; Porritt et al. 2013). They indicate that overheating risk increases with floor level in high-rise structures, with the strongest heat load in the attics (Hamdy, Carlucci, Hoes, & Hensen 2016; Mavrogianni et al. 2012). Enhanced roof insulation and window retrofitting decreases overheating risk (Mavrogianni et al. 2012). There have been contradictory findings on the use of exterior wall insulation: a slight reduction (Fosas et al. 2018; Porritt et al. 2013) or a slight increase of overheating risk (Mavrogianni et al. 2012; Mulville & Stravoravdis 2016). Internal wall insulation increases the overheating risk (Fosas et al. 2018; Tink, Porritt, Allinson, & Loveday 2018). Finally, external shading has been found to reduce overheating strongly (Porritt, Cropper, Shao, & Goodier 2012), while user behaviour, especially window ventilation behaviour, significantly reduces heat stress (Mavrogianni et al. 2014; Porritt et al. 2013). However, this body of research on overheating in residential buildings has primarily been done in the UK.

Approximately 40% of all publications related to the general topic of overheating in residential buildings (monitoring, simulation, health, surveys) are conducted in the UK (Chen 2019). This is very surprising because the UK typically has relatively cool summers (except London because of urban heat islands) compared with other more southern countries in Europe. Residents in France, Spain or Germany are known to be affected by higher summer temperatures, and buildings are typically not equipped with cooling devices. This is verified by Thomson, Simcock, Bouzarovski, & Petrova (2019) who compared the heat burden for different countries in Europe, with the separate mention of share of low-income residents. The present investigation contributes to our knowledge of factors in a broader continental European context by undertaking an overheating risk analysis for MFH in Erfurt and Dresden in Germany. This will extend the detailed knowledge already present for the climatic conditions and UK building typologies.

1.3. Climate justice issues

The concept of climate justice includes a set of ethical and political considerations for those made vulnerable or disadvantaged by CC. This can be within a society (a country, region or city) or between countries. For the focus of this study, at least two main issues are discussed in relation to the residents of MFH: fuel poverty (financial disadvantage) and health risk/well-being in the context of living in MFH.

Fuel poverty can be correlated to heating and cooling the dwelling which affects households with a low income (Hajat, Kovats, & Lachowsycz 2007). In Germany, the focus of fuel poverty has been on heating, since mechanical cooling is uncommon in Germany. However, hotter summers caused by CC is expected to shift climate zones in future. If mechanical cooling were to be implemented in German dwellings, this would lead to negative environmental, financial and social consequences for households, and summer fuel poverty (Mavrogianni et al. 2015).

Heat stress-related health risk and other limitations on well-being are already major concerns in Germany. However, the investigation of heat stress is highly complex and dependent on multiple variables, that is, health, age, agency or social isolation (Hajat et al. 2007; Mavrogianni et al. 2015). Vandentorren et al. (2006) and Vardoulakis et al. (2015) investigated the vulnerability of residents to summer heat and showed that residents with the following characteristics have an enhanced heat-related health risk:

- Elderly people with lack of mobility or chronic diseases.
- Low social status.
- Socially isolated individuals.
- Living in dwellings that lack thermal insulation, have the bedroom directly beneath the roof or small dwelling area.

Elderly people aged over 65 years are generally affected by the overheating of their homes because they spend a majority of their time indoors (>90%) during the summer (Basu & Samet 2002). In addition, heat stress is more likely to have adverse effects, including fatalities, among residents at the lower end of the socioeconomic spectrum (Thomson et al. 2019). In terms of well-being, van Loenhout et al. (2016) found that an increase of 1°C of indoor temperature raised the risk of sleep disturbance by 24% (in the temperature range of 20.8–29.3°C). However, Head et al. (2018) found a lack of detailed epidemiological studies investigating the effect of indoor dwelling temperature on health outcomes.

2. Methods

2.1. Residential building types

Two representative examples of MFH with different design and residents’ social structure are the types GZH and LPC. GZH buildings (Figure 1a,b) were primarily constructed in Germany in the period 1870–1918 (categorised as MRG3 by Schinke et al. 2012), and similar to those found in old town centres throughout Central Europe. Their thick brick walls are not insulated and, characteristically, they have a saddle roof as well as wooden beam ceilings in the individual flats. In contrast, LPC buildings (Figure 1c,d) were erected between 1960 and 1990 as a typical form of social housing
(categorised as MR6 by Schinke et al.). The walls consist of large panels of reinforced concrete with a thin core of insulation, while the ceilings are made of reinforced concrete. MFH types represent 53% of the German residential building stock (see Appendix A). Both buildings are inhabited and located in city districts with other similar building types. The LPC is located in Dresden and the GZH is in Erfurt. In each studied building, no elevator is installed.

2.1.1. MFH resident characteristics

The climate justice aspect involves understanding the demographics and vulnerability: the residents’ age, income and lifestyle. Fortunately, user surveys were conducted by Baldin and Sinning (2019a, 2019b) for the neighbourhood types in which the two MFH are located. As the majority of the residential buildings in the surveyed neighbourhoods

![Figure 1](image-url): (a) East-facing street view of the Gründerzeithaus (GZH) building; (b) floor plan of the GZH; (c) the large-panel construction (LPC) building seen from the south-west; and (d) floor plan of the retrofitted LPC multifamily housing (MFH). The depicted top-floor plans are similar to the other floors in both buildings.
consist of LPC (Dresden) and GZH (Erfurt) buildings, respectively, the survey by Baldin and Sinning can be used to draw conclusions about the residents of the two selected MFH and compare them with each other. In the two studies, not only occupant data but also their behaviour during heatwaves were surveyed \((n = 178\) for Dresden, \(n = 203\) for Erfurt). The most relevant data for the focus of the present study are summarised in Table 1. While almost half the residents in the LPC district are pensioners, in the GZH neighbourhood type there were fewer than one-fifth. Almost half the residents live alone in the LPC neighbourhood compared with one-quarter in the GZH neighbourhood. Household income is somewhat lower in the LPC compared with the GZH neighbourhood, although the effect of the smaller household size with a high proportion of single residents is a likely factor.

Block population data from the immediate surroundings of the two MFHs provided a basis for evaluating the residents' age structures for both representative buildings and the immediate vicinity (Figure 2) (Landeshauptstadt Dresden 2019; Landeshauptstadt Erfurt 2020). The high share of older people for the LPC is even higher compared with the whole LPC district (Table 1). As both buildings have no elevators, it is assumed that elderly residents typically inhabit the lower floors in both types of buildings. However, there may be people with other vulnerabilities who are in the upper or top floors: people who are immobile, elderly or with chronic medical conditions. The survey did not identify people with these conditions.

Owing to the age structure and high proportion of people living alone, the LPC district is more likely to be vulnerable to summer heat. Therefore, special attention should be paid to adaptation measures for these residents.

### 2.2. Building properties

The two chosen buildings of type GZH and LPC are very different in terms of their physical structure and architectural design. While the GZH building has a stucco façade and a saddle roof with dormers, the LPC has a clear cubic structure with no decorative elements on the façade and a ventilated cold roof (Figure 1a,c). The two buildings have similar footprints of 230 and 195 m², respectively. However, the LPC building has six full storeys in contrast to only four full storeys and a converted attic in the GZH building, giving total floor areas of 1070 and 725 m², respectively. The LPC has three dwellings on each level with floor areas between 55 and 65 m² (cf. Figure 1d), while each floor of the GZH building has only two flats each with a larger floor area of about 80 m² (cf. Figure 1b). The LPC MFH has a total of 18 dwellings compared with the GZH with only 10 flats.

**Table 1**: Resident data conducted from the citizen survey for the districts of the investigated large-panel construction (LPC) (Dresden, Germany) and Gründerzeithaus (GZH) building (Erfurt, Germany), respectively.

| LPC district (%) | GZH district (%) |
|------------------|-----------------|
| **(a) Employment** | | |
| Pupil, student, trainee | 2% | 18% |
| Employed | 31% | 58% |
| Unemployed | 13% | 5% |
| Non-Working | 4% | 2% |
| Pensioner | 48% | 18% |
| **(b) Net household income per month** | | |
| <€1000 | 23% | 14% |
| €1000–1500€ | 27% | 21% |
| €1500–2000€ | 20% | 15% |
| €2000–3000€ | 19% | 26% |
| >€2000 | 11% | 25% |
| **(c) Household lifestyle** | | |
| Alone | 46% | 24% |
| Alone with a child | 6% | 4% |
| With partner, no child | 30% | 28% |
| With partner and child | 12% | 26% |
| Flat-sharing community | 3% | 15% |
| Other | 2% | 3% |

Sources: Baldin and Sinning (2019a, 2019b).
The structural components of the buildings are also different (Table 2). The thick exterior and interior brick walls of the GZH building provide considerable thermal storage capacities, helping to mitigate extreme summer temperatures. In contrast, the large panel elements of the LPC building include a thin insulating layer in the exterior wall, ensuring a lower transmission heat loss ($U$-value) in winter than the brick walls of the GZH building which lack such insulation. The buildings have different ceiling constructions and characteristics. The GZH building has suspended wooden beam ceilings with a low $U$-value, and low heat storage capacities are found; the LPC building has prestressed concrete ceilings which offer considerable heat transmission from one level to the other as well as a high heat storage capacity. The top floors of the two buildings are also rather different. Originally, the attics of GZH MFHs were not used for residential purposes. However, today most attics have been converted into living space, often using dry wall construction, which offer low heat storage capacity. The GZH building in the present study has such a converted attic. Its well-insulated roof contrasts with the ventilated cold dwelling roof on top of the top floor of the LPC. Although the LPC roof is not insulated, the top-floor ceiling has a thin layer of insulating layer. Both buildings have cellars as well as balconies. The latter act as shading elements on the west-facing facades and, in the case of the LPC, also on the south-facing facade. The balconies of the GZH attic dwellings have used awnings.

Table 2: Structural components of the GZH and LPC multifamily housings (MFHs).

| Component        | GZH building                                                                 | LPC building                                                                 |
|------------------|------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Exterior walls   | Levels 1 and 2: 51 cm brick walls, $U = 1.0 \text{ W/m}^2\text{K}$          | Sandwich panel elements: 14 cm reinforced concrete/6 cm mineral wool/6 cm reinforced concrete, $U = 0.6 \text{ W/m}^2\text{K}$ |
|                  | Levels 3 and 4: 38 cm brick walls, $U = 1.2 \text{ W/m}^2\text{K}$          |                                                                              |
|                  | Attic: 25 cm brick wall with 6 cm calcium silicate boards for interior insulation, $U = 0.6 \text{ W/m}^2\text{K}$ |                                                                              |
|                  | Sandcastle panel elements: 14 cm reinforced concrete/6 cm mineral wool/6 cm reinforced concrete, $U = 0.6 \text{ W/m}^2\text{K}$ |                                                                              |
| Interior walls   | Mainly 38 cm brick walls and some drywalls; in attic only drywalls           | Reinforced concrete, mainly 15 cm and a few 7 cm thick                       |
| Basement ceiling | Wooden beam ceiling with 4 cm polystyrene insulation/2 cm dry screed/flooring, $U = 0.48 \text{ W/m}^2\text{K}$ | 14 cm prestressed concrete/2.5 cm mineral wool/5 cm anhydrite screed/0.5 cm impact sound insulation/flooring, $U = 1.2 \text{ W/m}^2\text{K}$ |
| Ceilings         | Suspended wooden beam ceilings/1 cm mineral wool/2 cm dry screed/flooring, $U = 0.5 \text{ W/m}^2\text{K}$ | 14 cm prestressed concrete/3 cm anhydrite screed/0.5 cm impact sound insulation/flooring, $U = 3.7 \text{ W/m}^2\text{K}$ |
| Top-floor ceiling | –                                                                            | 14 cm prestressed concrete/final layer of 6 cm mineral wool, $U = 1.0 \text{ W/m}^2\text{K}$ |
| Roof             | Saddle roof with 16 cm between-rafter mineral wool insulation and 2.5 cm plasterboard interior, $U = 0.25 \text{ W/m}^2\text{K}$ | Cassette roof of reinforced concrete (cold roof)                            |
| Windows          | Double insulation glazing, $U_s = 1.8 \text{ W/m}^2\text{K}$ and $g = 0.7^a$ | Double glazing $U_s = 2.8 \text{ W/m}^2\text{K}$ and $g = 0.75^a$           |

Note: $^a$Frame ratio of all windows was calculated by measuring the glazing and frame areas; the $g$-value stands for the energy transmittance of the glazing; and $U_s$ is the thermal transmittance coefficient of the whole window, including the glazing and frame.
2.3. Thermal building simulation

To estimate the heating demand in winter as well as room temperatures in summer, the MFHs were modelled using the thermal building simulation software IDA ICE 4.8 (EQUA 2018). The simulations were run for one year at a time step of less than one hour to allow a detailed analysis of the evolving operative room temperatures and heating demand for each room. Building components and material layers are entered as inputs to reproduce realistic heat storage capacities and transmissions of each room to the building exterior as well as to neighbouring rooms.

In Germany, inhabited rooms of residential buildings are typically heated by radiators or floor heating to comfortable temperatures of between 20 and 24°C in winter. Dwellings are cooled only by passive measures (i.e. opening the windows at night). This kind of cooling is highly effective because of the relatively cool nights during summer, when temperatures generally fall to <20°C.

For the thermal building simulation, the following boundary conditions were applied:

- Chosen location of both buildings: Dresden, Germany.
- Internal loads: 4.17 W/m² (daily 24 hours) in inhabited rooms, according to DIN 4108-2 (2013).
- Air exchange between rooms: all room doors are closed.
- Shading: for the GZH building, the building on the opposite side of the street was taken into account; shading of trees is not considered.
- Cooling by window ventilation in summer based on the following:
  - Window opening control: windows opened when the outside air is cooler than the room air and room air >23°C (depending on the window-opening schedule).
  - Window-opening schedule: windows fully open from 1800 to 2200 and 0600 to 0700 hours; tilted at night from 2200 to 0600 hours.
  - Wind and temperature gradient-driven air exchange through windows is taken into account in the building simulation tool IDA ICE.
  - Degree of window opening: defined by opening profiles of the installed windows.
- Minimum room air temperature (heating): 22°C (except for the unheated bedroom and corridor).

2.3.1. CC adaptation measures

Several alternatives were modelled:

- External sun protection systems to reduce solar irradiance. Simulations were conducted for different orientations.
- Sun-protection glazing with \( g < 0.4 \), where \( g \) is the energy transmittance of the glazing.
- Triple glazing.
- Mechanical ventilation systems for improved air exchange: standard balanced domestic ventilation systems with a maximum rate of 1 h\(^{-1}\) (air change rate per hour) and those with a higher air exchange rate of at least 2 h\(^{-1}\). The simulation assumed the system is activated when the indoor air temperature is >23°C (and the outdoor air is cooler).
- Phase change materials (PCMs) (Hodzic, Pont, Tahmasebi, & Mahdavi 2019). However, because of the high cost of around €200/m² PCM plasterboard (working out at €70,000 for one attic dwelling in the GZH building), much cheaper and equally effective sun protection systems and ventilation systems are generally preferred.
- Improved roof insulation or installing light-reflecting roof coverings.

2.3.2. Quality of overheating simulation

The quality of the modelling was validated using measured data during operation. Data loggers were installed in selected rooms in summer 2018 and 2019 to record room temperature and CO\(_2\) content. During the absence of the residents in the holiday season, verified by the constant CO\(_2\) content of approximately 400 ppm, the thermal qualities of the respective rooms could be assessed without the influence of residents. Baseline measures of thermal masses, transmissions and window characteristics could be compared with the simulation model. This test validated the temperature simulations (Figure 3). Open room doors and internal transmission to adjacent rooms were found to have a non-negligible influence, indicating the importance of simulating the temperature course in particular rooms within the whole building.

2.3.3. Realistic window ventilation

A large number of studies have pointed out the influence of the inhabitant on window opening on overheating (Baborska-Narożny, Stevenson, & Grudzińska 2016; Fabi et al. 2012; Fosas et al. 2018; Hamdy et al. 2016; Mavrogianni et al. 2014). However, most studies assumed a simplified air exchange rate when the window was opened. In reality, the air exchange of open windows depends on several variables: wind direction, wind speed, temperature difference of the outside air to room temperature and the degree of opening of the window. The building simulation tool IDA ICE offers the possibility to include all these influences. Therefore, the wind and outdoor temperatures of the weather data set and the flow of air into and out of the building were taken into account by means of pressure coefficients and height-stratified wind speed profiles. This dynamic approach is reflected in the measured values of the buildings during the period of use.
There is no standard procedure for simulating the ventilation behaviour of the windows (Fosas et al. 2018; Hamdy et al. 2016; Mavrogianni et al. 2016; Porritt et al. 2012). Therefore, we conducted a ventilation survey in the GZH and LPC district to find out when and how residents open their windows (fully open or tilted) and used cross-ventilation on average summer days and on hot days. The survey \( n = 36 \) for LPC, \( n = 43 \) for GZH) showed all possible ventilation behaviour from residents who did not open their windows at all to residents who left their windows open during the day. However, the average ventilation behaviour showed the following characteristics: windows were opened briefly in the morning after getting up and closed during the day. They were typically completely open in the evening until 2300 hours. At night, half were tilted open and the other half were reported fully open.

### 2.4. Weather data

As Chen (2009) stated in his review, no consistent way of choosing weather data for overheating risk analysis by building simulation can be found in the literature. From a simulated hot spell, weather recording to TRY or DSY weather data have been used.\(^1\) In the present study, localised data for Dresden city (including the urban heat island effect), for the test reference year, version 2015 (TRY 2015 Summer), provided by the German Meteorological Service, was used (DWD 2017). Based on long-term measurements and observation series, this data set includes several meteorological parameters for each hour of the year. Specifically, TRY 2015 Summer describes the climate conditions of a warm summer and a typical winter in Dresden. Figure 4 shows the outdoor temperature over the course of the year; Table 3 gives an overview of some meteorological parameters for 2015. To ensure that the chosen weather data are representative, we compared the heating demand and overheating of the buildings with the weather data from the DWD of the last five years.

In general, it should be noted that the focus of the study is not to determine exact values of overheating, but to compare existing buildings and adapted buildings as well as different types of buildings and show the effect of user behaviour on overheating in the dwelling. When it comes to the exact numbers for overheating, a variation of different weather data sets and also synthetic weather data is necessary.

### 2.5. Overheating criteria

No universally accepted definition and criteria for overheating in residential buildings is available (Chen 2019). Typically the overheating criteria of the DIN EN 15251:2012 (2012) and the derived Chartered Institution of Building

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\(^1\) As stated by Chen (2009).
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Both are based on a working environment and are therefore more or less limited to a healthy workforce (Anderson et al. 2013). In Germany, overheating assessment is commonly performed using the national standard DIN 4108-2 (2013), showing some deviations from DIN EN 15251:2012-12 (procedure B) when taking into account the national annex for Germany. As noted previously, the focus of the study is not to determine exact values for overheating but to compare overheating for different building types, retrofitting and resident behaviour. The German standard DIN 4108-2 divides the country into three summer climate regions with different climatic conditions (DIN 2013). The city of Dresden is assigned to summer climate region C, which foresees a maximum acceptable indoor operative temperature of 27°C. This upper boundary is used to calculate the so-called ‘overtemperature degree-hours’ (Jenkins, Patidar, Banfill, & Gibson 2014) as a measure of overheating within the rooms of a house. These DH (overheating degree-hours) values are summed over a year. For residential buildings, an upper limit for DH of 1200 Kh/a (Kelvin hours/annum) is specified as the standard and has to be achieved in every room of a new building for every hour in a day independent on room usage. However, note that the overheating risk analysis here is only oriented on the standard DIN 4108-2:2013-02 using the specified definition of DH and given the internal heat gains of the rooms. However, ventilation behaviour as well as weather data differ from this standard because of the more precise data required for the current investigation, as discussed above.

3. Results

3.1. Effective CC mitigation measures: reducing transmission losses

The first question to be answered is: Which retrofitting options for the LPC and GZH MFHs are most effective at reducing the heating demand and, thus, strengthen CC mitigation? For the LPC building, a standard retrofitting package for prefabricated buildings was considered. In fact, this package is currently being used by the housing association owner for the chosen LPC. These measures (described in Table 4) are to add an insulating layer to the walls, the top-floor ceiling and the basement ceiling, as well as to replace the windows. The thermal building simulation showed that this combination of measures is an efficient approach, resulting in $U$-values typical of new buildings and in line with Germany’s energy-saving standard for version 2014 (BRD 2013). Of course, more ambitions retrofitting measures are possible, for example, to meet the standards for passive housing. However, these are not typical for such renovation work.

Table 3: Characteristics of the test reference year TRY 2015 Summer for Dresden city.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Annual average temperature       | 10.5°C    |
| Minimum temperature              | –18.7°C   |
| Maximum temperature              | 35.7°C    |
| Number of hot days (>30°C)       | 16        |
| Number of tropical nights (>20°C)| 9         |
| Total direct radiation for the year | 564 kWh/m²a |
| Total diffuse radiation for the year | 562 kWh/m²a |

Table 4: Climate change (CC) mitigation measures for the GZH and LCP multifamily housings (MFHs) to reduce heating demand in wintertime.

| Component          | GZH building                                      | LPC building                                      |
|--------------------|---------------------------------------------------|---------------------------------------------------|
| Walls              | External insulation with 2 cm vacuum insulation panels, $U = 0.20$ W/m²K | External insulation with 10 cm mineral wool insulation, $U = 0.20$ W/m²K |
| Roof or top-floor slab | No change, $U = 0.25$ W/m²K                        | 14 cm of cellulose injection insulation on top-floor slab, $U = 0.22$ W/m²K |
| Basement ceiling   | No change, $U = 0.48$ W/m²K                        | 10 cm mineral wool beneath, $U = 0.27$ W/m²K       |
| Windows            | Triple insulation glazing $U_g = 1.0$ W/m²K and $g = 0.5$ (same window opening profile and frame ratio as the existing windows) |                                                     |
| Ventilation system | Natural window ventilation                        |                                                   |

Note: $U_g$ is the thermal transmittance coefficient of the whole window, including the glazing and frame.
3.2. Impact of CC mitigation measures

The simulated heating demands for the GZH and the LPC buildings in the existing non-retrofitted state are depicted in Table 5. The annual heating demand per mean m² floor space in the existing buildings is higher in the LPC than the GZH. This can be attributed to the fact that the GZH building is part of a large group of buildings (a terrace); hence, heat losses by transmission can only occur on two sides. In contrast, the investigated LPC is freestanding. Furthermore, the roof of the existing GZH building is better insulated than the top-floor ceiling of the LPC, and the current windows of the GZH show lower losses by transmission (Table 2).

In the next step, CC mitigation measures discussed in section 2 were implemented in the building simulation models (Table 4) to reduce the heating demand and, thus, the GHG emissions. The effect of the enhanced insulation and window replacement can be clearly seen in Figure 5 and Table 5. For both buildings, the heating demand drops to <40 kWh/m²a, that is, less than half the previous value for the LPC and nearly half the previously value for the GZH building. Thus, the two refurbished buildings show comparable energy efficiencies as regards heat demand, as well as a clear reduction in GHG emissions. The reduction in heating demand for the LPC is more marked because of the retrofitting of the entire building envelope, whereas only the facade and windows were changed in the GZH simulation. Note that the given heating demands only consider the heating requirements for living space (useful energy) while ignoring the production of waste heat by distribution and heat generation.

3.3. CC adaptation measures: reduction of overheating risk in summer

Four questions arise in relation to the overheating in the investigated buildings:

- How pronounced is the overheating of the individual rooms and dwellings for the existing GZH and LPC buildings and how do the buildings differ?
- Does thermal retrofitting (Table 4) weaken or improve heat resilience in the buildings?
- Are CC adaptation measures required to reduce overheating in the buildings? If so, which measures should be implemented?
- Most importantly: What influence do residents have on overheating in their dwelling?

3.3.1. Overheating risk analysis in the existing GZH and LPC MFHs

Figure 6a shows the simulated room temperature in west-facing rooms on the first and top floors of the existing GZH and LPC buildings over 10 summer days. On hot days with outdoor air temperatures >30°C, thermal inertia ensures

| Table 5: Simulated heating demand of the existing GZH and LPC buildings before and after retrofitting. |

| Heating demand | Existing (kWh/m²a) | Retrofitted (kWh/m²a) |
|----------------|---------------------|-----------------------|
| GZH            | 72                  | 39                    |
| LPC            | 97                  | 38                    |

Figure 5: Simulated heating demand over the course of a year for (a) the GZH and (b) the LPC buildings in the existing (unrefurbished) and retrofitted (refurbished) states (enhanced insulation; refurbished).
that temperatures are lower inside the buildings. The significant effect of night-time cooling by window ventilation (fully opened and tilted; see section 0) because of the cooler outside temperature is also clearly visible. Comparing the changing temperature in the rooms of the GZH and LPC buildings, there are three things to note. First, the rooms on the first floor show similar temperature patterns because of their similar thermal masses, identical orientation and a comparable level of balcony shading. Second, temperatures in the top-floor rooms are significantly higher than those

![Simulated room temperature curves](image)

**Figure 6:** Simulated room temperature curves for 10 summer days in (a) the existing LPC and GZH buildings for west-facing living rooms shaded by balconies; (b) an east-facing bedroom of the GZH building; and (c) a west-facing bedroom of the LPC. The variants in (b) and (c) are: 1, existing state; 2, thermal retrofitting; and 3, including heat resilience measures. The investigated rooms are circled on the building views. The outdoor air temperature is indicated for comparison.
of the first floor because of the solar heating of the roof, while the first-floor rooms are cooled by the underlying basement. This pattern of increased temperatures in higher floors can also be seen in Figure 7a,b. Third, there is a significant difference between the GZH and LPC building in the daily temperature pattern of the top-floor rooms. This can be attributed to the much lower thermal storage capacity of the drywall interior in the converted attic of the GZH building compared with the solid walls and ceilings of the LPC. These lower thermal masses lead to a faster increase and decrease in the room temperature over the course of the day. In addition to the detailed picture of the evolving room temperatures, the number of overtemperature degree-hours’ gives a good indication of the level of overheating in each room during the whole summer.

Figure 8 (variant 1) shows a significant increase in DH27 (overheating degree-hours above a maximum room temperature of 27°C, specified by DIN 4108-2 for the climate region of Dresden) on higher floors. The influence of balcony shading is also evident on the west facades of both the GZH and LPC buildings. Considering the threshold value for DH27 of 1200 Kh/a, the unshaded rooms show overheating above this critical value, indicating the need for heat adaptation measures.

3.3.2. Impact of CC mitigation measures (thermal retrofitting) on heat resilience

Figure 6b,c clearly shows lower room temperatures for both retrofitted buildings. In particular, mainly the enhanced insulation of the top-floor ceiling in the LPC building contributes to the significant decrease in temperature. In addition, overheating is reduced by the lower g-value of the new triple glazing (compared with the existing double glazing), as well as lower solar heat gain through the opaque building envelope (enhanced insulation). The same effect can be seen in Figure 8 (variant 2), which lists the DH27 values for the retrofitted buildings: DH27 is halved for almost all rooms of the GZH and LPC buildings in comparison with their non-retrofitted states. Only in the attic of the GZH building is no significant reduction gained, again due to the low thermal masses of the drywall interior.

The marked reduction in DH27 is an impressive confirmation that a typical thermal retrofitting to reduce heating demand can also enhance the heat resilience of an uncooled building during hot summer months. In other words, CC mitigation measures (to reduce GHG emissions) can also act as CC adaptation measures (to reduce overheating).

Figure 7: Distribution of maximum room temperatures simulated in the existing and refurbished (climate change (CC) mitigation and adaptation measures) GZH and LPC buildings for two facade orientations. For the framed rooms, the DH27 (overheating degree-hours above a maximum room temperature of 27°C) are also shown in Figure 8.
3.3.3. Additional CC adaptation measures

Although the thermal retrofitting of the buildings leads to a significant increase in simulated heat resilience, some rooms and dwellings still show high overheating. In particular, the attic of the GZH building and rooms unshaded by balconies still have DH27 values around 1200 Kh/a (Figure 8). Clearly, these rooms require local adaptation measures.

Various CC adaptation measures and combinations were simulated in IDA ICE for both buildings to determine the most effective and feasible to reduce overheating in all dwellings. Table 6 overviews the chosen measures, namely external sun protection elements for west-, east- and south-facing windows without balcony shading for both buildings, and an exhaust ventilation device in the attic bathrooms of the GZH.

The impact of the heat-resilience adaptation measures at reducing room temperature can be clearly seen in Figure 6b,c. In particular, the combination of sun protection and exhaust ventilation system serves to lower room temperatures in the attic of the GZH building by about 2 K.

Figure 8 (variant 3) has even more striking evidence of the positive effect of combining thermal retrofitting of the whole building with individual heat resilience measures. Here, the DH27 for all facade orientations and building levels is <500 Kh/a. Also note the substantially more uniform distribution of low overheating in the buildings (Figure 7b,d) compared with the unrefurbished case (Figure 7a,c).

3.3.4. Climate justice and overheating risk

Since the described retrofitting options are quite expensive, not all residents will be able to afford such an upgraded MFH which is usually associated with higher rental prices. Therefore, it is necessary to consider options for residents to take action themselves to reduce the heat stress in their dwelling. In addition to installing an opaque, highly reflective interior sunshade, residents can lower the thermal load during heatwaves by avoiding cooking or running electrical devices, but this has a relatively low impact. It is more effective to open all windows fully at night (even if there is no discernible breeze) to allow an influx of cooler air from outside and also to use cross-ventilation. On the other hand, the risk of burglary or outside noise and air pollution can make it impossible to open windows at night. To show the enormous relevance of the residents’ window ventilation behaviour is varied in the thermal simulation of the GZH and the LPC buildings in two ways:

- Low ventilation: the window-opening schedule is changed and only from 0700 to 0730 and from 1800 to 2200 hours when windows are fully opened if the outdoor air is cooler than inside.
In the results discussed in sections 3.3.1–3.3.3, windows are fully opened in the evening and morning and tilted at night (see section 0). The window doors to the balcony stay closed at night in all dwellings and no cross-ventilation is used. The results for the non-retrofitted MFH depicted in Figure 9 show the range of overheating risk as influenced by the residents’ ventilation behaviour. For the existing GZH building, there is a considerable drop in DH27 to <700 Kh/a for all rooms by full use of night cooling (variant 1a), including the attic. While the values for the LPC building drop much less significantly, they do become <1200 Kh/a. This is a remarkable impact considering the inferior insulation of the top-floor ceiling and the old windows (Table 2). In contrast, residents who left the windows closed at night (variant 1b) means the heat burden is enormous compared with the assumed standard ventilation which underpins the effect of windows only tilted at night for night-time cooling (variant 1). The effects of closed windows on high overheating were also observed by other studies (Fabi et al., 2012; Vellei et al., 2016). The lack of knowledge of the residents about the importance of night cooling is a fact. Other reasons why the windows have to stay closed at night might be pollution, crime, noise, limited resident mobility or the fact that residents are also not covered by their building and content insurance in the case of open windows or doors.

Therefore, the question arises if the effect of no night ventilation might be less pronounced for the retrofitted MFH (including the CC mitigation and adaptation measures). In Figure 9, variant 3a exhibits significantly lower overheating than non-existing night ventilation in the non-retrofitted building (variant 1a), but is more pronounced for the GZH building. However, the increase in ventilation behaviour (variant 3) in the retrofitted building is nevertheless clearly leads to DH27 to nearly 3000 Kh/a for the LPC building. For the retrofitted GZH, the installation of exhaust ventilation system leads to good night-time cooling and, thus, low overheating, even if no window ventilation is used in attic dwellings at night.

4. Discussion

4.1. Interplay of CC mitigation and adaptation measures

The simulations demonstrate that standard thermal retrofitting measures, such as enhanced insulation and window replacement in representative MFH, not only lower heating demands during the winter but also significantly decrease overheating risk in summer. Thus, conventional CC mitigation measures to reduce GHG emissions enhance the heat resilience of the considered buildings, and, as a consequence, can simultaneously be seen as CC adaptation measures. Such measures are highly desirable as they can effectively deal with CC in two ways: by addressing both the origin and the impact of CC. However, additional complementary CC adaptation measures (both physical interventions and inhabitant practices) are needed to improve heat resilience further. Furthermore, the simulations show that simple individual retrofitting measures can ensure low overheating for all inhabitants, regardless of the location of their dwelling in both building types, thus avoiding the need for active cooling. However, for optimal heat resilience, passive protective measures for overheating are insufficient if they are not accompanied by window-opening behaviours to cool the dwelling at night. User behaviour sustaining a consistent ventilation regime has enormous impact on overheating.

4.2. Heat resilience

The thermal building simulations enabled the identification of the most effective passive adaptation measures for the management of overheating (cf. section 0). The most important physical measure to lower the different levels of overheating found in the dwellings from the top to the ground floor is the reduction of solar heat gains through protective measures for overheating are insufficient if they are not accompanied by window-opening behaviours to cool the dwelling at night.

Figure 9: Simulated annual overtemperature degree-hours >27°C (DH27) for different window ventilation behaviour dependent on the building retrofitting: 1, existing state with standard ventilation; 1a, existing state with less ventilation; 1b, existing state with high ventilation; 3, a CC mitigated and adapted building with standard ventilation; and 3a: a CC mitigated and adapted building with less ventilation (depending on orientation and building level) for the GZH and LPC buildings.
improved roof or top-floor ceiling insulation. Second, triple-glazed windows can significantly reduce the amount of solar heat radiation reaching the interior. It is important to ensure that these windows are completely opened for ventilation, thereby ensuring effective night-time cooling. Third, an external shading system should be installed for rooms with large windows and high levels of solar exposure. Fourth, massive components with a high thermal storage should be used for building renovations, especially attic conversions.

4.3. Climate justice

4.3.1. Merits of thermal retrofitting for summer heat reduction

Owing to thermal retrofitting, the heating demand of the dwellings in both building types can be halved on average (cf. Table 5). Assuming heating costs of €0.08/kWh, the monthly heating costs are reduced by about €0.20/m² of living space in the GZH and €0.40/m² in the LPC building. However, these savings in heating costs are more than offset by significantly higher rents in retrofitted MFHs, as buildings are usually completely renovated in addition to the energy-related retrofitting. This problem is clearly related both to fuel poverty (Heindl 2015) and to climate justice in the notion of 'a just distribution justly achieved' (Harvey 1973; Hughes 2013). At the building scale, poorer groups may be disadvantaged by the improvements made to their space. According to the present research, the monthly rents of a dwelling in a retrofitted LPC is around €1/m² higher, which is only partly compensated by reduced heating costs.

In both building types, uneven summer overheating of dwellings was found before retrofitting, with significantly higher heat loads for residents in upper floors and sun-exposed rooms (Figure 7), which is in accordance with findings from the literature (Thomson et al. 2019; Vandentorren et al. 2006). As long as no elevator is installed, usually the upper floors are not inhabited by elderly residents (who are particularly vulnerable to heat stress). In both existing buildings, no elevator was originally installed and the accessibility to living space for elderly people was usually limited to the lower and less overheated floors.

As part of the retrofitting concepts for LPC, elevators are usually installed, and also top-floor dwellings are made accessible for elderly people. At the same time, the heat load in the top floor of the retrofitted LPC is significantly reduced by insulating the top-floor ceiling, replacing windows and partially installing sun protection. Thus, the upper floors are made bearable for the elderly. In general, all dwellings of the retrofitted LPC and GZH show similarly reduced overheating if night-time cooling is used by adequate window ventilation (Figure 8, variant 3), leading to an improved climate justice in terms of heat resilience between all residents in both building types.

Both building types show comparable overheating risk in the state before and after retrofitting (Figure 8). The LPC contain a much higher proportion of heat-vulnerable residents: two-thirds are older than 60 years and a significant proportion live alone (cf. Figure 2). Additionally, the rents of non-retrofitted LPC are usually lower those in GZH for comparable locations in the city. These are mostly occupied by socially and/or economically disadvantaged groups. As a result of retrofitting, a higher number of vulnerable residents can benefit from improvements in the case of the LPC, thus offering generally less costly dwellings at a comparable heat stress level if compared with the GZH.

There is significant potential for improving heat stress for disadvantaged and the elderly while still preserving comparably low rents. This is because the renovation of LPC buildings is easier to realise than in GZH—given the prevalent ownership structure in Germany. While the ownership of apartments in GZH is usually individual owner-occupiers, LPC buildings are usually operated by housing cooperatives or large proprietors. This allows the present findings to be feed into decision-making processes for the LPC. This proved to be the case in this project involving cooperation with the LPC. It was also shown that retrofitting the GZH is worthwhile. The challenge now is to reach the dispersed owners, for example, involving professional associations or landlord’s associations.

4.3.2. Living without thermal retrofit: behavioural options and communication challenges

Optimising window ventilation at night (cf. Figure 9) shows the enormous influence of residents on overheating, which has also been confirmed by previous studies (Bouchama et al. 2007; Ezratty & Ormandy 2015; Lomas & Porritt 2016; Toulemon & Barbieri 2008; Vandentorren et al. 2006). This result applies to both retrofitted and non-retrofitted buildings, confirming the ‘occupancy overrides design’ principle (Morgan, Foster, Poston, & Sharpe 2016). This opens further potential for improving climate justice, particularly for the most disadvantaged. This is important because the proposed retrofitting measures will typically drive up rents, forcing most disadvantaged groups to move to other buildings with a low heat-protection standard. The results provide guidance to reduce the heat burden for this group, but admittedly a lower level of heat stress reduction is achieved.

The key is the optimised behaviour enabling effective passive ventilation by using night-time cooling. What sounds self-evident requires the implementation of a consistent ventilation regime by residents. Often, optimised behaviour is impeded because of residents’ lack of knowledge, missing routines or more compelling reasons such as traffic noise, limited mobility or the risk of burglary, the latter applying mainly for the lower floors.

An essential challenge is the education and motivation of those most affected to make use of night cooling. It is well known this is a non-trivial task. LPC buildings are home to people who are often immobile, elderly or with chronic medical conditions and, thus, may not be able to implement appropriate night ventilation. Baborska-Narożyń et al. (2016) trained residents in an overheating tower block in northern England to adapt their behaviour to summer heat reduction via night ventilation and the use of exhaust fans and curtains. However, they found that residents often could not adequately implement the recommendations.
Some elderly people have a delayed and insufficient perception of heat stress (Head et al. 2018) and, thus, often underestimate the health risks from high temperatures. In an ageing society, this calls for new solutions. Climate justice for vulnerable or disadvantaged residents such as the elderly calls for innovative approaches beyond well-developed communication designs and education efforts. This may imply new responsibilities for a variety of actors, for example, building owners, local action groups and special task forces. The question arises whether building owners (or others) should provide and maintain cooled refuge rooms for vulnerable tenants who cannot control ventilation or are in special need for assistance. This is not merely a technical question, but raises several other social, financial and community issues.

4.4. Caveats and study limitations
Although numerous simulations were performed and validated, the results and their generalisability are limited for the following reasons:

- The heat exposure of inhabitants is strongly affected by their actions, not only by window ventilation, which was discussed, but also by their lifestyle, duration of presence and mobility.
- Inhabitants’ use of ventilation has an enormous influence on the overheating risk of the dwelling. It was not possible to ascertain what the typical individual ventilation behaviour is in the dwellings (the survey results do not necessarily reflect real ventilation behaviour). Current international standards on overheating do not take window ventilation sufficiently into account. There is still an enormous knowledge gap in the evaluation of inhabitant behaviour.
- Depending on the selected boundary conditions, the degree of overheating in dwellings can be very different. The focus of the study was the comparison of heat loads before and after retrofitting measures and, thus, not focusing absolute values but their change. However, even this change is shown to be strongly dependent on user behaviour.
- The simulations used a test reference year as a weather data set with a warm summer and average winter for the present decade and not future climatic considerations. The effect of hot summers increasing in the next decades was not investigated.
- The sensation of heat depends on the individual’s perception and may also change over time due to global warming. In this study, the overheating risk exceeding room temperatures >27°C was assessed. So far, however, not enough is known about which limit temperatures really lead to a higher health risk for people in a certain region depending on age, gender and other factors.
- The generalisability of the results to other GZH and LPC buildings is limited because of the orientation of the building, location and climate and details such as the presence of balconies. Some conclusions concerning the top-floor dwellings, the impact of ventilation behaviour, enhanced roof insulation, window replacement or exhaust air-ventilation systems on overheating risk are generalisable for most residential buildings.

5. Conclusions
Some retrofit actions will have disproportionate negative financial consequences for residents depending on the magnitude of the financial burden. Other factors are under the control of inhabitants themselves. However, due to a lack of technical understanding and access to information on window opening for summer night-time ventilation, residents are unsuccessful at exercising personal agency to mitigate summer overheating successfully.

Suitable CC mitigation and adaptation measures were examined for two common types of MFH aimed at reducing heating demand in winter and reducing overheating in summer. The investigated LPC and GZH MFHs represent two typologies commonly found in Germany and throughout Central Europe. These buildings are generally more susceptible to overheating than (for example) single family houses because of their construction and typical location within a dense urban fabric.

This research identified two sets of actions. The first set of actions requires retrofit and adaptation of the building fabric by building owners. The other set of actions involved the inhabitants’ agency. The significance of these findings for climate justice will involve measures taken to reduce energy demand (climate mitigation) and improved thermal adequacy (both in winter and summer). The findings show that mitigation and adaptation measures require coordination of both social and technical aspects, and that passive technical measures alone are likely to be insufficient.

Evidence suggests that the capital expenditure cost of retrofit (and other refurbishment measures that may accompany this) often results in higher rents. This can be prohibitively expensive for poorer sections of society—impacting their ability to pay or displacing them altogether. The economics of retrofit for mitigation and adaptation requires further policy clarity to avoid additional burdens being placed on people who are economically disadvantaged.

The influence of the inhabitant is remarkable. Passive overheating measures are not sufficient if the resident cannot open some windows at night. Public education, training and communication are therefore needed to ensure inhabitants understand and implement appropriate ventilation practices. However, a segment of the population who cannot comply because of lack of agency are likely to become increasingly vulnerable—those who are immobile, elderly or with chronic medical conditions. Specific policies are needed to identify those who are vulnerable and provide them with additional forms of assistance to ensure they do not experience overheating and heat stress.
Based on thermal simulations, measured data, demographic data and other evidence, several conclusions can be drawn:

• Generally, the residents in unrefurbished LPC buildings with lower rents are not more burdened by summer heat than residents in typical (unrefurbished) GZH flats if sufficient window ventilation occurs. The simulation demonstrates that typical residents of the unrefurbished LPC with lower incomes and elderly people are not more affected by summer heat.

• The standard thermal retrofitting of such building types aimed at enhancing their thermal insulation as well as the installation of triple glazing can halve the energy demand for heating and, thus, cut GHG emissions (see section 0). An unintended side effect is the considerably reduced overheating especially for the top floor to a level similar to the ground floor (see section 0).

• For exposed rooms still suffering from uncomfortably high temperatures, further physical interventions for adaptation are needed. Such CC adaptation measures are external sun-protection systems and ventilation systems in attic dwellings of GZH buildings to enhance the influx of cool night-time air. A well-distributed low amount of overheating can be achieved in all MFH regardless of their orientation or floor level by combining thermal retrofitting measures with heat resilience measures (Figure 8, variant 3).

• Inhabitants can implement effective behavioural measures by actively managing a ventilation regime of opening windows to facilitate night-time cooling.

• Inhabitants can increase the overheating risk of their dwelling tremendously by unintentional practices. Insufficient window ventilation and night-time cooling occurs for immobile residents and inhabitants with outdoor noise or risk of burglary.

Note

\(^1\) TRY is the test reference year provided by the German Meteorological Service; and DSY is the design summer year provided by the Chartered Institution of Building Services Engineers (CIBSE) (https://www.cibse.org/weatherdata).

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Competing interests

The authors have no competing interests to declare.

Data accessibility

Detailed building data of the two MFH types, GZH and LPC, will be published contemporaneously in the Databank of Buildings and Infrastructure of the Leibniz Institute of Ecological Urban and Regional Development (see http://ioer-bdat.de/en/).

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### Appendix A

#### A.1 Allocation of the selected multifamily houses (MFHs) to building typologies

Initially, we had to determine which residential buildings to choose as representative types. As can be seen in Figure A.1, with reference to the number of buildings, single- or two-family houses form the majority of all residential buildings in Germany. However, considering the stock of dwellings, 53% of these are found in MFHs (three or more dwellings) and 48% are in single- or two-family houses. Regarding the number of affected residents, CC mitigation and adaptation measures are more effective in the case of MFHs. Furthermore, MFH are common in Germany’s larger cities, which tend to suffer from the heat island effect, burdening residents with additional overheating. In this context, CC adaptation measures are of great value for these types of buildings. Therefore, the focus of the investigation was placed on MFHs rather than single- or two-family houses.

Data on these two building types are available at both national and regional levels. Regarding Germany’s total stock of MFHs, 29% were erected before 1950, the period when GZH buildings were typical (Destatis 2018; Ortlepp, Gruhler, & Schiller 2016). In comparison, 22% of MFHs were erected in the period 1970–89, when LPC buildings were frequently constructed. Unfortunately, more differentiated data on the age of building construction are not freely

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**Figure A.1** Allocation of the selected multifamily houses (MFHs) to building typologies.
available at the national level. A more precise classification can only be achieved by using regional data for the city of Dresden, the location of the investigated LPC building. As can be seen in Table A1, around 14% of Dresden’s stock of residential buildings (highlighted in italics) are of the GZH type, based on the construction year (until 1918) and the standard number of dwellings (three to 12). In comparison, LPC buildings (highlighted in bold in Table A1) only make up around 2–6% of all residential buildings, classified by the period of construction (mainly 1970–90) and the number of dwellings (more than 12). However, the data are not entirely consistent: it is to be supposed that almost half the LPC buildings were built before 1970 and others exhibit fewer than 12 dwellings. In total, around 44% of residential buildings in Dresden are MFHs. This figure is about 27% above the national average. Since for LPC buildings more than 20 dwellings in one building is not unusual, the ratio of dwellings in LPC buildings is much greater than the 6–12% compared with dwellings in other residential buildings. Along with its representative nature, an additional reason for choosing an LPC building for investigation is that this type has been identified as particularly susceptible to overheating (Founda, Pierros, Katavoutas, & Keramitsoglou 2019).

Table A1: Dresden’s stock of residential buildings classified by the number of dwellings and the year of construction: the italic figure indicates Gründerzeitthaus (GZH) buildings, while the bold figure indicates large-panel construction (LPC) buildings.

| Construction year group | 1–2 | 3–12 | >12 |
|-------------------------|-----|------|-----|
| Until 1918              | 12% | 14%  | 2%  |
| 1919–45                 | 17% | 10%  | 0%  |
| 1946–69                 | 3%  | 5%   | 1%  |
| 1970–90                 | 3%  | 4%   | 2%  |
| After 1990              | 21% | 5%   | 2%  |

Source: Destatis (2018).

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