Future Climate Resilience Through Informed Decision Making in Retrofitting Projects

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Abstract. High energy use for space conditioning in residential buildings is a significant economic factor for owners and tenants, but also contributes to resource depletion and carbon emissions due to energy generation. Many existing dwellings should thus be retrofitted in order to fulfil the ambitious EU carbon emission mitigation goals by 2050. To investigate how future climate resilience can be implemented in the design process of retrofitting measures, this study concentrates on real case studies that have been retrofitted during the past decade. The performance of retrofitting measures for four case studies in Denmark and Germany were investigated under future climate projections and compared between the non-retrofitted initial stage of the buildings and the retrofitted stage. Building performance simulations were employed to investigate how severe the effects of climate change until the end of the 21st century on the material choice and system design is. Results show that summertime thermal comfort will be a major challenge in the future. Energy use for space heating was seen to decrease for periods in the future, also the severity of cold events decreased, resulting in a decline of heating peak loads. Additionally, not considering extreme events was proven to lead to miss-dimensioning thermal systems. Overall, the study shows that adaptation of informed decisions, accounting for the uncertainties of future climate, can bring a significant benefit for energy-efficient retrofits, potentially promoting adequate passive measures as well as free cooling to prevent overheating and enhance heat removal.

Keywords: Climate change · Resilience · Retrofitting buildings · Residential buildings · Building stock · Building Performance Simulation · Climate action · Future climate

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1 Introduction

Climate change is a widely discussed topic amongst politicians, the public and media [1]. In order to comply with the Paris Agreement, the global average temperature must not rise more than 2 °C compared to pre-industrial levels and efforts must be made to decrease the number to 1.5 °C [2, 3]. However, the fifth assessment report by the Intergovernmental Panel on Climate Change (IPCC) reveals that climate change will accelerate, rather than decelerate [4]. Furthermore, research shows that weather extremes such as heat-waves will occur more frequently and last over longer periods in the future [5, 6]. The 2030 Agenda for Sustainable Development by the United Nations (UN) set 17 Sustainable Development Goals (SDG) to achieve a better and more sustainable future by 2030 [7, 8], which two of the goals, SDG11 (sustainable cities and communities) and SDG13 (climate action), are addressed in this work by investigating some major energy retrofitting strategies for buildings.

Approximately 75% of the entire building stock is considered energy inefficient [9]. One example is the annual energy use of dwellings in Germany built before 1990 which is almost 50% higher than those built after 1990, when the regulations for mitigating the energy use of buildings were set [10], this can likely be upscaled to other central European countries. Thus, the main focus for retrofitting projects are the pre-1990 buildings in order to save operational energy. This study, however, analysed four buildings that were built before 1970. The bottom step of the Kyoto pyramid [11], which is seen as a general approach to mitigate the energy use in the building stock, is to reduce heat losses and thus, limit the transmission losses by retrofitting their thermal envelope [12]. The concept of energy-efficient retrofitting describes that buildings should be renovated to among others diminish the use of operational energy by lowering the transmission losses and installing systems with high efficiencies [13]. Motivations for building owners and operators were introduced by the EU authorities as well as local governments with a three-step system. Firstly, houses are needed to be classified in an energy labelling system to benchmark the energy-efficiency [14]. Secondly, a renovation roadmap has to be established by property owners to set milestones for energy-efficiency measures [15]. Lastly, the EU member states created funds for subsidies and low-interest loans that are provided to property owners to be able to afford retrofitting measures [15]. Evidently, vast amounts of resources are dedicated to retrofit the European building stock. However, one major challenge is assessing the impact and efficiency of the retrofitting strategies for future climatic conditions. As climatic conditions of the future have a high impact on the performance, thermal comfort, and economic payoff for retrofit measures, considering them when designing retrofit strategies seems essential. Therefore, informed decision making about the appropriate passive and active retrofit strategies of existing dwellings throughout the 21st century was assessed in this work.

This study investigates the energy performance of some common retrofitting strategies for residential buildings in Denmark and Germany on four case studies. Impacts of climate change are thoroughly assessed by studying energy use and indoor thermal comfort under future climate projections. Another major goal is to find how building performance is affected by changing climatic conditions and what indicators

can be integrated in the decision-making process at each design stage. Four actual case studies retrofitted in the last decade were assessed in this study by comparing the simulated performance of the non-retrofitted buildings with the retrofitted buildings for three 30-year periods until the end of the 21st century. Two case studies were located in Aarhus and Copenhagen, Denmark and two in Stuttgart, Germany. Thermal comfort in living spaces and energy use of the buildings were evaluated in the study. The impact assessment was performed by applying representative future climate scenarios and modelling the future performance of the buildings with Building Performance Simulations (BPS). The cases and the measures which were carried out throughout the retrofits were modelled and simulated with the limitations that the respective buildings and retrofit designs had.

2 Methodology

2.1 Building Energy Models

Four residential buildings located in Denmark and Germany were modelled; all built before 1970 and undergone major retrofits within the past decade. Case studies were selected to represent a spectrum of constructions that are typical for the countries or regions they are representing. Perspective views of the buildings are displayed in Fig. 1 and some basic information, including the window to wall ratios (WWR) are shown in Table 1. All cases along with their setpoints, parameters and assumptions were based on specifications by the companies owning the buildings and by building physicists involved in the process of certifying the buildings. This represents a limitation of the scope, which was done in order to assess the performance of measures as they were carried out in practice.

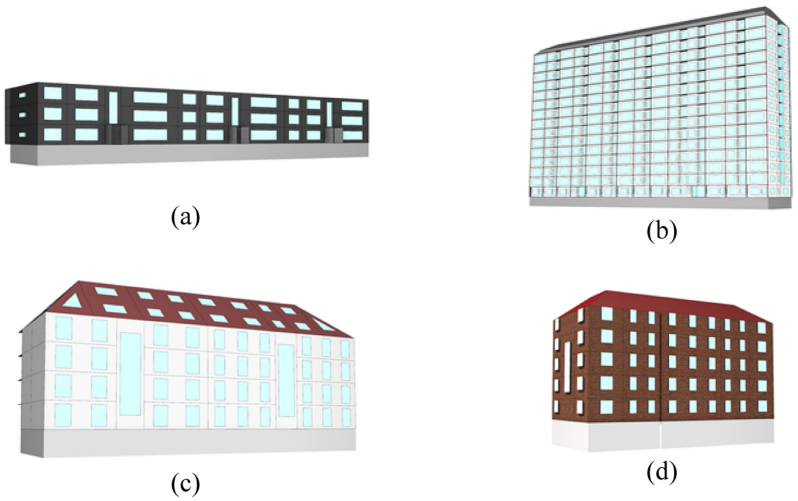

Fig. 1. Models of the case studies, not to scale: (a) Case 1, Aarhus, Denmark; (b) Case 2, Copenhagen, Denmark; (c) Case 3, Stuttgart, Germany; (d) Case 4, Stuttgart, Germany.

Specifications for HVAC, infiltration and shading were modelled as displayed in Table 2. In all case studies, no active cooling system was applicable; for case 3 and case 4 no active ventilation system was installed. Both Danish projects did not compose any moveable external shading devices, the German buildings were equipped with exterior shutters for windows and skylights in case 3. Setpoints and shading design were modelled according to the specifications of the building owners while infiltration rates were according to on-site measurements before and after the retrofit, or country-specific regulations as further discussed in [16].

Table 1. Model specifications for Cases 1–4.

Case	Heated floor area [m^2]	Number of floors	Number of thermal zones	WWR North [%]	WWR East [%]	WWR South [%]	WWR West [%]
Case 1	1 915	3[a]	71	0–5[b]	30–35[b]	0–5[b]	71
Case 2	10 750	15[a]	516	12–15[b]	30–38[b]	15–21[b]	39–48[b]
Case 3	1 225–1 525[b]	4–5[a,b]	50–59[b]	26–34[b]	0	20–43[b]	0
Case 4	1 135	5[a]	60	20	15–22[b]	31	15–22[b]

[a]Basement is excluded in number of floors.
[b]First indication before retrofit, second indication after completion.

Table 2. Heating, Cooling, Infiltration, Ventilation and Shading specifications.

Case	Heating setpoint [°C]	Cooling setpoint [°C]	Infiltration rate (50 Pa) [h^{-1}]	Ventilation rate $\left[\frac{l}{s \times m^2}\right]$	Ventilation type	Heat recovery [%]	Shading type
Case 1	21	N/A	2.1–1.2[a]	0.3	Extraction – balanced[a]	0–82[a]	N/A
Case 2	21	N/A	1.8–0.9[a]	0.4	Extraction – balanced[a]	0–75[a]	N/A
Case 3	22	N/A	5.0–3.0[a]	N/A	N/A	N/A	Ext. Shutters
Case 4	22	N/A	5.0–3.5[a]	N/A	N/A	N/A	Ext. Shutters

[a]First indication before retrofit, second indication after completion.

Table 3. Building envelope area and thermal conductivities.

Case	Area roof [m^2]	U-value roof $\left[\frac{W}{m^2 \times K}\right]$	Area floor [m^2]	U-value floor $\left[\frac{W}{m^2 \times K}\right]$	Area wall [m^2]	U-value wall $\left[\frac{W}{m^2 \times K}\right]$	Area wall gable [m^2]	U-value wall gable $\left[\frac{W}{m^2 \times K}\right]$
Case 1	674	0.35[b]–0.08[a,b]	674	1.90–0.26[a,b]	1 354–1 016[a]	0.39[b]–0.18[a,b]	0–3 438[a]	- –0.12[a,b]
Case 2	875	0.23[b]–0.11[a]	875	0.54[b]–0.17[a,b]	5 650	0.54[b]–0.15[a,b]	1 685	0.33[b]–0.16[a,b]
Case 3	442–430[a]	4.05–0.13[a,b]	299	1.11–0.15[a]	854	1.92[b]–0.18[a]	N/A	N/A
Case 4	456	1.59[b]–0.28[a,b]	256	1.59[b]–0.26[a,b]	904	1.46–0.48[a,b]	N/A	N/A

[a]First indication before retrofit, second indication after completion.
[b]Thermally-bridged U-value.

Thermal conductivity specifications for building envelope constructions were set according to Table 3. Areas of roof, floor and walls are gross areas without considering openings of all kinds. U-values including thermal bridges were determined in a pre-study [16]. Case 1 and case 2 were built with different constructions for the gable wall than the oblong façades, therefore, different conductivities were obtained. Table 4

provides an overview of the properties and areas of glazing materials. Case 1, 2 and 4 did not compose skylights; for case 3, skylights were specified separately. G-value of the glazing describes the solar energy transmittance, T_{vis} stands for the visible transmittance and frame ratio defines the ratio between glazing and frame.

Table 4. Glazing area and specifications.

Case	Area glazing [m^2]	U-value glazing $\left[\frac{W}{m^2 \times K}\right]$	g-value [%]	T_{vis} [%]	Frame ratio [%]
Case 1	492–524[a]	2.8–1.1[a]	63–50[a]	78–75[a]	20
Case 2	2 105–3 100[a]	2.0–0.9[a]	63–50[a]	78–70[a]	20
Case 3 Windows	140–239[a]	2.7–0.9[a]	63–50[a]	78–60[a]	30
Case 3 Skylights	8,9–71,5[a]	5.4–1.0[a]	90–50[a]	30–65[a]	10–30[a]
Case 4	203–225[a]	2.7–1.3[a]	63–60[a]	78–60[a]	30

[a]First indication before retrofit, second indication after completion.

2.2 Weather Data

For the estimation of location-based building performance, weather data is the most critical input to carry out BPS [17]. The current standard for BPS is the use of weather data composing hourly data, based on historical weather observations typically ranging from 20–30 years and composed into weather files on an hourly resolution over a one-year time frame representing the months with most typical conditions over the assessed timespan [18]. A common format is the typical metrological year (TMY) which includes several meteorological metrics. Selecting the most typical conditions for a multiple-year timeframe based on historical weather measurements also entails two disadvantages. Firstly, extreme weather conditions are underrepresented due to selection of typical months, which leads to averaging [19]. Secondly, basing design decisions in the built environment on historical climate measurements does not represent realistic conditions for the decades in which buildings are meant to withstand weather exposure [20, 21]. Moazami et al. [20] thoroughly discuss the need for climate data that accounts for climate change and its uncertainties in building energy simulations.

TMY files sourcing from the IWEC (International Weather for Energy Calculations) [22] were used in BPS to validate the scripts and models. Future climate conditions were simulated with weather files synthesized according to Nik´s method [23, 24]. The weather file sets were retrieved on the basis of RCA4 Regional Climate Models (RCM) [25], developed by the Rossby Centre at the Swedish Meteorological Hydrological Institute (SMHI). A total number of 13 future climate projections over a 90-year period, from 2010 to 2099, that was generated by five global climate models (GCMs) and forced by three Representative Concentration Pathways (RCPs); RCP2.6, RCP4.5 and RCP8.5 were considered. The timeframe until the end of the 21st century was divided into three 30-year periods to be able to compare results for multiple periods: 1) near-term (NT, 2010–2039), 2) medium-term (MT, 2040–2069), and 3) long-term (LT, 2070–2099). Typical Downscaled Year (TDY) weather files were synthesized based on the month representing the most typical temperature within the 30-year period. To account for weather extremes, additional files representing the extreme warm and extreme cold weather conditions within the 30-year and 13 climate

predictions matrixes were derived. Extreme Cold Year (ECY) files were hereby representative for the coldest month over the periods. Extreme Warm Year (EWY) files contrarily characterised the warmest months composed into one-year weather files. For more details about applied future weather data sets, the reader is referred to [23].

Figure 2 compares the temperature profile for TDY, ECY and EWY during LT period. The grey background represents all the considered climate scenarios (13 scenarios, each for 30 years) that were used to synthesize TDY, ECY and EWY. The shown temperature graphs are retrieved from Aarhus weather data sets used for case 1. For case 2 located in Copenhagen, weather data retrieved from the RCM for Copenhagen was used. The two last cases, which were in Stuttgart, were simulated with weather files for Munich as it was the closest geographical location for which data was provided.

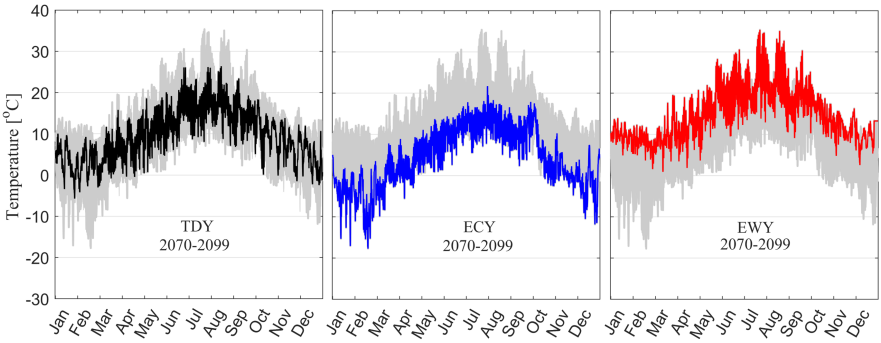

Fig. 2. Temperature variations for TDY, ECY and EWY weather files for the long-term period from 2070-2099 in Aarhus. Grey background is representative for the entire 30-year weather data.

Figure 3 shows the temperature curves in January and February for the NT, MT and LT TDY files of Munich compared with the TMY file for Stuttgart. It can be observed, that, between January and February, the TDY files show very few and only short-term events with temperatures under 0 °C. The TMY file, based on temperature measurements between 1982 and 1992, shows significantly long and frequent cold periods.

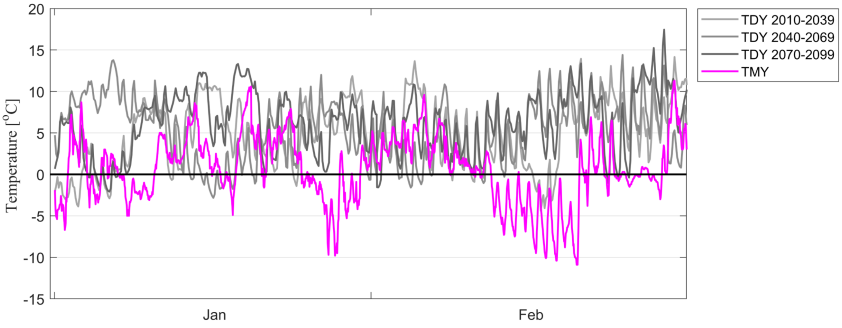

Fig. 3. Temperature variations for TDY NT, MT and LT files for Munich in comparison to the TMY file for Stuttgart based on historical climate measurements.

2.3 Building Performance Simulations

Numerical modelling through BPS was employed to analyse indoor thermal comfort, heating energy use and heating system sizing. Simulations were carried out through the EnergyPlus engine by means of Rhinoceros 3D-modelling [26] and Grasshopper visual scripting [27] using Ladybug Tools plug-ins [28]. The iteration of the workflow was carried out with the TT Toolbox plug-in [29]. The building masses were modelled according to the interior space volumes and glazing as well as frames were assigned parametrically following the window to wall ratios (WWR). Shading by external elements were modelled as opaque surfaces. Moveable shading, presented in some cases, was controlled by a variable schedule, which was enabled during nights when the exterior temperature is under 15 °C, during day and night when the exterior temperature exceeds 24 °C and when the solar radiation incidence was over 400 W/m^2. For all the cases, natural airflow by window ventilation was specified with a variable setpoint controlled by the interior temperature over 24 °C and exterior temperature between 21 °C to 26 °C. 30% of the window area was opened when the setpoint was met. Infiltration, as well as ventilation rates, were case sensitive according to the respective specifications, the same applies for heating setpoint temperatures. Lighting power density was specified as 7 W/m^2 for all cases, density of people was set to be equivalent of four people in 100 m^2 heated floor area. Equipment loads and schedules for occupancy, occupancy activity, lighting, equipment and ventilation were based on ASHRAE standard 90.1-2004 [30]. The indoor thermal comfort was assessed with the adaptive comfort model according to EN 15 251 [31] comfort band II for residential buildings and was plotted as XY-scatters. Validation of the building models and scripts was conducted by comparing energy use data from measurements and calculations received from building owners with simulation data obtained with TMY files.

3 Results and Discussion

3.1 Indoor Thermal Comfort

Results of the indoor comfort study are displayed in Fig. 4 where the presented values indicate the percentage of time exceeding the thermal comfort boundaries. As the measures are based on the adaptive comfort model, the percentage of hours in discomfort displays both time uncomfortable due to cold-stress and time uncomfortable due to heat-stress, relating to the operative temperature being below or above the comfort band temperatures for the entire year, regardless of the occupation. The diagrams in Fig. 4 show the results for TDY periods on the left side, ECY periods in the middle and EWY periods on the right. All measures are averages from zone-specific discomfort values; normalization has been applied according to the floor area. Only lettable spaces were considered in the indoor comfort study. As the extreme cold and warm year scenarios are unlikely to occur continuously, their results can only be used for comparison and drawing (pessimistic) boundaries. By comparing the results retrieved for TDY periods in the initial stage and in the retrofitted stage, an increase of discomfort can be seen over all cases and periods. Case 3 shows an intensive increase of thermal discomfort between initial and retrofitted building. For retrofitted cases 1

and 4, a quantitative increase of hours in discomfort can be seen throughout the TDY periods towards the end of the century. Case 2 shows a slight decrease, whereas for case 3, the outlier is the MT period with an increase in discomfort of 10%. The decrease in case 2 could be explained by the declining number of hours with cold-stress during wintertime, which outweighed the increase of hours in heat-stress. For both cases 1 and 2, the heating setpoints were at 21 °C, leading to a number of hours with cold-stress during wintertime. Especially for zones with large window surfaces this was seen, leading to the conclusion, that the thermostat setpoint will be adjusted by occupants in order to adapt to a comfortable indoor temperature.

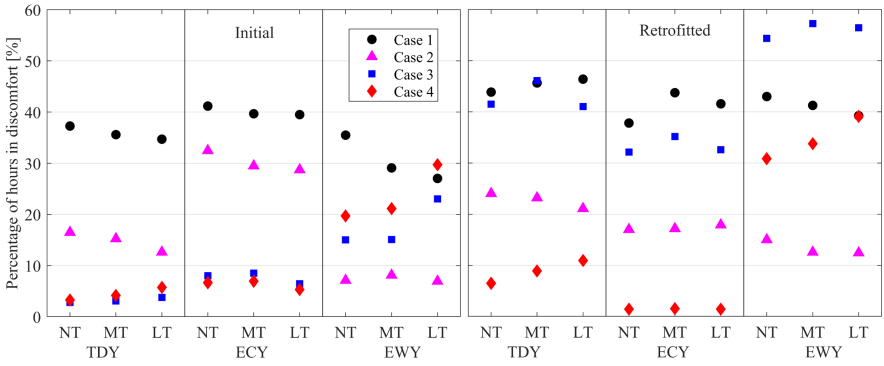

Fig. 4. Percentage of hours in discomfort according to EN 15 251 comfort band II. Non-retrofitted initial buildings on the left, retrofitted buildings on the right.

For the hours of heat-stress and overheating, the possibilities of adaptation were limited. The employed passive measures such as natural window ventilation and shading explored in cases 3 and 4 proved to be insufficient to reduce overheating issues, the setpoints for shading and natural ventilation should thus be reconsidered by the designers. The increase in overheating towards the end of the 21st century indicates that insulation and airtightness measures must be designed in regard to future climate. This entails that, in order to take informed decisions, future climate projections should be considered. Case 3, which showed extraordinarily high percentages of discomfort in the retrofitted building, demonstrates that the addition of 200 mm of thermal insulation outside the thermal mass leads to heat being trapped in the building. Results retrieved for case 4, which is exposed to the same climatic conditions as case 3, were significantly better. Here, the thermal insulation was realized on the inside of the building, resulting in the breaking of thermal mass from the occupied spaces. However, the cases do not allow for comparative conclusions to be drawn, as both airtightness and conductivity of the envelope constructions among others were different.

3.2 Energy Use

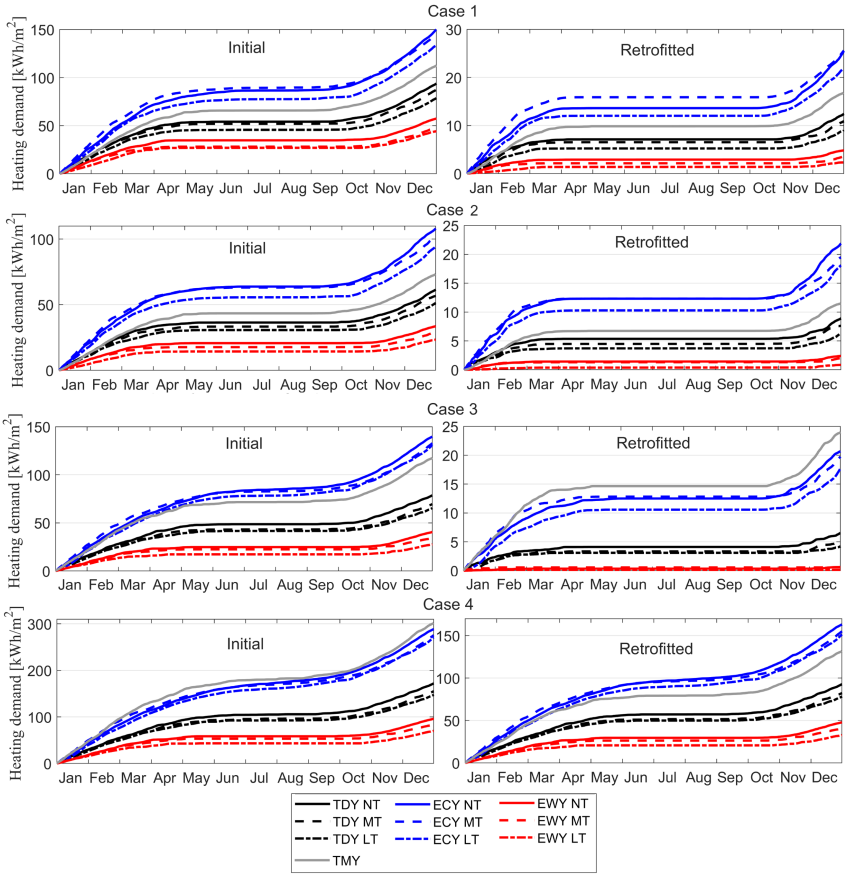

Fig. 5. Cumulative heating energy demand. Scale (initial/retrofitted) adjusted for better visibility.

Figure 5 represents the cumulative heating energy demand for the case studies in both non-retrofitted and retrofitted stages. All diagrams show a total of 10 data sets, obtained using TMY, TDY, ECY and EWY files for NT, MT, and LT periods. Steep periods represent the heating season while the flat periods reflect the times where there is no need for heating. For all four case studies, major reductions of overall heating demand can be seen from the initial to the retrofitted stage. Throughout the case studies, the energy demand for heating was obtained the highest for ECY periods and the lowest for the EWY periods due to the temperature averages which were the lowest for ECY periods and the highest for EWY periods. An exception can be seen in heating demands in cases 3 retrofitted stage and case 4 initial where higher heating energy demands for TMY files were obtained. This inconsistency can be explained by the temperature

differences in wintertime as shown in 2.2. For all the periods within the future climate files, a decrease from the NT period towards the end of the 21st century was observed. The differences between the 30-year periods were 5% to 12% for the initial buildings and 5% to 25% for the retrofitted buildings. For the cases 1 and 2, the differences between the results identified for TMY files compared to TDY NT files are between 19% to 35% higher, revealing a larger effect than the one between the TDY periods. For cases 3 and 4, the differences are more significant and reach from 41% to 250%, showing the importance of taking future climate data into account.

3.3 System Sizing

The heating loads of the building were assessed with a statistical analysis seen in Fig. 6. The combination of data sets for TDY, ECY, EWY (called 'Triple') over the considered periods are investigated as suggested by Nik [23] for the initial and retrofitted stages. A comparison with the results for the respective TMY files is given, as the first boxplots for each case. Here it is important to notice that TMY data samples contain 8 760 values representing all hours of one year BPS results, whereas the 'Triple' data sets compose three times as much, representing all hourly data for TDY, ECY and EWY files summed up, thus containing 26 280 values. The reasoning for using 'Triple' data sets is to reflect weather extremes into the system design. Not considering weather extremes in system design but only results from TDY files would result in underestimating loads given during extreme cold or extreme warm periods. The study has shown that especially the cold extremes from BPS with ECY weather files should be considered when designing heating systems. This was in line with previous findings by Moazami et al. [20]. More detailed results showing individual data for TDY, ECY and EWY files can be found in [16]. The findings presented in this article are combining the results for typical and extreme conditions in order to provide adequate building and zone heating systems. This suggests a mild shift in thermal

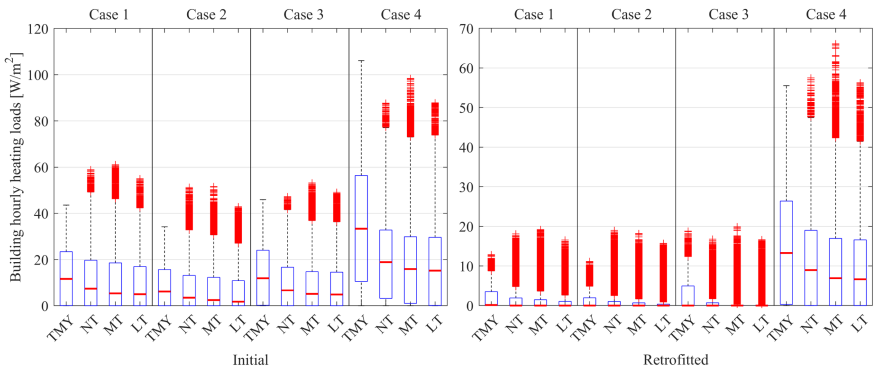

Fig. 6. Hourly heating loads 'triple' data sets and TMY data sets for cases 1–4 from left to right. Non-retrofitted initial building performance (left), retrofitted building performance on the right. TMY: typical metrological year (8 760 values); NT; MT; LT (All 26 280 values). Scale adjusted for better visibility. (Color figure online)

system and device dimensioning strategies which aims for higher resilience in future climate. The discussion is based on results within the whisker range of the boxplot diagrams, the median is shown with a red line within the blue box which is representing the interquartile range. Outliers, plotted as red lines in the upper extrema, are representing a very small fraction of occurrence, so that they were neglected.

Throughout all the cases, the highest heating peak loads were observed for TMY files. This was excepted for case 1 in the initial stage, which showed a slightly lower upper whisker range than throughout the future climate scenarios, which can be explained by not as low winter-temperatures or not as long-lasting cold periods as in the TDY files. Another possible explanation is the location difference between Copenhagen for the TMY file and Aarhus for future weather data. Furthermore, the heating peak loads were seen to be gradually decreasing for the future weather periods for the results obtained for NT to LT. For cases 1–3 in the retrofitted stage, the median is as low as 0 W/m^2, which indicates that for at least 50% of the time on an annual basis, there is no heating need. System design according to TMY files suggests that the heating systems would be over-dimensioned for weather predictions from 2010–2099. This finding emphasises the importance of using future climate projections in the decision-making process, especially to promote resilient design. The decision about dimensioning thermal systems has great influence on economic factors and over or under-dimensioning can have crucial importance on the thermal as well as economic performance of a project.

4 Conclusions

This work investigated the resilience of building retrofits for future climate and the need to consider climate change in the planning and implementation of retrofitting projects. As performance indicators, indoor thermal comfort, heating energy demand and heating system sizing were investigated by means of numerical simulation of the building performance. The impacts of future climate, its long-term changes, and extreme conditions were evaluated for four case studies located in Denmark and Germany. Future climate projections were incorporated in the simulations through weather files derived according to Nik´s method [23]. Each case was studied for the period of 2010–2099, divided into three 30-year periods. Each time period was represented by three weather files to account for the most typical conditions as well as extreme warm and extreme cold conditions.

The study shows that mitigating the energy use for heating was successful through the retrofits of all four case studies. In all cases, the heating demand decreases while approaching the end of the 21st century, indicating the effect of global warming. According to the results, accounting for future climate will provide a more realistic prognose for the energy performance of buildings will be during the usage stage. The severity and frequency of extreme heating loads decreased for the retrofitted buildings, and the heating periods became significantly shorter than the non-retrofitted buildings. Increased thermal discomfort due to heat-stress was seen for all cases when using future climate projections.

Based on the obtained results, it can be concluded that taking future climate projections into account when designing both passive and active measures would be beneficial to evaluate their effectivity, leading to performance-oriented design decisions. The presented method can thus become beneficial when designing according to bioclimatic design principles. Findings from this study suggest that future climate projections and extreme scenarios should be considered for decision-making in the system design to make buildings resilient to climate change and extreme events and to prevent economic and/or performance failures.

Designs that are based on considering future climate conditions enable us to retrofit buildings more sustainably and resource efficiently. Scalability of results was seen between the cases studied, but applicability of the conclusions to other cases in different locations, size and typologies must be studied further.

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