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Effective and robust energy retrofitting measures for future climatic conditions—Reduced heating demand of Swedish households

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ABSTRACT

This article quantifies the energy saving potential and robustness of nine energy retrofitting measures, as well as four combinations of these, for residential building stocks of three major cities in Sweden and for five scenarios of future climatic conditions, downscaled by a regional climate model (RCM). The retrofitting measures are evaluated for five temporal resolutions of hourly, daily, monthly, annual and 20-years during the period of 1961 through 2100. The evaluation takes into account a very important uncertainty factor of future climate data, induced by different global climate models (GCMs). The application of a statistical method for assessing the retrofitting measures is being evaluated.

Results verify the consistency and reliability of the comparative assessment and confirm the possibility of assessing the retrofitting measures without the need for long-term simulations and considering climate uncertainties. Among the considered retrofitting measures, a combination of an improved thermal insulation of the building envelope with energy efficient windows is the most effective and robust retrofitting measure, while tuning the indoor set-point temperature to 20 °C can also contribute to significant energy savings.

1. Introduction

Improving the energy efficiency of buildings through retrofitting is a key part of energy saving, carbon dioxide (CO_2) reduction and climate change adaptation strategies for countries with established building stocks. Retrofitting buildings is promoted in European countries and guidelines are provided to meet the EU energy and climate change objectives by 2020 and to take forward its 2050 decarbonisation agenda [1,2]. Retrofitting usually involves a combination of techno-economic measures that are aimed at reducing the energy demand for operation of buildings and, if necessary, at improving the indoor comfort, but also at guiding building owners and tenants to use the building in an energy efficient way. There exist a variety of retrofitting measures; easy to implement measures, such as using efficient light sources, as well as comprehensive and combined measures such as upgrading the building services and envelopes.

Selection of proper retrofitting measures and assessment of their long term benefits are challenging tasks due to numerous retrofitting options and their direct and indirect impacts on the building performance. Several approaches and techniques exist for planning and assessment of retrofitting strategies, which commonly take into account availability, applicability, cost and energy efficiency of the measures, as well as building energy simulations (e.g. [3–7]). Multi-objective optimization techniques are often needed in the retrofit analysis (e.g. [8–12]), as well as methods to deal with uncertainties and risks that arise in the assessment [13–16].

Climate is the most important boundary condition for building simulations and when climate change is taken into account, uncertainties in meeting the desired performance of the retrofitted buildings increase due to inherent uncertainties of the climate models (see [17–19]). Several researchers have shown that climate change affects the energy performance of buildings (e.g. [4,18,20,21–24]), even after retrofitting buildings (e.g. [3,16,25,26]). Moreover it has been shown that climate change uncertainties, presented as different climate scenarios, can affect building simulations significantly (e.g. [4,18,20,24]). Importance of these effects vary depending on the considered time resolution;

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for example differences in the hygrothermal and energy performance of buildings due to climate uncertainties can increase on the daily or seasonal scales compared to the annual or periodical (20-year or 30-year) scales (e.g. [4,18,19,28]). Although uncertainties in model predictions of future climate are large, scientific evidences for warming of the climate system are unequivocal [27]. Climate changes will be observed on different time scales: long-term, e.g. higher average temperatures over decades and short-term, e.g. much warmer summer daily hours or much colder winter night hours. For all these reasons, both the climate change and climate uncertainties should be included in retrofit analyses.

Consideration of climate change in the retrofit analysis brings two major aspects which, in combination with multiple retrofitting options, make the assessment laborious: 1) very large sets of weather data (e.g. over 100 years on hourly resolution) and building data, and 2) important uncertainties due to future climate scenarios. Statistical methods have been proven adequate for efficient analyses of large data sets produced by building simulations (e.g. [4,26,28]). A particular statistical method has been developed previously by the authors for assessing the future performance of retrofitting measures in terms of their effectiveness and robustness on five time resolutions of hourly, daily, monthly, annual and 20-years [26]. The effectiveness is quantified as an average energy saving percentage for space heating demand over a period of time, due to retrofitting, while robustness is quantified by calculating the standard deviations of the effectiveness values among several time periods and climate scenarios. Robustness is a gauge for quantifying the variations of the effectiveness; lower variations among periods or scenarios deals with higher robustness of the retrofitting measure. The ideal case is having no variations (zero) which means an absolutely robust retrofitting measure. The method was exemplified on two selected retrofitting measures implemented on sample buildings from a building stock (city of Stockholm, Sweden), and for five different climate scenarios. Results of the analysis showed that the relative performance of the retrofitted buildings, compared to the non-retrofitted ones, does not change considerably over time, regardless the climate scenario and time resolution. It was further concluded that the relative performance of the considered retrofitting measures could be assessed by considering an arbitrary 20-year period from any climate scenario, while their future performance could be estimated based on the future performance of the reference or non-retrofitted buildings.

The present work evaluates the application and consistency of the suggested statistical method from [26] further by including a more representative portfolio of single retrofitting measures (i.e. nine measures) and four combinations of these, applied on sample buildings of three major cities in Sweden: Stockholm, Gothenburg and Lund. For all the considered measures, their effectiveness in decreasing the energy demand for space heating and their robustness against climate change and its uncertainties are studied for five temporal resolutions: hourly, daily, monthly, annual and 20 years. One of the most important uncertainty factors of future climate data in energy calculations, induced by different global climate models (GCMs) [19], is taken into account. More than verifying the consistency of the suggested statistical method, this article aims at assessing the effectiveness and robustness of the considered retrofitting measures for uncertain future climatic conditions of three cities in Sweden.

This article is divided into three major parts: Section 2 briefly describes the background knowledge about the considered building stocks, retrofitting measures (single and combined) and future climate scenarios, and also the previously developed statistical method which is used in the assessment. Results of the energy simulations and the retrofitting measures are assessed thoroughly in Section 3. Firstly, consistency of the statistical method is evaluated for the five temporal resolutions for the buildings in Stockholm and thirteen retrofitting options. Then, the possibility of relying on the relative performance of the retrofitted buildings for only one 20-year period and one climate scenario is assessed. In the second part of Section 3 the performance and robustness of the retrofitting measures are evaluated for the buildings in all three cities, by looking into five temporal resolutions. Finally section 4 describes the conclusions of this work.

2. Methods and data sets

In this section the methods and data sets which are used in this work are discussed as the following: (1) Statistical representation of the building stock; describing three building stocks which are studied in this work, (2) Energy retrofitting measures; explaining nine single retrofitting measures and four combinations of them, (3) Climate data and uncertainties; providing a deeper insight about the climate data sets which are used in this work and the considered uncertainties, (4) Modelling the energy performance of the building stock; containing more information and specific references about the building models and (5) Assessment method; describing the statistical applied statistical method in brief. For each subsection there are specific references which the readers are referred to, discussing the previous works of the authors in connection with the current article.

2.1. Statistical representation of the building stock

The residential building stocks of Stockholm, Gothenburg and Lund are represented by 153, 184 and 52 sample buildings respectively, for which statistics on the average thermal transmittance of the building envelopes (U-value), the heated floor area and the window area are shown in Fig. 1. These buildings belong to a group of 1400 buildings that have been chosen statistically to represent all residential buildings in Sweden, and characterized in an extensive field investigation [29], conducted in year 2005. This data is the major source of information for modelling and assessment of energy performance of Swedish residential building stock and has already been used in previous works by the authors, e.g. [18,30,31].

There are weighting coefficients for the sample buildings, quantifying the frequency of the sample buildings in the existing building stock. For example for Stockholm the input data consists of around 450 thousand dwellings (50 and 400 thousand dwellings for single-family dwellings (SFDs) and multi-family dwellings (MFDs) respectively) in around 62 thousand buildings (44.9 and 17.1 thousand SFD and MFD buildings respectively), corresponding to a heated floor area of around 42.9 million m^2 (7.5 and 35.4 million m^2 for SFDs and MFDs respectively). For Gothenburg the input consists of 270 thousand dwellings (for Lund: 220 thousand) of which 60 and 210 thousand for SFDs and MFDs respectively (for Lund: 56 and 9 thousand), in around 62 thousand buildings (for Lund: 65 thousand) of which 44.9 and 17.1 thousand are SFD and MFD buildings respectively (for Lund: 55 and 165 thousand). These correspond to a heated floor area of around 26.9 million m^2 (for Lund: 20.6 million m^2) divided into 8.2 and 18.7 million m^2 for SFDs and MFDs respectively (for Lund: 0.8 and 1.2 million m^2)—The number of dwellings modelled in Stockholm corresponds to 20% and 70% of the SFDs and MFDs respectively accounted in the national statistics [32] for the so-called “big Stockholm” and, in Gothenburg, to 35% and 80% of the SFDs and MFDs,respectively, of the so-called “big Gothenburg” in the same statistics. The number of dwellings is not available in the statistics for the city of Lund.

Impacts of climate change on the energy performance of the residential building stock of the considered cities as it was in year 2005, which is referred as the non-retrofitted or the reference case in this paper, have been studied previously [18,19]. The heating/cooling

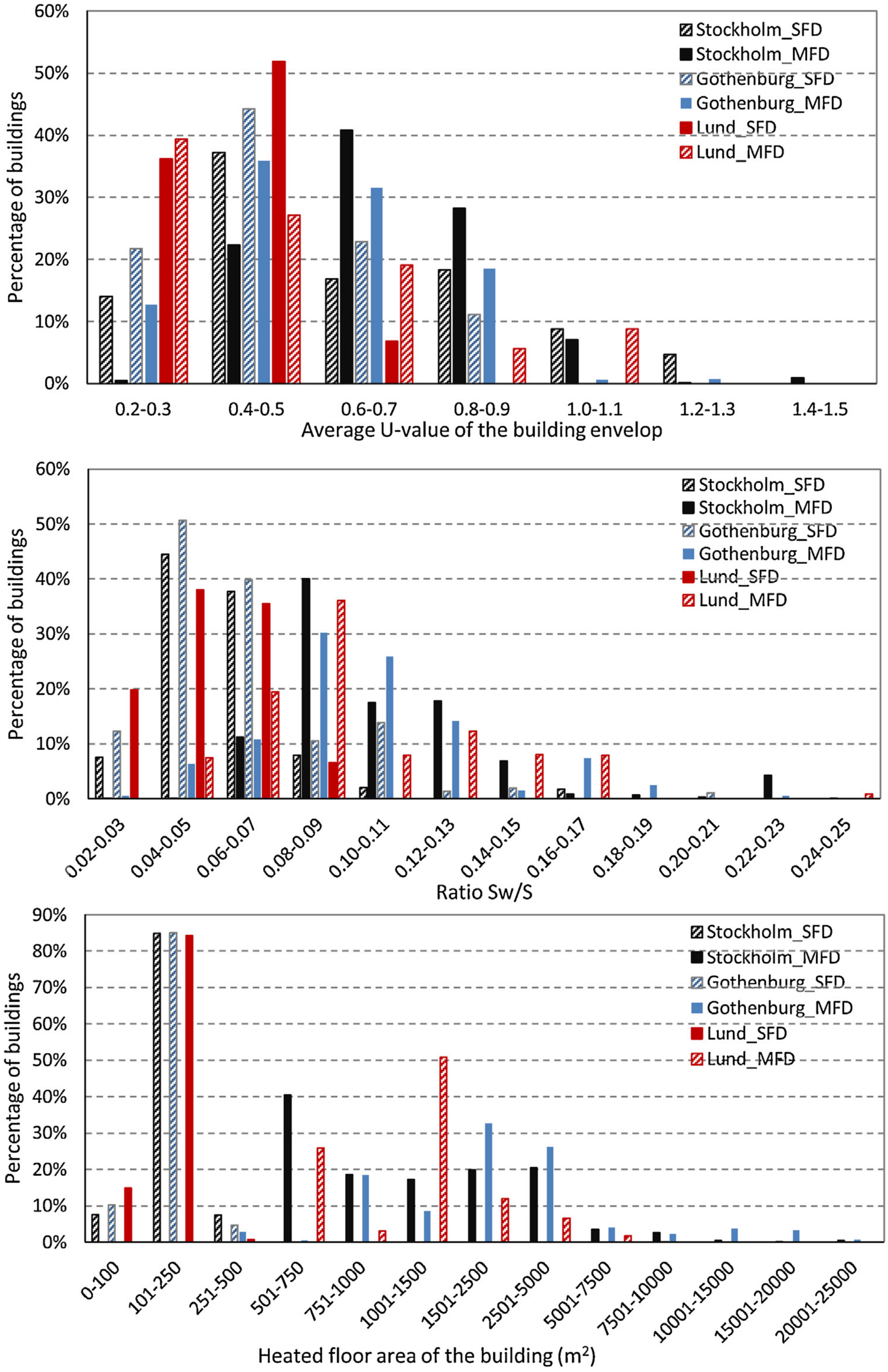

Fig. 1. Statistical distribution of the buildings' average U-value [W/m^2 K], window area [Sw, in m^2; provided as a ratio of the total building envelop S], and heated floor area [m^2] for the building stocks of Stockholm, Gothenburg and Lund in year 2005 (extracted from the input in this work). SFD, Single-family dwelling; MDF, multifamily dwelling.

demand and the indoor temperature of the sample buildings were simulated and assessed for several climate scenarios, including the same five which are used in this work. According to the previous results, the heating demand for the residential building stock will decrease substantially in future. For example in Stockholm, the 20-year average of the heating demand will be around 105 kW h/m^2 during 2081–2100; this is about 30% lower than the heating demand during the during 1990–2011. Previous studies showed that GCMs can induce differences in heating demands up to 30 kW h/m^2 (around 30%) in the 20-year mean values. Uncertainties are larger when variations are taken into account; differences in the standard deviations reach to values larger than 50% of the average heating demand. Although the cooling demand was higher in future, it was still very small and negligible. For more information about the reference building stock and impacts of climate change on its energy performance, the reader is referred to [18,19].

Table 1
Retrofitting measures studied in this work. Individual retrofitting measures are named as N# and packages as P#.

N1	Increased insulation of cellar/basement
N2	Increased insulation of facades
N3	Increased insulation of attics/roofs
N4	Replacement of windows
N5	Upgrade of ventilation systems with heat recovery, for SFDs
N6	Upgrade of ventilation systems with heat recovery, for MFDs
N7	Installation of efficient lighting equipment
N8	Installation of efficient appliances
N9	Installation of thermostats to set the minimum indoor air temperature to 20 °C
P1	Improved building envelope (N1–N4)
P2	Improved ventilation and windows (N4–N6)
P3	Installation of efficient lighting and appliances (N7 and N8)
P4	All individual retrofitting measures (N1–N9)

[*] SFD: Single Family Dwelling, MFD: Multi Family Dwelling.

2.2. Energy retrofitting measures

Nine individual energy retrofitting measures are investigated in this work, as listed in Table 1. These are the most common retrofitting measures and result from grouping a list of 23 measures suggested in the above referred database [29]; the grouping is validated in [33], and described in [30]. The first four measures, N1–N4, assume an improvement of the building envelope, i.e. a lower mean overall thermal transmittance (U-value), by adding thermal insulation to, respectively, the cellar, wall or roof as well as by window replacement. For residential buildings, the assessments of the optimal level of insulation have been done for each building by the Swedish National Board of Housing, Building and Planning (Boverket), (cf. Table 3.3. in [34]). Therefore the additional layers of insulation are different for various buildings. When replacing the windows (N4), a U-value of 1.1 W/m^2 K is assumed for the new window, corresponding to low-e insulated glazing. The installation of ventilation systems with heat recovery in SFDs and MFDs are assumed in measures N5 and N6 respectively. For SFDs – generally lacking a mechanical ventilation system – N5 implies the installation of mechanical exhaust-only ventilation with specific fan power of 1.5 kW/m^{3}s, 20% heat losses from the fan, and exhaust-air heat recovery with an efficiency of 75%. For MFDs – which mostly have a mechanical exhaust-only ventilation system in the non-retrofitted buildings – N6 implies an upgrade to exhaust-supply ventilation system with heat recovery. N7 and N8 assume a decrease by 50% in the electricity consumption for lighting and appliances. N9 assumes that by installing thermostats the minimum indoor air temperature is set to 20 °C, from the current monitored indoor temperatures of 21.1 °C in SFDs and 22.3 °C in MFDs reported in [34]. Some characteristics of the building stock in three cities before and after retrofitting are compared in Table 2.

Additionally, several packages of measures have been created for this work to investigate implementation of multiple measures at the same time, following different technical, constructive and operational considerations. Namely, package 1 assumes an overall improvement of the building envelope by insulating the cellar, facades and roofs as well as replacing the windows to meet the regulation in force [35], i.e. overall U value of 0.4 W/m^2 K. Package 2 assumes improvements in the ventilation system, i.e. installation of heat recovery and airproofing of the building envelope through windows' replacement. Package 3 assumes that the electrical power demand for lighting and appliances decreased by 50% by installing more efficient equipment. Finally, package 4 represents a comprehensive retrofitting of the building in which all measures 1–9 are implemented simultaneously. The process of buildings retrofitting has its own uncertainties (e.g. [13–15]), e.g. induced by workmanship, material properties, installation techniques and etc., which are not considered in this work to limit the uncertainties and being able to track those induced by having climate data sets.

2.3. Climate data and uncertainties

Future climate conditions of three cities are considered in this work: (1) Gothenburg on the west coast of south-west with the oceanic climate which is very influenced by the nearby ocean, (2) Lund in southern Sweden with oceanic climate and (3) Stockholm on south-central east coast of Sweden with humid continental climate. For instance, in Stockholm, according to measurements, the average annual temperature is 6.6 °C and has increased for about 1 °C during 1991–2010 compared to 1961–1990 [36]. The climate data, used in this work, are results of the regional climate model RCA3, created by the Rossby Centre, climate modelling unit of the Swedish Meteorological Hydrological Institute (SMHI). Regional climate models (RCMs) are used to downscale results from the global climate models (GCMs) dynamically, achieving a higher spatial resolution over a specific region [37]. The coarse spatial resolution of GCMs (often 100–300 km) is not suitable for building simulations. For this work RCA3 were used, downscaling five GCMs to a 50 km horizontal resolution: (1) ECHAM5, (2) CCSM3, (3) CNRM, (4) HadCM3 and (5) IPSL (for details see [17,18]). RCA3 is capable for downscaling climate data from GCMs with the time resolution down to 15 min, however the time resolution for the climate data which were used in building simulations is one hour (for details see Ref. [4]). RCA3 climate data were synthesized by coding in Matlab before being used in the energy simulations.

Average values for the outdoor temperature in the periods of 20 years between 1961 and 2100 and their standard deviations are shown in Fig. 2 for the considered cities. There are large differences between scenarios; for example RCA3-IPSL has much lower average temperatures than the other scenarios (e.g. RCA3-CNRM) but shows the largest standard deviations. Although all scenarios predict higher future temperatures, the global warming rate is not identical. For example for the case of Stockholm, during 2081–2100 the average temperature is around 2.5 °C higher than during 1961–1980 for RCA3-CNRM, while this increment is around 4 °C for RCA3-IPSL. Standard deviations decrease by time in Fig. 2 for all the scenarios, though not at the same rate.

2.4. Modelling the energy performance of the building stock

The energy performance of the building stock is modelled with the so-called ECCABS building-stock model [38]. The energy performance of each sample building – described in Section 2.1 – is modelled mathematically in Simulink/Matlab, as a linear explicit discrete time-variant system, based on the lumped system analysis approach. According to the classification of calculation procedures in ISO 13790 [39], the model is detailed – hourly specification of the input data and the results – and dynamic – takes into account the thermal mass of the building at each time step. The energy demand of the sample buildings is extrapolated to the building stock by means of weighting coefficients. Accuracy of the energy model has been verified by inter-model comparisons and empirical validations [38]. The building stock model has already been used to investigate the building stock of Sweden [19,30,31] as well as of various European countries [40], [41].

To decrease the computation time of simulations, each building of the considered building stocks is simulated only once during each 20-year period. In this way, each building experiences climatic conditions of only a single year during a 20-year period, though in reality all the buildings experience all the years. This simplification does not affect the long term simulation results, as shown in [19].

Table 2
Assumed values for relevant building characteristics before and after retrofitting, for building stocks in three cities and for retrofitting measures N1–N6.

	Stockholm		Gothenburg		Lund	
Average U value of the building Envelope [W/m^2 K]						
	Retrofitted	Non-retrofitted	Retrofitted	Non-retrofitted	Retrofitted	Non-retrofitted
N1	0.51	0.58	0.63	0.71	0.61	0.69
N2	0.47	0.52	0.57	0.69	0.52	0.62
N3	0.46	0.50	0.57	0.61	0.54	0.58
N4	0.39	0.50	0.53	0.64	0.50	0.60
Solar energy transmittance of windows (g-value) [–]						
N4	0.57	0.70	0.58	0.69	0.58	0.69
Efficiency of the heat recovery system [%]						
N5	75	2	75	6	75	5
N6	75	4	75	6	75	7

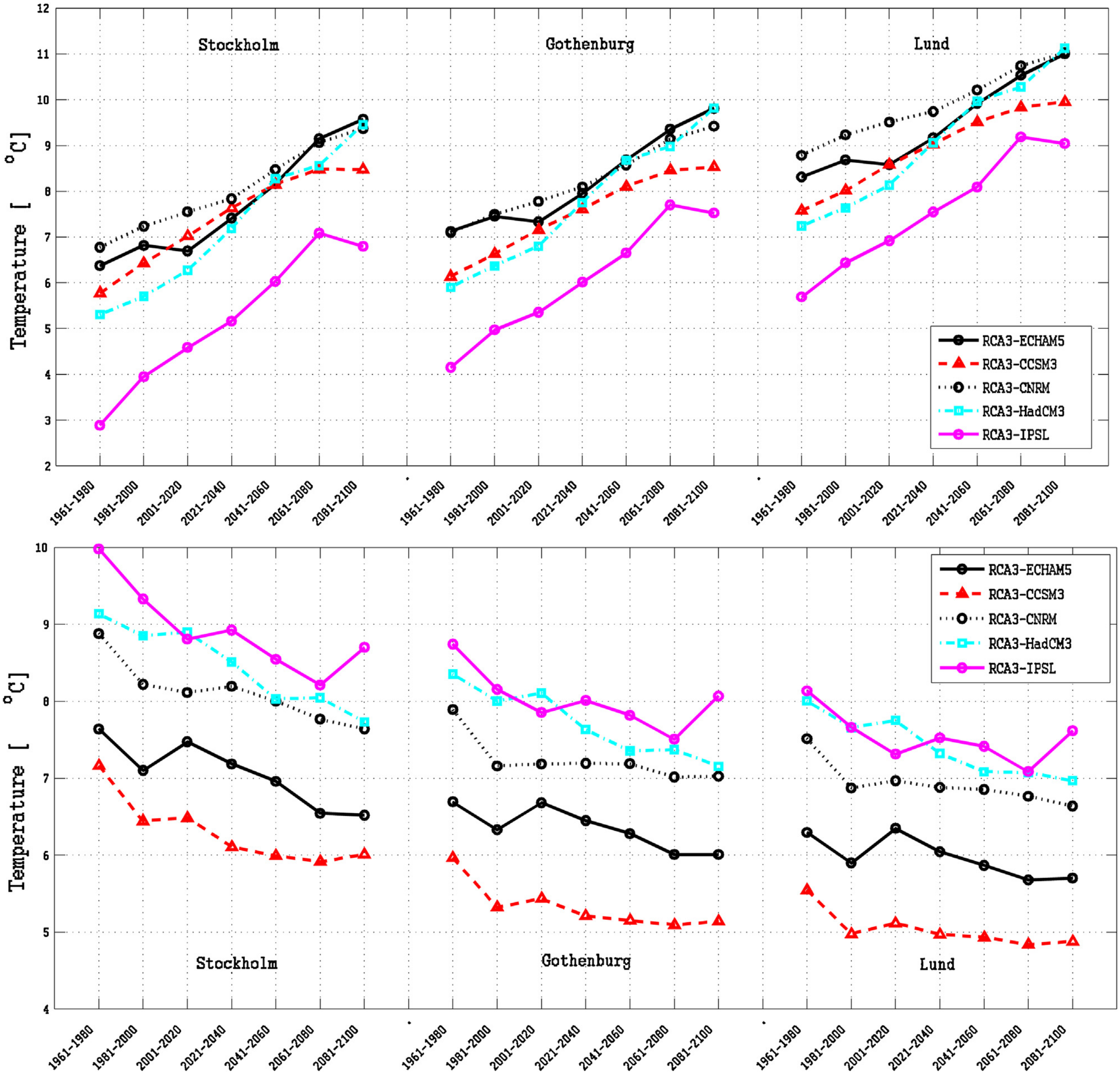

Fig. 2. Averages (top) and standard deviations (bottom) of the outdoor temperature in three cities during 20-year periods over 1961–2100. Five scenarios of the RCA3 regional climate model are compared when it has been forced by different GCMs.

2.5. Assessment method

A recently developed method for assessing the effectiveness and robustness of retrofitting measures against climate change [26] is used in this work. Capabilities of the method have been assessed for few cases previously, considering both for heating and cooling demand. The focus in this work is only on the space heating demand (as described in more details in [38], which is also in accordance with EU regulations [42]) since the need for cooling demand is very low for the considered buildings as it has been shown previously [18,19]. In short, the approach is mainly comparative analysis: the energy performance of the non-retrofitted building stock is considered as reference and compared to the performance of the retrofitted buildings in five time resolutions, i.e. hourly, daily, monthly, annual and 20 years. This approach is necessary because climate variations are expressed at all specified time resolutions. Comparing the 20-year performance of the measures provides a long term assessment, while the comparisons at the hourly scales reveal their performances during extreme climatic conditions. To avoid biasing the effects of climate uncertainties in the energy calculations, the energy demand for domestic hot water is not considered in the analysis since it is defined as a constant term in the model (proportional to the building floor area) and not a function of outdoor temperature.

Buildings are simulated before and after retrofitting, using exactly the same climate data and time period. Relative difference (*RD*) of the corresponding space heating demand at any time resolution is defined as the following:

$$RD = 100 \times \frac{\left(Q_{h,i}^{after} - Q_{h,i}^{before}\right)}{Q_{h,i}^{before}} \tag{1}$$

where Q_h is space heating demand in kW h/m^2 and *i* is the building number. *after* and *before* correspond to after retrofitting and before that (reference building) respectively. RDs [%] are calculated for each climate scenario, retrofitting measure and time resolution.

Similarly to the energy simulations, *RD*s are calculated during the 20-year periods, resulting in seven sets of *RD*s during 1961–2100 for each time resolution. The calculated *RD*s and their variations are used to study the relative performance, i.e. the effectiveness of the retrofitting measures; their mean values and (sample) standard deviations (both in percentage) are calculated for all the buildings according to relations (2) and (3). In this way, the relative differences of the retrofitted building versus the non-retrofitted one are represented by two values, $\overline{RD}$and *sd*:

$$\overline{RD} = \frac{1}{n-1}\sum_{i=1}^{n} RD_i \tag{2}$$

$$sd = \left(\frac{1}{n-1}\sum_{i=1}^{n}\left(RD_i - \overline{RD}\right)^2\right)^{\frac{1}{2}} \tag{3}$$

which *n* is the number of buildings in the considered building stock, $\overline{RD}$[%] is the average of the relative differences among the buildings and *sd*[%] is the standard deviation of the relative differences among the buildings. All the values are calculated for each of the five temporal resolutions, providing an overview of the efficiency and robustness of the retrofitting measures. The applicability of the method has been evaluated for few cases in Stockholm [26] and Gothenburg [43] previously and is being more evaluated in this work. For a detailed description of the method, the reader is referred to an earlier work [26].

3. Assessment results

In this section results of the assessment are presented. Firstly, results for the residential building stock in Stockholm are explained in detail to investigate the reliability and consistency of the suggested statistical method for relative comparisons of the retrofitting measures.is investigated if it is possible to rely on the comparative assessment of retrofitting measures among several climate scenarios and time periods and if it is possible to rely on less number of scenarios and time periods. The method and the suggested approach is consistent if it works for all the retrofitting measures. Afterwards, the effectiveness and robustness of the retrofitting measures are investigated for all three cities by assessing their relative performance in five temporal resolutions.

3.1. Detailed results for stockholm

As it was shown in Fig. 2, climate uncertainties induce considerable differences in expected future outdoor temperatures and Fig. 3 shows how these differences affect the space heating demand for the reference building stock in Stockholm, for two climate scenarios: RCA3-CNRM and RCA3-IPSL, which show the maximum difference in Fig. 2. Although both the scenarios in Fig. 3 indicate lower space heating demand in future, differences in the distribution of the heating demand and its average (even for large temporal resolution of 20 years) are not negligible. As it has been shown in a previous work [19], on the 20-year time scale, having different GCMs could induce differences up to 4 °C and 3 °C in the average and standard deviation of the outdoor temperature, resulting in more than 30% differences in the 20-year average of the heating demand. These differences can increase when the temporal resolution increases, e.g. looking into monthly or daily demands (see Ref. [19] for details). These differences also exist for the retrofitted buildings, which can make the assessment and decision making procedure difficult. If the comparative analysis works for all the retrofitting measures, climate scenarios and time resolutions, there will not be a need for simulating the retrofitted buildings for every time period and climate scenario. Let's assume that the monthly heating demand for a retrofitted building is around 20% less than in the non-retrofitted building for RCA3-CNRM during 1961–1980. If the difference stays around 20% for any other period (e.g. 2081–2100), or any other climate scenario (e.g. RCA3-IPSL), then we can rely on having a retrofitting measure with 20% lower monthly heating demand, despite of the future changes in climate. This feature could save a lot of the computation time which is further studied for all thirteen retrofitting measures.

Table 3 shows results of the comparative assessment of P4 retrofitting measure – which is a package of all nine individual measures – for the monthly temporal resolution as an example for describing the outcomes of the statistical method in more detail. Average values and standard deviations of the relative differences (*RD*s) for the heating demand are shown for the five climate scenarios, each split in seven 20-year periods. The average values, obtained for each climate scenario, are shown in the 'Overall Mean' row for each climate scenario, while the "SD" row shows the standard deviations for each column during seven time periods. Averages and standard deviations are also calculated for the same and each 20 year period in all the climate scenarios, shown in the "Scenarios mean" and "Scenarios SD" columns in Table 3. Those values in the four rightmost columns of the "Overall mean" row (i.e. −36.0, 19.6, 0.5 and 0.8 in Table 3) are used in this work to assess and compare the retrofitting measures. They summarize the performance of the retrofitting measure, while several climate scenarios and 20-year time periods have been taken into account. The first value, −36.0%, quantifies the change in the average monthly heating demand of the building after retrofitting (which is called effectiveness of the retrofitting measure here). The second value of 19.6% is the average differences between the calculated effectiveness month to month. For example, for the considered case if RD of space heating demand in month 1 is 30%, in month 2 this difference varies in the range of 30 − 19.6% and 30 + 19.6%. The other two values in the same row (under Scenarios SD) give an overall view of the uncertainties induced by climate scenarios during seven time periods. For example, variations of the *Overallmean* ($\overline{mean}$) among time periods and climate scenarios are around 0.5%, while for the monthly variations it is around 0.8%. These four numbers are themselves the averages over the seven time periods, where variations

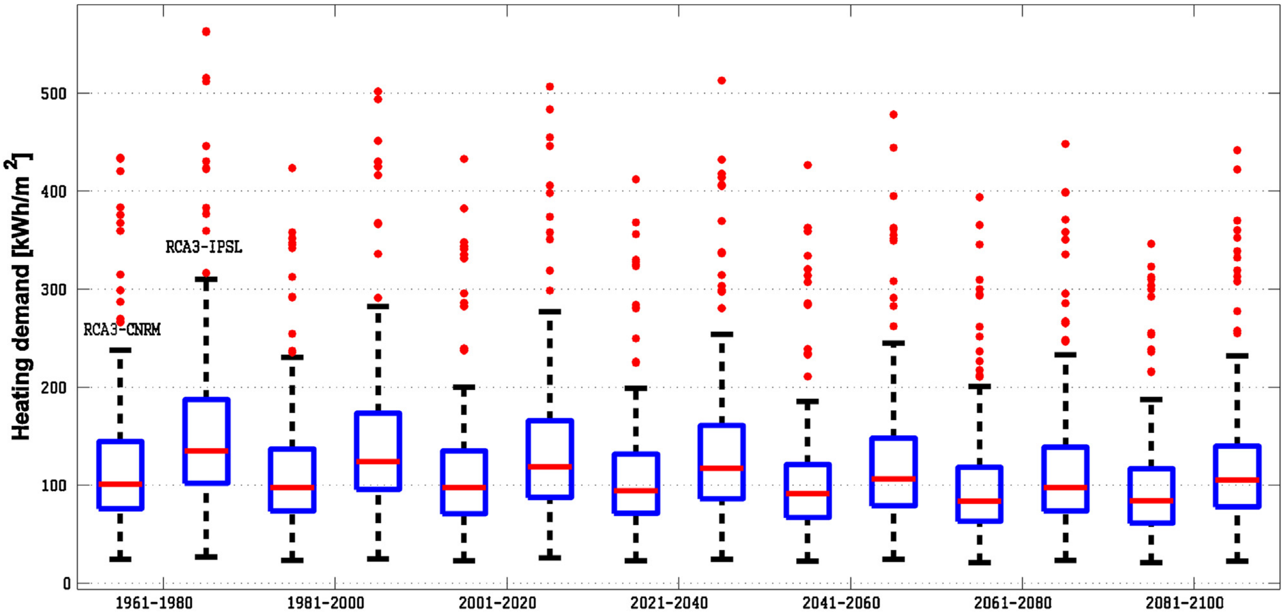

Fig. 3. Distribution of the annual heating demand for the building stock in Stockholm. Results are for two climate scenarios during 1961–2100: RCA3-CNRM and RCA3-IPSL.

Table 3
Periodical mean RDs and standard deviations, both in [%], for P4 retrofitting measure (which includes all measures) and five climate scenarios for the monthly temporal resolution.

Time period	RCA3-ECHAM5		RCA3-CCSM3		RCA3-CNRM		RCA3-HadCM3		RCA3-IPSL		Scenarios mean		Scenarios SD	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	$\overline{mean}$	$\overline{sd}$	S_{mean}	S_{sd}
1961–1980	−35.8	19.2	−35.4	17.0	−35.5	19.9	−35.7	20.6	−35.0	17.5	−35.5	18.8	0.3	1.5
1981–2000	−35.6	18.6	−35.9	18.5	−35.2	19.9	−35.2	19.1	−35.5	19.4	−35.5	19.1	0.3	0.6
2001–2020	−35.6	21.0	−35.8	20.1	−35.2	19.9	−36.8	21.7	−35.0	19.9	−35.7	20.5	0.7	0.8
2021–2040	−36.0	20.1	−36.4	20.6	−36.0	19.3	−36.5	19.6	−35.9	19.3	−36.1	19.8	0.3	0.6
2041–2060	−36.6	20.5	−35.8	20.5	−35.8	19.4	−36.3	18.7	−36.5	19.8	−36.2	19.8	0.4	0.8
2061–2080	−35.4	19.5	−36.2	19.7	−36.4	19.3	−36.8	18.6	−36.5	19.7	−36.3	19.4	0.5	0.4
2081–2100	−37.1	20.1	−37.2	19.3	−35.6	18.9	−37.4	20.2	−35.0	20.0	−36.4	19.7	1.1	0.6
Overall Mean	−36.0	19.9	−36.1	19.4	−35.7	19.5	−36.4	19.8	−35.6	19.4	−36.0	19.6	0.5	0.8
SD	0.6	0.8	0.6	1.3	0.4	0.4	0.7	1.1	0.7	0.9	0.4	0.5	0.3	0.4

exist from one period to another. These variations (0.4, 0.5, 0.3 and 0.4), illustrated in the “SD” row under the four discussed values, are very small and considered negligible for the considered case in Table 3. Such small variations among time periods indicate that it is possible to rely on the comparative results despite of the number and time span of the 20-year periods. Therefore, it is possible to assess the relative performance of the P4 retrofitting measure for future climatic conditions only by looking into its performance during 1961–1980 and we can assume that these conclusions should not differ if any other period(s) is used for the assessment.

Another interesting finding in Table 3 is the small standard deviations among scenarios (i.e. S_{mean} and S_{sd} under the column “Scenarios SD” vary between 0.3% and 1.5%, with the average values of 0.3% and 0.4%) which means that the relative performance of P4 is not significany affected by the selected climate scenario and it is possible to rely on the relative performance of P4 based on only one climate scenario. In other words, its relative performance is robust against climate uncertainties for the monthly temporal resolution. Thus for assessing the relative performance of the retrofitted building it is possible to calculate the relative difference of P4 only for one 20-year period and one climate scenario. Future performance of the retrofitted building, compared to t *n*-rrofitted, will show similar difference for any time period and any climate scenario.

In the following, the possibility of relying only on one 20-year period in assessing the relative performance of retrofitted buildings is evaluated for all the retrofitting measures for the building stock

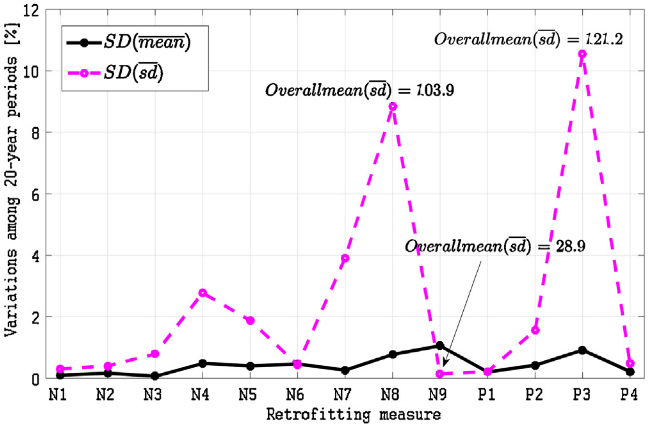

Fig. 4. Standard deviations among seven 20-years periods for the periodical mean value of the relative differences,$SD\left(\overline{mean}\right)$, and their variations, $SD\left(\overline{sd}\right)$, when the relative differences have been calculated for the hourly temporal resolution.

of Stockholm. Standard deviations of the mean values of the different scenarios among the seven 20-year periods,$SD\left(\overline{mean}\right)$ which is equal to 0.4 in Table 3, and their variations, $SD\left(\overline{sd}\right)$ which is equal to 0.5 in Table 3, are shown in Figs. 4–8 for the five temporal resolutions. The variations are generally very small and mostly lower than 2%. However there are some exceptions: $SD\left(\overline{sd}\right)$ shows larger

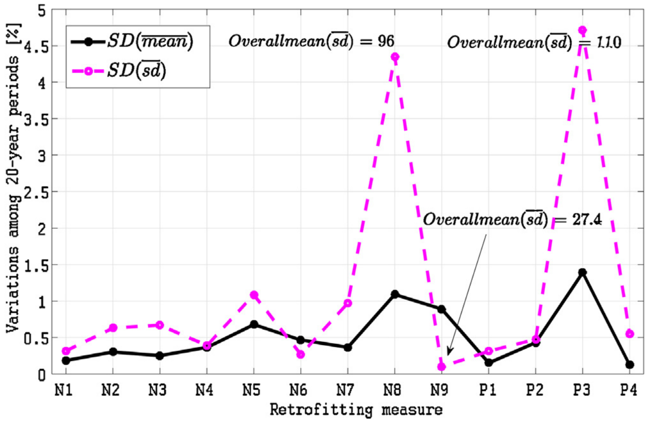

Fig. 5. Standard deviations among seven 20-years periods for the periodical mean value of the relative differences, $SD\left(\overline{mean}\right)$, and their variations, $SD\left(\overline{sd}\right)$, when the relative differences have been calculated for the daily temporal resolution.

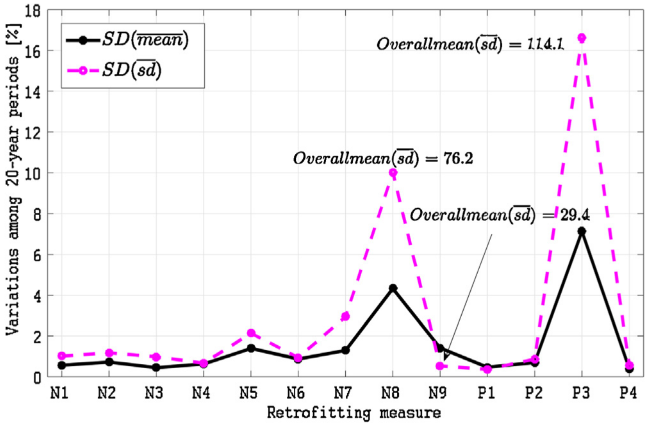

Fig. 6. Standard deviations among seven 20-years periods for the periodical mean value of the relative differences, $SD\left(\overline{mean}\right)$, and their variations, $SD\left(\overline{sd}\right)$, when the relative differences have been calculated for the monthly temporal resolution.

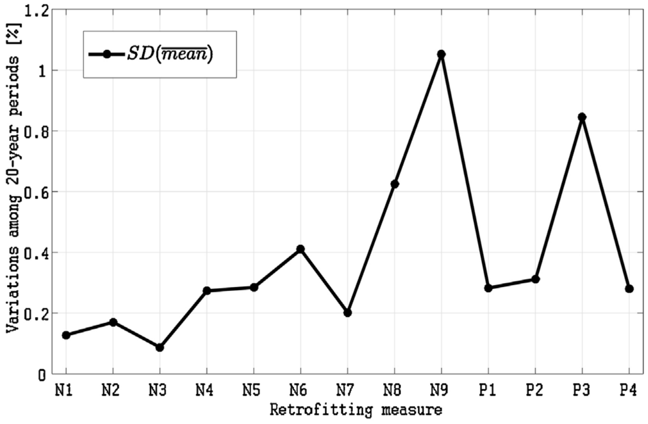

Fig. 7. Standard deviations among seven 20-years periods for the periodical mean value of the relative differences, $SD\left(\overline{mean}\right)$ when the relative differences have been calculated for the annual temporal resolution.

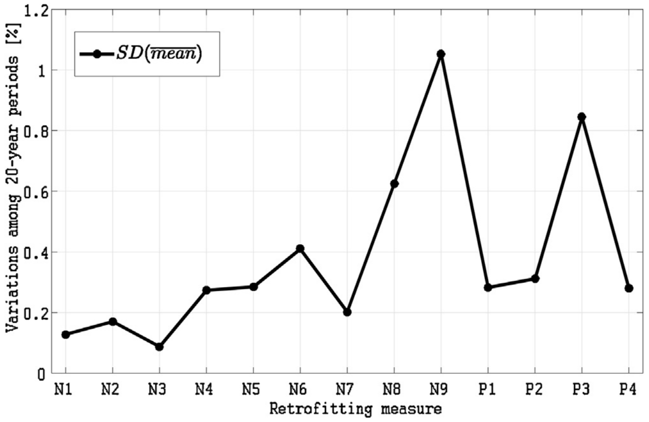

Fig. 8. Standard deviations among seven 20-years periods for the periodical mean value of the relative differences, $SD\left(\overline{mean}\right)$ when the relative differences have been calculated for the 20-year temporal resolution.

values for N8 and P3 during the hourly, daily and monthly temporal resolutions. P3 (installing efficient lighting and appliances) is affected by N8 (installing efficient appliances only) and its standard deviations can be larger since the variations are affected by the operational schedules of new appliances after retrofitting. However comparing with the overall mean of $\overline{sd}$, which are written in the figures, it is possible to neglect these two exceptions. Moreover, it will be shown that these two measures are not efficient for decreasing the space heating demand. In general, the relatively low standard deviations in Figs. 4–8 indicate that one can rely on the comparative assessment of retrofitting measures using only one 20-year period. This conclusion is valid under the assumption that all measures are implemented at the same time, and that there are no other renovations during the observed period. Also, there may be other effects that are not visible here due to the model limitations (i.e. lumped approach).

3.2. Comparison of the retrofitting measures

The energy efficiency and robustness of nine single retrofitting measures as well as four combinations of retrofits are compared in this section for five temporal resolutions, using the four statistical variables (Overall Mean of the Scenarios mean and Scenarios SD in Table 3) which were introduced in the previous section. Whereas for Stockholm results are based on considering all the seven 20-year periods, for Gothenburg and Lund the comparative assessment has been made only for the period 2041–2060, since considering only one period does not affect the assessment results, as it was discussed in the previous section. It must be emphasized that when the effectiveness and robustness of the retrofitting measures are assessed in this work, each building is compared to itself exactly at the same time step before and after retrofitting (for each temporal resolution). Therefore the calculated relative differences reflect the effectiveness of the retrofitting measure on each single building during the considered time period. The corresponding relative difference, calculated according to the described method, is not comparable with the relative difference for the whole building stock. For example if *A* is the relative change in the space heating demand of the whole retrofitted building stock during 20 years compared to the non-retrofitted one (e.g. using two values of the total heating demand [kW h/m^2] in 20 years), and *B* is the relative difference according to the presented method, *A* and *B* should not be equal, nor having any specific correlation.

The relative performance of the retrofitting measures for the hourly temporal resolution is shown in Table 4. Retrofitting packages P1 (improved building envelope: N1–N4) and P4 (all measures: N1–N9) are the most effective in reducing the heating demand in Stockholm ($\overline{mean} = -30.4\%$ for each), while in Gothenburg and Lund they stand after lowering the indoor temperature (N9), having almost half effectiveness of N9. This points to the fact that the building stock in Stockholm has larger improvement potentials just by insulating the building envelopes than the other

Table 4
Comparing efficiency and robustness of nine single energy retrofitting measures (N) and four packages (P), considering future climate and its uncertainties, for the hourly temporal resolution. Values, all in [%], correspond to the overall mean, representing seven 20-year periods.

Measures	$\overline{mean}$			$\overline{sd}$			S_{mean}			S_{sd}		
	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu
N1	−13.9	−12.5	−14.7	20.2	22.2	23.7	0.4	0.2	0.6	1.1	1.3	2.0
N2	−19.4	−10.0	−16.1	23.2	30.1	31.8	0.5	0.2	0.4	1.5	2.0	3.4
N3	−7.0	−8.3	−8.2	24.1	31.7	38.6	0.2	0.1	0.2	2.4	1.3	5.6
N4	−14.7	−17.1	−11.9	35.3	41.9	52.2	0.5	0.6	1.6	5.8	5.2	11.1
N5	−6.0	−8.0	−7.3	32.3	37.8	43.5	0.5	0.7	0.8	3.4	1.7	2.2
N6	−9.1	−11.9	−8.6	17.2	19.1	21.5	0.8	1.0	0.7	1.1	1.0	3.9
N7	5.0	5.6	5.8	61.3	71.4	78.1	0.5	0.6	0.6	10.8	12.5	3.6
N8	13.0	14.4	14.6	103.9	115.2	124.1	1.0	1.5	1.4	17.8	18.1	13.3
N9	−27.6	−30.7	−32.3	28.9	33.3	35.2	1.7	1.7	2.0	1.1	1.8	1.4
P1	−30.4	−17.6	−14.3	18.2	15.1	12.8	0.7	0.4	0.4	0.7	0.7	1.0
P2	−13.4	−16.2	−11.0	33.0	50.3	43.0	0.6	0.3	0.5	5.0	4.4	3.2
P3	16.9	18.6	18.9	121.2	131.6	147.6	1.4	1.9	1.7	20.6	19.9	8.5
P4	−30.4	−17.7	−16.5	23.6	17.4	31.2	0.7	0.4	0.6	1.3	1.2	2.4

cities with lower U-values (see Fig. 1). From the other variables reported in the three last major columns of Table 4 one can assert that P1 has smaller variations in the hourly scale (e.g. $\overline{sd} = 18.2\%$ for Stockholm) than P4 (e.g. $\overline{sd} = 23.6\%$ for Stockholm). This means that uncertainties in estimating the hourly performance are smaller for P1 than for P4. For example, if the heating demand for the retrofitted building is A% lower than the non-retrofitted during one hour (or the considered time step), the difference for the next hour can reach $A \pm 18.2\%$ for P1, while for P4 it can reach $A \pm 23.6\%$. S_{mean} corresponds to the uncertainties in calculating $\overline{mean}$ due to having different climate scenarios: it is negligible for both P1 and P4 (the maximum S_{mean} is 0.7%). S_{sd} represents how climate uncertainties affect the variations of the calculated RDs, as summarized in Table 4. Although P4 show a larger S_{sd} value than P1 in all the three cities, variations due to climate uncertainties are very small. In general, comparison of P1 and P4 indicates that both the measures reduce the average hourly heating demand similarly, while the relative performance of P1 is less affected by the hourly variations of climatic conditions as well as the climate uncertainties.

The other retrofitting measures which reduce the heating demand in Table 4 are N1-6, N9 and P2, which their effectiveness varies depending on the city. The remaining measures do not decrease (N7-8 and P3) but increase the heating demand. Lowering the indoor air temperature to 20 °C than 21.2 °C (N9) reduces the heating demand significantly; more than 30% in Gothenburg and Lund and around 28% in Stockholm. The relative importance of this measure is more visible in Gothenburg and Lund with better U-values of the building stock on average than in Stockholm, as it was discussed above. However, even in Stockholm it is reasonable to assume that the most effective retrofitting package for reducing the heating demand is the combination of P1 and N9. Among the measures for improving the building envelope, N4 (improving windows) induce more energy saving for heating in Gothenburg, where in Lund and Stockholm improving the facade insulation is more effective. N4 shows larger values for $\overline{sd}$ in all the cities (compared to N1-3), with the average of 43% among the cities; therefore N4 has the largest uncertainty in the hourly temporal resolution among the four retrofitting measures for improving the U-value of the building envelopes.

Upgrading the ventilation system (N5 and 6) decreases the heating demand on the hourly scale between 6% to 12%. Not surprisingly, reductions in the power for lighting and appliances (N7, N8 and P3) increase the space heating demand due to less amount of heat that is dissipated from these sources, as discussed in [30]. The uncertainties due to differences between time steps increase for these retrofitting measures (larger values for $\overline{sd}$), reflecting the larger variations among time steps. The variations are due to assumptions made in the modelling, where lighting and appliances are used as constant heat sources. In particular, the added heat gain from lighting that occurs during night, when the heating demand is larger, induces larger standard deviations. In other words the uncertainties due to the time step for N7, N8 and P3, strongly depend on their assumed operating scenarios. Although their variations due to climate uncertainties are larger than the other retrofitting measures, still these values remain very small when assessed as average performances (S_{mean} values lower than 2%). However uncertainties for their variations, S_{sd}, are larger than for the other retrofitting measures and it can be concluded that these measures are less robust.

For the daily temporal resolution in Table 5, the three most effective retrofitting measures for Stockholm are N9, P1 and P4 with quite similar effectiveness and small differences in variations. This is similar to the hourly scale, as well as the monthly scale in Table 6 and the annual and the 20-year scales in Table 7 for Stockholm. However the efficiency orders are not similar for all the temporal resolutions; for the daily and the monthly scales N9, which corresponds to lowering of indoor air temperature to 20 °C, decreases the heating demand on average to levels equal and even less than P1 and P4, although with larger variations and lower robustness. For Gothenburg and Lund, with better insulation of the building envelopes than Stockholm, the most effective measure for the daily time resolution is decreasing the indoor air temperature (similar to the hourly resolution), as well as for the other temporal resolutions. There are changes in the ranking of the retrofitting measures in the daily resolution comparing to the hourly, however these changes are very small and negligible, while efficiencies are increasing and uncertainties decreasing.

For the annual and the 20-year temporal resolutions in Stockholm, N9 is the third most efficient measure after P1 and P4, showing larger variations and consequently lower robustness, while for Gothenburg and Lund, N9 is the second most efficient for the 20-year scale, showing smaller differences with P1 and P2. However it is not the case for Stockholm and the 20-year average performance of N9 is around half efficient of P1 and P4. For the annual and 20-year temporal resolutions only the average performance of the retrofitting measures are considered as well as their variations among the climate scenarios. Between P1 and P4 illustrated in Table 7, the only clear advantage regarding the mitigation of the heating demand is only for Lund which is maximum 3%. The finer temporal resolutions helps to distinguish the differences between P1 and P4, showing that P1 has less variations and is more robust comparing to P4 for all the hourly, daily and monthly temporal resolutions.

As already discussed, the effectiveness of the retrofitting measures depends on the considered temporal resolution and the non-retrofitted status of the building stock. For example for the

Table 5
Comparing efficiency of nine single energy retrofitting measures (N) and four packages of them (P), for daily temporal resolution. Values, all in [%], correspond to the overall mean, representing seven 20-year periods.

Measures	$\overline{mean}$			$\overline{sd}$			S_{mean}			S_{sd}		
	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu
N1	−15.6	−14.1	−17.2	18.1	18.9	20.2	0.5	0.5	0.9	1.1	1.5	2.5
N2	−21.3	−10.9	−17.9	20.7	26.5	25.5	0.5	0.4	0.6	1.4	2.4	2.9
N3	−7.3	−8.5	−8.6	22.4	28.1	35.1	0.3	0.4	0.8	2.6	2.6	5.2
N4	−17.1	−19.7	−14.0	20.6	25.1	31.2	0.5	0.6	1.0	1.7	2.9	3.0
N5	−7.5	−10.3	−9.3	27.9	29.4	35.1	0.7	1.3	1.8	2.5	3.7	5.9
N6	−12.1	−15.4	−11.4	18.5	20.7	18.4	1.1	1.4	1.2	1.1	1.4	1.3
N7	9.9	12.0	12.8	48.6	64.0	65.1	1.2	1.7	2.2	6.8	8.3	14.4
N8	25.0	28.4	29.6	96.0	111.5	115.7	2.7	3.3	4.3	12.4	13.5	18.2
N9	−32.7	−36.3	−37.9	27.4	27.8	28.2	2.0	2.0	2.5	0.7	0.9	1.2
P1	−32.6	−19.3	−15.5	16.5	13.5	10.4	0.9	0.4	0.6	0.6	1.0	0.7
P2	−16.0	−18.2	−13.4	21.0	31.0	29.1	0.6	0.8	0.6	1.6	3.0	3.4
P3	32.1	36.5	37.8	116.1	130.7	142.0	3.4	4.3	5.2	14.8	18.3	22.6
P4	−32.6	−19.5	−18.2	23.0	15.9	29.9	0.8	0.4	0.5	1.5	1.9	4.1

Table 6
Comparing efficiency and robustness of nine single energy retrofitting measures (N) and four packages of them (P), for monthly temporal resolution. Values, all in [%], correspond to the overall mean, representing seven 20-year periods.

Measures	$\overline{mean}$			$\overline{sd}$			S_{mean}			S_{sd}		
	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu
N1	−17.8	−16.4	−19.7	13.2	12.2	14.8	0.6	1.1	0.7	1.5	2.0	0.6
N2	−23.5	−13.9	−21.1	14.8	12.1	15.8	0.9	1.1	1.8	1.7	2.3	2.6
N3	−9.2	−11.2	−12.7	9.5	12.1	15.5	0.6	0.6	1.4	1.2	3.0	2.7
N4	−20.2	−23.5	−18.5	13.9	15.7	14.8	0.7	1.1	1.6	1.3	2.5	2.7
N5	−10.3	−13.7	−14.2	14.9	16.0	20.2	1.4	2.4	2.1	2.5	3.6	1.2
N6	−15.6	−20.8	−15.2	18.5	22.7	17.3	0.9	1.8	1.6	1.2	2.8	2.4
N7	12.4	13.7	16.5	22.2	24.1	30.0	1.6	2.8	4.1	3.2	7.2	5.3
N8	43.0	46.4	49.2	76.2	78.3	76.2	5.9	9.9	7.7	12.9	26.5	12.7
N9	−38.3	−42.4	−44.2	29.4	28.9	29.2	1.3	1.7	1.6	0.9	1.8	1.2
P1	−35.4	−21.4	−17.3	15.9	11.0	8.6	0.5	0.5	0.3	0.5	1.0	0.7
P2	−19.4	−20.7	−17.6	15.0	19.6	18.1	0.7	1.4	1.0	1.0	2.6	1.4
P3	63.0	66.2	70.4	114.1	116.7	106.6	9.8	16.7	16.9	22.1	41.8	18.6
P4	−36.0	−21.9	−22.5	19.6	12.1	19.1	0.5	0.6	0.4	0.7	1.2	1.6

Table 7
Comparing efficiency of the single energy retrofitting measures (N) and four packages (P) for the annual and 20-year temporal resolutions. Values, all in [%], correspond to the overall mean, representing seven 20-year periods.

Measures	Annual						20-year					
	$\overline{mean}$			S_{mean}			$\overline{mean}$			S_{mean}		
	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu	Stk	Gbg	Lu
N1	−11.3	−10.2	−12.0	0.3	0.2	0.4	−4.8	−3.4	−4.3	0.2	0.1	0.1
N2	−16.1	−8.4	−13.7	0.4	0.2	0.4	−7.9	−4.8	−5.9	0.3	0.2	0.3
N3	−5.8	−7.1	−7.3	0.2	0.2	0.2	−5.7	−3.3	−5.9	0.2	0.2	0.3
N4	−14.3	−16.7	−13.0	0.4	0.4	0.3	−11.0	−11.3	−4.8	0.3	0.3	0.1
N5	−4.0	−5.8	−5.8	0.4	0.6	0.7	−8.4	−8.8	−1.3	0.2	0.3	0.1
N6	−5.8	−8.0	−5.7	0.6	0.8	0.6	−6.7	−8.5	−3.6	0.4	0.5	0.4
N7	2.8	3.2	3.4	0.3	0.3	0.3	3.1	4.1	3.7	0.3	0.4	0.4
N8	8.4	9.8	10.1	0.9	1.0	1.1	9.4	12.6	11.2	1.0	1.3	1.2
N9	−20.2	−23.9	−25.5	1.5	1.6	1.8	−18.4	−21.4	−23.4	1.7	1.9	2.1
P1	−26.2	−15.0	−12.3	0.6	0.4	0.3	−35.7	−25.6	−22.9	1.1	0.7	0.9
P2	−12.6	−15.6	−10.2	0.4	0.5	0.5	−14.6	−17.2	−9.1	0.4	0.9	0.5
P3	11.3	13.2	13.6	1.2	1.3	1.5	12.6	17.0	15.1	1.3	1.7	1.6
P4	−26.3	−15.1	−14.1	0.6	0.4	0.5	−35.8	−25.6	−25.8	1.1	0.7	1.2

first four single retrofitting measures (N1–N4), during the first four temporal resolutions (from hourly to annual), the order of effectiveness in decreasing the heating demand is N2, N4, N1 and N3 (the only exception is the annual scale for Lund which N4 is around 1% more efficient than N1). Among the retrofitting measures for better insulation of the building envelope (N1-4), insulating attics/roofs (N3) shows the lowest efficiency in all the cities. N2 is the most effective one and the largest difference with N3 in Stockholm is equal to 14.3% in the monthly scale. This order changes in the 20-year temporal resolution; for example in Stockholm it is N4, N2, N3 and N1 with a maximal difference of 6.2%. In other words, on the long term differences between the effectiveness of these retrofitting measures decrease, however on the short term larger differences are expected, which affects the design strategies and comfort conditions.

4. Conclusions

Thirteen retrofitting strategies for the residential building stocks of cities of Stockholm, Gothenburg and Lund in Sweden were investigated under five different scenarios for future climatic conditions until year 2100. This work only looked into the uncertainties induced by future climate data sets and did not consider uncertainties induced by retrofitting buildings (e.g. building materials, workmanship and etc.) as well as changes in human behaviour, material properties or the building operation by time. The method which was used in the framework of this study helps to assess the effectiveness and robustness of the retrofitting measures for different temporal resolutions. The effectiveness shows how much a retrofitting measure decreases the space heating demand in a building over a time period, while the robustness shows how much this result is influenced by climate uncertainties.

According to the performed analysis for three cities, five climate scenarios and thirteen retrofitting measures, it is possible to rely on single 20-year period (e.g. 2081–2100 instead of seven 20-year periods for the time frame 1960–2100) to assess the relative performance of different retrofitting measures on different temporal scales. This feature decreases the calculation efforts significantly with respect to the amount of series of climate data and simulations, the requested computation load, as well as time required for post-processing and analysis of the simulation results.

Climate uncertainties induced by different climate scenarios are larger than those induced by the temporal variations among 20-year periods. In many cases, when the relative performance of the retrofitted buildings is studied, it is possible to neglect the uncertainties induced by climate data. This is applicable to many of the basic retrofitting measures, such as improving the thermal insulation of the buildings envelope, for which one can rely on the relative performance of the retrofitted building for a reference climate scenario (e.g. past climate data) during a reference period (e.g. 1981–2000). By being able to neglect climate uncertainties and rely on the relative differences, it is possible to estimate the future performance of the retrofitted building indirectly, by assessing the future performance of the non-retrofitted or the reference building. It is important to remember that the climate uncertainties still play a big role in assessing the future performance of buildings, but not when the relative performance of the retrofitted buildings is compared to the non-retrofitted one.

Results show that the relative performance of the retrofitting measures with respect to their effectiveness and robustness against climate change depends on the non-retrofitted status of buildings and the considered temporal resolution. One retrofitting measure may decrease the heating demand for an hourly scale more than another measure, while for the monthly scale it is on the way around. For such cases, selecting the proper retrofitting measure depends on the temporal resolution which is the most significant for design and also on the size of the variations; the small differences in the average values can be compensated by larger difference in standard deviations. However, when comparing the retrofitting measures to each other, the most efficient and robust retrofitting measures usually showed the same favourable impact at all temporal resolutions. When the effects of some of the measures are very similar on average conditions, their variations during different temporal resolutions help to distinguish the most robust measure among them. For example if two retrofitting measures are showing similar effects for the monthly time scale (assuming no price, availability or etc. preferences), depending on the design criteria of the building (e.g. the maximum user comfort) a retrofitting measure with a more robust performance on the daily/hourly temporal resolution can be selected. However it is important to remember that selecting a suitable retrofitting measure is usually a multi-criteria decision making procedure, affected by several factors related to economy, availability and etc., which have not been considered in this work.

Regarding the reduction of the energy demand for space heating, the study showed that the improvement of the thermal insulation of the building envelope as well as windows' replacement (N1–N4, which are combined as package P1) are the most effective retrofitting measures for Stockholm which the U-value of the building stock is higher than the other cities. These measures are furthermore very robust regarding their relative performance during different temporal resolutions. According to the results, tuning the indoor set-point temperature to 20 °C leads to significant reductions in the space heating demand, especially in Gothenburg and Lund where buildings have better insulated envelopes, however this retrofitting measure is less robust in finer – hourly and daily – time resolutions compared to the other retrofitting measures.

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