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Assessing the efficiency and robustness of the retrofitted building envelope against climate change

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Abstract

Evaluating the performance of retrofitted buildings for future climatic conditions can be a challenging task since different scenarios and uncertainties exist both for retrofitting of buildings and for future climate. This paper evaluates the energy performance of four retrofitting measures – applied to the building envelope – of the residential building stock in Gothenburg, Sweden. The energy efficiency of the measures is evaluated both on long and short terms, while their robustness against climate uncertainties and extreme climatic conditions is studied. The assessment is carried out using a statistical method, which has been developed specifically for this kind of analysis. The considered measures are ranked by looking into their average performance and their variations during different time scales, i.e. from one hour to 20 years. The analysis helps to identify the retrofitting measures with the most efficient and the most reliable performance for future climatic conditions.

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1. Introduction

Many European countries promote retrofitting buildings to decrease energy demand and CO_2 emissions, facing climate change, meanwhile motivating the economy and job/building market [1]. Retrofitting buildings is usually a

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costly investment with long term expectations, therefore it is important to consider the adaptability of the retrofitted buildings to future climate. Retrofitted buildings should provide the desired energy performance and indoor comfort, not only for current climatic conditions, but also for future climate with its long and short term changes. The 5th assessment report of the Intergovernmental Panel on Climate Change confirms climate changes which induce increase in temperature, climate variability and extreme events [2]. These changes affect the building performance on long and short terms; e.g. there will be less heating demand in the heating dominated regions of Europe, while there will be stronger and more frequent cold winter days or hot summer days. Not preparing for the future changes increases risks, costs and the severity of damages, which can jeopardize the living conditions and the economy.

With the help of dynamic climate models it is possible to assess the future performance of buildings, using different weather data sets. Similar to any other numerical model, climate models are affected by uncertainties, which cannot be neglected in many cases. Moreover, there are several available models and none of them is exact. Therefore to have a reasonable impact assessment of climate change, several climate models and uncertainties should be considered [3]. Having several climate data sets, which can cover e.g. 140 years with the hourly time scale, as well as the existence of many buildings and retrofitting options to assess, increase the calculation load enormously. This makes the assessment, and consequently the decision making procedure, difficult.

In this paper four energy retrofitting measures of the building envelope are studied during 1961-2100, using five climate scenarios. The study is focused on the effects of the measures on decreasing the heating demand of the building stock. The effectiveness and robustness of the measures are assessed during five time scales of hourly, daily, monthly, annual and 20 years, considering climate variations in different time scales. The effectiveness is defined as the energy efficiency of the retrofitted building compared to the non-retrofitted, while the robustness is the stability of the relative performance of the retrofitted building (compared to the non-retrofitted) against uncertainties of climate and its evolution by time. A statistical method which has been developed specifically for the assessment of various retrofitting options for buildings considering climate uncertainties, is used in this work [4].

In this work, climate data from RCA3, the Rossby Centre regional climate model (RCM), downscaling five global climate models (GCMs) to 50km horizontal resolution for the city of Gothenburg in Sweden, are used: 1) ECHAM5, 2) CCSM3, 3) CNRM, 4) HadCM3 and 5) IPSL (for details see [3] and [5]). On a global scale, GCMs are used to simulate the climatic conditions [6]. GCMs have a rather coarse spatial resolution (often 100-300 km), which is not suitable for building simulations. Regional climate models (RCMs) are used to downscale results from the GCMs dynamically, achieving a higher spatial resolution over a specific region [5]. Using the numerically simulated climate data in the building simulations introduces different uncertainties. It has been shown that the most important uncertainty factor of future climate data are those induced by the changes in the large-scale circulation determined by the GCM [3, 7].

2. Energy model of the building stock and retrofitting measures

The residential building stock of Gothenburg is represented by 184 buildings, which have been chosen statistically in an extensive field investigation (BETSI programme [8]), conducted by the Swedish National Board of Housing, Building and Planning (Boverket) in year 2005. The energy performance of the building stock is modelled as a dynamic lumped system in Simulink toolbox of Matlab, where each building is represented as one zone, and incorporates hourly-based calculations of energy balance in the zone [9]. The thermal inertia of a building is described by its effective internal heat capacity according to ISO 13790 [10]. Accuracy of the energy model has been verified by Mata et al. [11], by inter-model comparisons and empirical methods. The Simulink model has been previously used for impact assessment of climate change on the existent building stock of Stockholm [7]. For each climate scenario the energy simulations were performed in the periods of 20 years; 1961-1980, 1981-2000 … 2081-2100. During every 20-year period, each building was simulated only for one year, for retrofitted and non-retrofitted buildings in hourly scale. More information about simulating the long term performance of the building stock is available in some earlier works [3, 7]. The average annual heating demand of the building stock during seven 20-year periods for the reference building stock are roughly 140, 135, 130, 126, 120, 114 and 105 [kWh/m^2], from 1961-1980 to 2081-2100 respectively.

Four energy retrofitting measures are considered in this paper (Table 1), namely: improved U-value of cellar/basement, facades, attics/roofs and replacement of windows (respectively referred as energy saving measures (ESMs) 1 to 4 in [12]). User behaviour and post-installation changes are not considered.

Table 1. Energy retrofitting measures and the percentage of changes

Retrofitting measure	Description	Average of the new U-value for the building envelopes [W/m²K]	Average of the new window transmittance [-]	Percentage of change [%]	
				U-value	Window transmittance
N1	Change in U-value of cellar/basement	0.51	0.7	-11.2	0
N2	Change in U-value of facades	0.47	0.7	-9.5	0
N3	Change in U-value of attics/roofs	0.46	0.7	-8.0	0
N4	Replacement of windows	0.39	0.57	-21.3	-18.6

3. Method for assessing the long term performance of the retrofitting measures

The statistical method used in this work is based on calculating the differences of the retrofitted building from the non-retrofitted, using averages and standard deviations during five time scales: hourly, daily, monthly, annual and 20-year periods. Relative differences (RDs, in percentage) during each time scale are calculated according to relation (1):

$$RD=100\times\frac{\left(\text{Heating demand}_{\text{retrofitted, i}}\text{-Heating demand}_{\text{reference, i}}\right)}{\text{Heating demand}_{\text{reference, i}}} \quad (1)$$

Where $retrofitted$ and $reference$ respectively represent the retrofitted and the non-retrofitted buildings and i is the building number (i = 1 to 184). RDs are calculated during the 20-year periods, for each climate scenario, each retrofitting measure and each time scale. Depending on the considered time scale, the heating demand [kWh/m^2] is accounted for hourly, daily, monthly, annual or 20-year time steps. The calculated RDs and their variations are used to study the performance of the retrofitted buildings; 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 between the retrofitted and non-retrofitted building are quantified by two numbers. The robustness of the retrofitting measures is assessed by quantifying variations of RDs among different time scales and different climate scenarios.

$$\overline{RD} = \frac{1}{n}\sum_{i=1}^{n} RD_i \quad (2)$$

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

The general performance of each retrofitting measure is summarized by four numbers for the first three time scales, showing average changes and their variations during the considered time scale, while for the annual and 20-years period it is represented by two numbers. In this way, the method enables knowing about the relative performance of the retrofitting measures with few numbers, while several uncertainties during five time scales have been considered. For more details about the statistical method, the reader is referred to an earlier work of the authors [4].

4. Assessment results

Results for one retrofitting measure and one time scale (monthly) are presented in detail in Table 2, which provides a better view of the assessment method. For each time scale and retrofitting measure, a similar table can be generated. Averages and standard deviations of RDs for the five climate scenarios have been calculated during seven 20-year periods. The “Overall Mean” row shows the overall mean of the calculated values over all the 20-year periods. The mean value of averages and standard deviations among five climate scenarios, are shown under “Scenarios mean” and “Scenarios SD” columns. The intersection of the mentioned columns and the “overall Mean” row, gives four values (**bold** numbers in Table 2) which are used further to compare the retrofitting measures. The first value among those four, **-15.99%**, tells how much the average monthly heating demand is changed comparing to the non-retrofitted building. The second value, **11.77**%, represents the monthly standard deviations. The other two numbers give an overall view about the uncertainties due to several climate scenarios during seven time periods. For example variations of $Overall\ mean$ ($\overline{mean}$) among time periods and climate scenarios is **1.03%**, while for the monthly variations it is around **2.05%**. Small standard deviations among scenarios, e.g. S_{mean} and S_{sd} under 'Scenarios SD' are smaller than 3% for all cases, means that is it possible to rely on the relative performance of the retrofitting measure out of only one climate scenario. Moreover, a small standard deviation in the last row, SD, means that the relative performance of the retrofitted building does not get affected considerably during time. In simple words, if the retrofitting measure decreases the heating demand for 15% during 2000-2020, most likely it will have the same effect during 2080-2100. Therefor it is possible to rely on one 20-year period for assessing the effectiveness and robustness of the retrofitting measure.

Table 2. Periodical mean RDs and standard deviations, both in [%], for N1 retrofitting measure and five climate scenarios for the monthly time scale.

	RCA3-ECHAM5		RCA3-CCSM3		RCA3-CNRM		RCA3-HadCM3		RCA3-IPSL		Scenarios mean		Scenarios SD	
Time period	mean	Sd	mean	sd	mean	sd	mean	sd	mean	sd	$\overline{mean}$	$\overline{sd}$	S_{mean}	S_{sd}
1961-1980	-16.05	11.19	-13.70	7.11	-16.11	12.78	-16.01	12.00	-15.18	10.88	-15.41	10.79	1.03	2.19
1981-2000	-16.10	11.10	-13.57	6.63	-16.50	13.00	-16.46	12.55	-15.16	10.83	-15.56	10.82	1.24	2.52
2001-2020	-16.29	12.15	-14.12	7.63	-16.37	13.22	-15.95	11.45	-14.93	9.50	-15.53	10.79	0.98	2.23
2021-2040	-16.11	11.21	-15.25	9.63	-16.00	12.01	-17.27	14.29	-15.26	11.73	-15.98	11.77	0.83	1.68
2041-2060	-17.10	13.45	-15.05	9.59	-16.07	11.75	-17.89	14.70	-15.91	11.47	-16.40	12.19	1.11	1.96
2061-2080	-16.64	12.76	-15.03	10.09	-16.32	13.02	-17.43	14.66	-15.43	10.65	-16.17	12.24	0.96	1.86
2081-2100	-18.12	15.01	-15.90	11.11	-16.37	15.51	-17.95	14.92	-15.92	12.48	-16.85	13.81	1.10	1.91
Overall Mean	-16.63	12.41	-14.66	8.83	-16.25	13.04	-17.00	13.51	-15.40	11.08	-15.99	11.77	1.03	2.05
SD	0.76	1.45	0.87	1.70	0.19	1.22	0.85	1.46	0.38	0.94	0.53	1.11	0.13	0.28

Using the four discussed values, the relative performance of the retrofitting measures are compared for the hourly, daily and monthly time scales in Table 3 and for annual and 20-years in Table 4. According to these two tables, the relative performance of the retrofitting measure depends on the considered time scale. For example for the hourly time scale, N1 decreases the heating demand on average for 12.39%, while for the 20-years scale the decrement is 3.39%. Variations of the relative differences due to the considered time scale confirms the necessity of using different time scales in assessing the relative performance of the retrofitting measures. Generally N1 retrofitting measure decreases the heating demand more than all the other measures on average ($\overline{mean}$ in the tables), except the 20-years scale which N2 marginally performs better. The other variables in the table help to distinguish the retrofitting measures better; for example N1 has smaller variations in the hourly and daily scales ($\overline{sd}$ in Table 3) than N2. For the hourly scale, if for one hour the heating demand is *A*% less than the non-retrofitted building, for the next hour (or the considered time step) this difference can be *A*±22.12% for N1, while for P4 is *A*±29.47%. This means that uncertainties in estimating relative performance of N1 during hourly and daily time scales are smaller than N2, therefore it is more likely that N1 shows the expected performance in future during the considered time scales than N2. In other words, concerning the relative performance of the retrofitting measures, the reliability of N1 is higher than N2.

S_{mean} in Tables 3 and 4 tells about uncertainties in calculating $\overline{mean}$ due to having different climate scenarios. These uncertainties also affect the variations of the calculated RDs, which are assessed by checking S_{sd} in Table 3. For example in Table 3, the average RDs of N1 are a bit more affected by climate uncertainties than N2 (N1 has larger S_{mean} than N2), while for their variation N2 is more sensitive (N2 has larger S_{sd} than N1). The maximum uncertainty in the relative performance of the retrofitting measures due to different climate scenarios occurs for N4 (replacing windows), where S_{sd} is 5.17% for the hourly scale. Still for all the cases both $\overline{mean}$ and S_{sd} are small enough to neglect the uncertainties due to climate scenarios in assessing the relative performance of the measures. This means that it is enough to rely on the relative performance of the retrofitting measures for one (or any) climate scenario. For investigating the future performance of the retrofitted building for several climate scenarios, it is enough to apply the relative difference to the performance of the reference (non-retrofitted) building, which has been simulated for several climate scenarios.

According to Tables 3 and 4, N4 decreases the average heating demand more than the other measures for all the time scales (check $\overline{mean}$ in tables), although variations of N4 during the hourly scale are large ($\overline{sd} = 43.06$). This can occur because of changes in the solar gains for N4, which on the hourly scale induces larger differences between the sunny and the dark hours and consequently larger relative variations. Better insulation of cellar (N1) is the second best measure for decreasing the heating demand, with the exception of the 20-year scale in Table 4, which N2 is more efficient. For the hourly and daily time scales $\overline{sd}$ for N1 is smaller than all the other measures, which makes its relative performance more robust. In general, to select between N1 and N2, N1 is more preferable since it decreases the heating demand for most of the time scales and moreover its relative performance has less variations and is less sensitive to uncertainties. Improving the roof/attic insulation, N3, will also decrease the heating demand, however less than the other measures, while its variations is almost in the same range of N2. In general, concerning decreasing of the heating demand, the considered retrofitting measures can be ranked, according to their relative effectiveness and robustness, in this way: 1) N4, 2) N1, 3) N2 and 4) N3.

Table 3. Comparison of the efficiency and robustness of four single energy retrofitting measures, considering future climate and its uncertainties, for hourly, daily and monthly time scales. Values, all in [%], correspond to the overall mean, representing seven 20-year periods.

	Hourly				Daily				Monthly			
Retrofitting measure	$\overline{mean}$	$\overline{sd}$	S_{mean}	S_{sd}	$\overline{mean}$	$\overline{sd}$	S_{mean}	S_{sd}	$\overline{mean}$	$\overline{sd}$	S_{mean}	S_{sd}
N1	-12.39	22.12	0.36	1.36	-14.13	19.02	0.50	1.51	-15.99	11.77	1.03	2.05
N2	-10.02	29.47	0.28	2.71	-10.98	26.04	0.39	3.11	-13.57	11.76	0.86	2.17
N3	-8.27	32.11	0.15	2.79	-8.46	29.81	0.35	3.20	-10.87	10.73	0.72	2.55
N4	-16.80	43.06	0.72	5.17	-19.62	24.99	0.66	2.56	-23.19	14.99	1.13	2.33

Table 4. Comparison of the efficiency and robustness of four single energy retrofitting measures, considering future climate and its uncertainties, for annual and 20-years time scales. Values, all in [%], correspond to the overall mean, representing seven 20-year periods.

	Annual		20-year	
Retrofitting measure	$\overline{mean}$	S_{mean}	$\overline{mean}$	S_{mean}
N1	-10.16	0.25	-3.39	0.14
N2	-8.38	0.25	-4.70	0.19
N3	-7.09	0.19	-3.27	0.15
N4	-16.59	0.41	-11.21	0.32

5. Conclusions

With the help of the applied statistical method, it is possible to assess the efficiency and the robustness of four measures to retrofit the building envelope in different time scales with few numbers. According to the results for the residential buildings of the Swedish city of Gothenburg, the uncertainties induced by different climate scenarios and different time periods (20-year periods) do not affect the relative performance of the considered retrofitting measures. Therefore it is possible to rely on one 20-year period and one climate scenario for assessing the relative performance of the retrofitting measures, which decreases the calculation load enormously. It is important to remember that not seeing the effects of climate uncertainties and time periods in the relative differences, does not mean they are not important. They still affect the absolute performance of the retrofitted building, which can be fairly estimated by applying the calculated relative difference to the simulated performance of the reference (or non-retrofitted) building for the desired climate scenario and time period.

As it was shown for all the four retrofitting measures investigated, the quantified relative performance of the retrofitting measures, their effectiveness and their robustness, depend on the considered time scale. It can be interpreted that the selection of the retrofitting measure can depend on the desired functionality of the building during the desired time scale. For example one retrofitting measure may decrease the heating demand in the hourly scale more than another measure, while during the monthly scale works on the way around.

Based on the effectiveness and the robustness of the relative performance of the considered retrofitting measures in different time scales, for the building stock in Gothenburg, improving the thermal properties of windows will decrease the energy need for space heating more than the other measures. After that, improving the insulation properties of cellar is more effective, while decreasing the U values of the facades and attics/roofs are coming next.

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