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Carbon efficiency of passive cooling measures in future climate scenarios: Renovating multi-family residential buildings in a Swedish context☆

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A B S T R A C T

Reducing greenhouse gas emissions while adapting cities to the consequences of climate change is one of the major challenges in the current energy transition towards a nearly carbon-free built environment. A pressing concern regards the rising of global and urban temperatures, which are expected to increase demand for building cooling and hinder the achievement of decarbonisation goals also in continental climate zones. However, available studies and assessment methods still largely overlook the environmental impacts of cooling measures in future climate conditions. This study investigates the efficiency of implementing passive cooling measures (insulation, triple glazing, solar shading, solar reflectivity of façade and natural ventilation) during the renovation of a Swedish multi-family residential building. Novel indicators and an integrated assessment method are developed by combining a climate and energy model with a carbon footprint assessment to evaluate the carbon efficiency of the measures. The results comparison between a baseline case and applied passive measures for Representative Concentration Pathways RCP4.5 and RCP8.5 in 2018, 2030 and 2050 indicates that natural ventilation, triple glazing and solar shading ensure cooling demand reduction between 13% and 56% and have the lowest carbon footprint among the assessed passive strategies. Implementing a combination of all assessed measures has the largest cooling demand reduction potential but poses a trade-off in terms of carbon footprint.

1. Introduction

Global warming challenges the thermal performance of our built environment by contributing to both the overall increase of average temperature and more frequent occurrences of extreme weather such as heat wavesIPCC [28]. According to the International Energy Agency [26], one-fifth of the energy used in buildings globally is due to cooling using fans and air conditioners. Studies have demonstrated that air conditioners are often bought during periods of excessive heat, such as heat waves, but continue to be used to keep lower, comfortable temperatures throughout the whole cooling period [48], resulting in higher electricity consumption and CO_2 emissions.

A warmer climate has the potential to substantially influence thermal comfort conditions in buildings, and increase cooling energy demand [42,49] . The number of homes with air conditioning in the European Union (EU) is expected to triple by 2050, increasing the dependency on affordable energy to ensure thermal comfort. However, the EU's energy and climate goals identify improving energy efficiency as a core approach towards full decarbonisation of the building stock until 2050, with reduced average primary energy use in the residential building stock as one of the main strategies [19]. Adapting the building stock to increasing temperatures caused by global warming therefore poses a major challenge to the ongoing energy transition.

The sustainable development goals (SDGs) [47] clearly address the need of adapting urban environments and buildings to new climate conditions. This includes making urban areas resilient, sustainable and inclusive (SDG 11), improving energy efficiency and ensuring access to affordable energy (SDG 7), as well as implementing climate change adaptation measures (SDG 13). Adaptation measures within the building context are intended to counteract the negative effects of global warming, e.g., by enhancing the thermal performance of the building to withstand future climate conditions. Adaptation measures can be classified into active or passive measures; active measures efficiently make use of building services, such as the utilization of an Heating, Ventilation, Air Conditioning (HVAC) system to supply cool air, whilst passive measures do not require active energy use, as in the cases of natural

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Table 1
Previous research on the impact of climate change for the energy use and thermal performance in buildings in Sweden. RCP = Representative Concentration Pathway, where RCP2.6 represents a low greenhouse gas concentration and substantial greenhouse gas mitigation, RCP8.5 is a high greenhouse gas concentration scenario considering business as usual, and RCP4.5 is a mid-scenario, considering partial greenhouse gas mitigation.

Authors, Year, Location	Climate data/climate change scenarios	Type	Results
[36], Stockholm	Projected data from regional climate models RCA3-ECHAM5-A1B-3, RCA3-CCSM3, RCA3-CNRM, RCA3-HadCM3, RCA3-IPSL	Representative building stock model, 153 sample buildings	+10–160 % (≈ 0.5–2 kWh/m2) of **annual cooling** demand on average by 2100, depending on climate model, for the building stock
[15], Växjö	Projected average seasonal air temperature changes for RCP4.5 applied to the reference (historical) weather data	Multi-family residential, 1 building (16 apartments), passive house standard or conventional insulation levels applied	+33–49 % (≈ 1–1.2 kWh/m2) **annual cooling** demand in 2100 depending on scenario and building type
[14], Växjö	RCP4.5 and RCP8.5, adjusted historical weather datafile based on the regional climate model RCA4-HadGEM2	Multi-family residential, 3 buildings; concrete prefab structure built 2014, massive timber-frame built 2009 and light timber frame built 1995.	+45–73 % (≈ 1.6–2.2 kWh/m2) **annual cooling** demand in 2050, +14–118 % **peak cooling** demand in 2090, depending on building type and climate scenario. 16–22 % total **overheating hours** by 2050 RCP8.5 depending on building type.
[45], Växjö	RCP4.5, adjusted historical weather datafile based on the regional climate model RCA4-HadGEM2	Multi-family residential, 1 building (24 apartments), as-built, passive house standard or conventional envelope insulation levels applied	+12–40 % (≈ 1.8–2 kWh/m2) of **annual cooling** demand by 2050 for RCP4.5, depending on building type.
[46], Växjö	RCP2.6, RCP4.5, RCP8.5 adjusted historical weather datafile based on the regional climate model RCA4-HadGEM2	Multi-family residential, 1 building (27 apartments), concrete structure with brick and wooden panels on façade, built 1970	25–36 % total **overheating hours** in 2090–2099 depending on climate scenario.
[25], Karlshamn	Projected data using regional climate models RCA4-CNRM-CN5, RCA4-ICHEC-EC-EARTH, RCA4-IPSL-CM5A-MR, RCA4-MOHC-HadGEM2-ES, and RCA4-MPI-ESM-LR as well as adjusting for the local micro-climate through simulation	Multi-family residential, 2 buildings, built in 1930, renovated repeatedly	+450–510 % **annual cooling** load by 2100, +210–290 % **peak cooling** demand in 2070, depending on scenario

ventilation, improved insulation, solar shading, change of thermal mass and change of windows and doors [35,2].

As the building sector strives towards increased energy efficiency, limited increase in cooling energy demand in the building stock and avoiding installation of cooling systems as well as excessive use of air conditioning as forms of adaptation to a warmer climate would be beneficial. This emphasises the need for passive solutions when considering global warming adaptation measures for existing buildings. According to EU guidelines [20], passive cooling adaptation measures should be prioritised over the implementation of active cooling systems, and low-carbon intense solutions should be selected where possible. The benefits of passive cooling are two-fold; firstly, it has the potential to provide increased thermal comfort for building occupants when active cooling solutions are unavailable or unaffordable; and secondly, it has the potential to decrease the strain on the electricity supply system of the region during warm periods [27] and thereby supporting the energy transition in the building sector. As the EU has forecasted that 80 % of the existing homes will be renovated by 2050 [18], there is a large opportunity to implement passive design strategies in the existing building stock within the next few decades.

1.1. Cooling loads and temperature rising in Sweden

Extensive research has been conducted to determine the impact of global warming on the building stock energy use. The average global trend shows a decrease in heating energy demand and an increase in cooling energy demand [2]). This trend has also been observed in European northern countries. Research studies modelling the cooling needs for different climate change scenarios in Sweden consistently show a decrease in annual space heating demand and an increase in space cooling demand [36,46,25]. However, the magnitude of the variation changes considerably with the building type and method of study.

Traditionally, Swedish residential buildings are not equipped with active cooling systems due to low cooling demand but make use of natural ventilation [24,36] . Only a few studies exist on the performance of passive cooling measures in the Swedish climate, however, their effectiveness in future climate scenarios has been demonstrated, see Table 1. Tettey et al [45] suggest that a combination of best available technology for lighting and other appliances combined with passive measures such as solar shading has the potential of almost eliminating the increased cooling demand over the next century. Dodoo and Gustavsson [14] show that solar shading and increased airing combined with solar shading were relatively effective measures in reducing annual cooling loads. Nik and Kalagasidis [36] modelled a representative building stock including all building types in Stockholm for a range of future climate scenarios for the coming century, showing that the increased cooling demand could be mitigated using natural ventilation for the average building stock. A study by Hosseini et al [25] simulated the energy use for two buildings, built according to the standard building code, in future climate scenarios on the Swedish south coast, including microclimate effects such as the urban heat island effect (UHI) and extreme weather scenarios. It was concluded that natural ventilation is an adequate strategy to mitigate the increased cooling loads for the average year in 2070.

1.2. Environmental impact and benefits from building renovation

While future climate scenarios pose the challenge of adapting Swedish buildings to new climate conditions, multiple studies have highlighted the potential of building renovations to reduce energy consumption and related greenhouse gas emissions. According to the Swedish National Board of Housing, Building and Planning, a report conducted in 2013 stated that 75 % of the existing buildings will need to undergo deep renovation before 2050 for the energy savings goals in the built environment to be met [9]). Furthermore, about a third of Sweden's current multi-family residential buildings was constructed during the years of 1961–1975, and since these buildings typically have a low-performing thermal envelope they represent a considerable mitigation potential [7]). Building renovation is a well-researched topic in Sweden, where many studies focus on improving energy efficiency for economical or environmental purposes. Hamid et al [23] conducted a literature review which suggested that renovations predominantly are evaluated on economic profitability and energy saving potential, and more rarely is environmental impact its own performance indicator. However, as energy saving can contribute to climate change mitigation due to reduced emissions associated with energy production, potential synergies can be derived. Interdisciplinary studies quantifying possible emission reductions due to energy savings by renovation has been conducted to highlight such synergies [34,32,41]. While this approach includes environmental impacts it only considers the operational phase of the building and ignores the environmental impact associated with the materials used in the renovation. This however is addressed by Ramírez-Villegas et al [39], who calculates the embodied carbon of renovation measures on a case study 250 km north of Stockholm, and deducts the reduced embodied carbon from energy savings, showing that both building envelope improvements and the installation of heat recovery systems was beneficial in terms of limiting environmental impact during a 50-year lifespan. Additionally, Österbring et al [50] studied the environmental impact of a range of renovation measures for the housing in Gothenburg using a building stock model. Setting investment capacity as the limiting factor, several environmental impact categories were assessed, showing a total reduction of greenhouse gas emissions (GHGs) by 2050 for the building stock.

Extending the scope to a European context, there are several studies that further support the notion that energy-saving renovation measures are beneficial in GHG reductions even when including material use. This is explored in studies in for example Serbia [3,4] where the measures included added thermal insulation, energy efficient glazing, and the installation of solar panels, and in Switzerland [33] where the measures included added thermal insulation and added ventilation features. However, the mentioned studies, among others, considered the environmental aspect of climate change mitigation due to GHG reduction, overlooking a potential shift in buildings' need for adaptation to a warming climate.

Reversely, studies on how climate change impacts buildings' energy demand in the Swedish context have mainly focused on how the annual energy demand will change, with a particular emphasis on heating demand variation and relatively new buildings (built in the 1990 s or later). The efficiency of passive measures has been proved in this context and most studies indicate that the future increased annual cooling demand would be mitigated by the incorporation of natural ventilation strategies [36,25]) , solar shading [14], and higher thermal envelope insulation [15,45] . Still, more comprehensive analyses are needed to understand the overall environmental performance of passive cooling measures, introduced through renovation, in terms of material carbon footprint and reduction of annual energy demand in future climate scenarios.

Thus, this study proposes a novel approach to evaluate, from a global warming perspective, the carbon efficiency of passive cooling measures to support decision-makers in the selection and prioritization of renovation measures for existing residential buildings. Residential buildings are of particular interest in the context of passive cooling in a Nordic climate since they are not traditionally equipped with active cooling systems. The study develops and applies an integrated assessment method which combines an energy model and an environmental impact assessment to overcome the traditional compartmentalized approach in assessment practices. Through the integrated assessment method, reduction in cooling energy demand, maximum temperature, overheating hours and material carbon footprint are compared for a set of passive cooling measures in future climate scenarios, allowing to inform sustainable decision making in implementing cooling measures. The study uses a multi-family residential building built in 1970 in Gothenburg, Sweden, as a test case.

Table 2
Case study building information and construction details.

Description	Parameter	Unit	Comment
Construction	Prefab concrete		
Construction year	1970		
Number of floors	4		Including basement
Number of apartments	18		3–4 rooms + kitchen
Heated floor area, A_{temp}	2526	m^2	
Heated air volume	5380	m^3	
Window area	287	m^2	
Window g-value	0.75	–	[43]
U-values			
Roof	0.084	W/ m^2K	Calculated
Ground Floor	2.58	W/ m^2K	Calculated
Wall	0.34	W/ m^2K	Calculated
Doors	2.5	W/ m^2K	[32]
Windows	2.8	W/ m^2K	[8]
Infiltration	1.1	l/sm^2	Case study assumption
Mechanical ventilation	0.35	l/sm^2	Exhaust only

2. Methodology

This study develops an integrated approach for energy performance and environmental assessment and applies it on a Swedish case study for two future climate scenarios. The energy performance of selected passive measures is evaluated through energy performance simulation of a multi-family house. The carbon footprint of the material used for the renovation measures is assessed by calculating the global warming potential (GWP). Furthermore, three indicators of carbon efficiency are developed and calculated to compare the passive measures considering carbon footprint and energy performance. This section describes the used data and methods in more detail, including: information about the case study building and its geometry, such as construction type, envelope and area (2.1); description of the selected renovation measures for the study, manner of application and the corresponding material use (2.2); description of the historical weather data and future climate projections (2.3); specifications, software and methods for the energy modelling (2.4); the material carbon footprint assessment (2.5); and description of the method for calculating the carbon efficiency as an interdisciplinary indicator of comparison for the climate adaptation cases and future climate scenarios (2.6).

2.1. Case study building

To represent a building type in Sweden which typically requires large-scale renovations, a multi-family residential building built in the 1970 s that had comprehensive data availability was selected as a case study. The building is situated in Uddevalla in Western Sweden, in a cool temperate climate zone. The building is located in a residential area with approximately 750 dwellings built in 1965–1975, subject to renovation in the upcoming years. The increased life expectancy of the building after the planned renovation is a minimum of 50 years. The planned renovation measures include added insulation, new windows and doors, and a new ventilation system with heat recovery to improve energy performance. The case study building, a four-story building including the basement, is divided into 18 apartments with two or three bedrooms, lounge and kitchen, and is mainly constructed with prefabricated concrete. The building is heated with district heating and has no cooling systems installed.

The summary reported in Table 2 indicates additional construction details measured or calculated on the building under study and derived from literature. According to the building owner, there is a great variation in infiltration rate between individual apartments. Kronvall & Boman [31] carried out measurements on 30 apartments built

Table 3
Description of cases and their abbreviations.

Cases	Description
AS-BUILT	As-built
RENO	+50 mm insulation, increased air tightness, double glazing, replace doors
1 – INS	RENO + added insulation
2 – GLZ	RENO + triple glazing
3 – REF	RENO + increased solar reflectivity
4 – SHAD	RENO + solar shading
5 – NV	RENO + natural ventilation
6 – COMB	RENO + combination of case 1–5

1940—–1988 in Sweden and found that the average infiltration rate for the buildings built between 1960–1975 was 2.8 air changes per hour (ACH) (with a standard deviation of 0.5—–5), which for the case study building corresponds to 0.8 l/sm2 (0.2—–1.4 l/sm2). To more accurately define the infiltration rate for the case study building, the model was calibrated through a comparison of heating loads per square meter between simulations' results and measured values in a reference building in the same area, (see Appendix I). The highest accuracy was achieved with an infiltration rate of 1.1 l/sm2, which gives an annual heating load within a 15 % margin, with the smallest variations during April-October and largest during December-February.. The thermal properties of the exterior floor, wall and roof have been calculated based on case study building construction data provided by the building owner.

2.2. Set of renovation measures

Five passive cooling measures were chosen based on the following criteria; 1) the measure is passive; 2) the measure is additive, i.e., it can be implemented in the operational life-cycle phase of the building; 3) the measure is effective on a building scale; 4) it is possible to assess the embodied carbon of the measure and; 5) the measure is effective when excluding microclimatic effects. The passive measures included in the study were addition of insulation, change to triple glazing, increase solar reflectivity of the façade, addition of solar shading devices and use of natural ventilation. Passive measures that have been excluded are, e.g., the addition of thermal mass, since it is not additive in the assessed case study, and the use of green structures, since microclimatic effects are excluded, and the assessment is done on a building (non-district) scale. A more detailed summary of the selection process of the measure is presented in Appendix II, Table A1. A set of eight energy simulations was carried out based on the selected passive measures, see Table 3. Firstly, the status quo case was constructed and simulated as a reference case. Secondly, the planned renovated building was simulated to be used as the renovation base case for comparison of the carbon footprint and the energy performance of the passive measures. Following, the five passive measures were applied to the renovation base case (case 1 to 5) and their energy performance was modelled. Lastly, a combined case is presented, which applies all passive measures to explore potential synergy effects (case 6). Appendix III further reports the detailed list of the properties of the construction layers for each case.

2.2.1. Case RENO – Base case

Since a renovation of the building of study is already planned, this is considered the base case and is based upon the planned renovation measures; 50 mm added insulation in exterior walls, increased air tightness, replaced doors, and replaced double-glazed windows. The carbon footprint of the added materials is not calculated, instead the difference in material use between the base case and the application of the assessed passive cooling measures is attributed to case 1–6 respectively. In the energy model, the U-value of exterior walls is reduced to 0.219 W/m^2K, the infiltration is reduced to 0.7 l/sm^2, the U-value of the windows are reduced to 1.4 W/m^2K, the G-value of the windows is reduced to 0.6 and the U-value of the doors is reduced to 1.2 W/m^2K. When renovating, the insulation can be added either the interior or exterior of the existing wall construction. Here, a theoretical simplification is used where the extra insultation is added to the existing layer of insulation in the middle of the sandwich wall as if it was newly constructed, to avoid any added impact from the choices of finishing materials on the interior or exterior wall. In reality, when such a measure is considered, great care needs to be taken in the detailed construction of the refurbished exterior walls, including factors such as moisture, appearance, heritage protection, fire safety, etc.

2.2.2. Case 1 – INS

The added insulation case consists of an extra 175 mm layer of insulation to the exterior walls, in addition to the previously existing insulation. The roof of the case study building is already well-insulated. The U-value of the exterior walls is decreased to 0.123 W/m^2K in the energy model. This option might not be beneficial in terms of cooling unless combined with a reduction of solar radiation through windows, since large heat gains risk getting trapped inside the building, exaggerating heat stress. However, since added insulation is commonly included in renovations with the aim of decreasing heating demand, the potential impact during warm periods is of interest.

2.2.3. Case 2 – GLZ

The improved glazing case investigates the incorporation of triple-glazed windows with low e-coating in the planned renovation. Compared to the double-glazed windows in the base case, this option offers further reduction of the U-value which limits heat transfer through the construction, and a further reduction of the g-value of the window, which decreases the amount of solar radiation that is let through the window and consequently reduces solar heat gains. Since double glazing is added in the renovation base case, the added material for the triple glazing is assumed to be one extra 4 mm thick windowpane, i.e., no added material for the frame is assumed. In the energy model, the windows are assumed to have a U-value of 0.9 W/m^2K and a G-value of 0.45. These changes could contribute to a lower heating demand during the heating season, since less cold outdoor air reaches the interior, but could also increase heating demand because of decreased heat gains due to solar radiation in winter.

2.2.4. Case 3 – REF

The solar reflectivity, or albedo, describes how much of the solar radiation is reflected by the material surface. The non-reflected radiation is instead absorbed. An increased solar reflectivity of the façade material can be used to decrease the amount of solar radiation which is transmitted through the exterior walls and therefore limit the potential warming effects from exterior walls exposed to solar radiation. Since the façade is being renovated, there is a possibility of using a highly reflective material to decrease the amount of absorbed heat in the construction. The exterior layer of the façade construction is in this case assumed to be a coating of light paint with a solar reflectivity of 70 %, reapplied once every five years to keep the solar reflectivity high [17].

2.2.5. Case 4 – SHAD

Solar shading is the placement of a shading material in connection to glazed areas to reduce the amount of solar radiation reaching the window, limiting solar heat gains. The carbon footprint from the solar shading case could vary to a great extent depending on material choice and design, however, for the simplicity of this study a standard solution has been assessed. The solar shading assessed is a horizontal aluminium sheet placed on the top of the window, extending 60 cm perpendicular to the exterior wall. Since automated control systems are not a passive measure, this alternative will be excluded from this case. Compared to automated or in other ways variable solar shading, the assumption of an always active solar shading system might impact the total thermal

Table 4
Overview of the simulated years and climate scenarios for the different simulation types included in the study.

Simulation type	Simulated years	Simulated climate scenarios
Annual cooling demand	2018, 2030, 2050	RCP4.5, RCP8.5
Peak cooling demand	2018, 2030, 2050	RCP4.5, RCP8.5
Overheating hours	2018, 2030, 2050	RCP4.5, RCP8.5
Maximum indoor temperature during peak conditions	2050	RCP4.5

performance negatively, for example through a potential increase in heating demand.

2.2.6. *Case 5 – NV*

Natural ventilation is the use of natural air flow to let outside air in for ventilation, which has a cooling effect if the outside air temperature is lower than the inside air temperature. Since the windows are operated manually, no carbon footprint is assumed to be associated with this case. The openable area fraction of the windows is assumed to be 50 %. The windows are assumed to be opened if the inside air temperature exceeds 24 °C and if the outside air temperature exceeds 22 °C. This is due to limitations in the energy model, in which the minimum outside air temperature for natural ventilation cannot be lower than the heating setpoint. This assumption might lead to an underestimation of the efficiency of the natural ventilation since the windows could be open down to outside air temperatures of 16–18 °C without causing discomfort. Due to additional modelling limitations the windows are assumed to be opened also if the outside air is warmer than the inside air, potentially contributing to a heating effect.

2.2.7. *Case 6 – COMB*

In Case 6 a combination of all the measures is assessed to explore potential synergy effects. The measures are included in the energy model and carbon footprint assessment in accordance with the methodological descriptions presented in section 2.2.1-2.2.6. The combined case can therefore be assumed to be associated with a high material use and consequently a large carbon footprint, however, also has the potential of increasing thermal and energy performance beyond the limitations of single measures due to synergy effects and is therefore of interest to this study.

2.3. *Climate data*

IPCCIPCC [29] has condensed the possible future accumulation of GHGs into four different Representative Concentration Pathways (RCPs). The low emission pathway (RCP2.6), is deemed increasingly unlikely since it requires immediate and heavy implementation of mitigation measures. Additionally, there are two medium emission pathways (RCP4.5, RCP6.0), and a high emission scenario (RCP8.5) which likelihood is debated. However, according to the latest climate report byIPCC [30]:67) potential carbon-cycle feedback loops could mean that the RCP8.5 scenario is feasible even with a GHG mitigation that aims at a lower emission pathway. Future climate can be modelled by using data from a historically hot year, as done by Pyrgou et al [37] and Van Hooff et al [24]. There are also several weather-generator tools and software that generate weather files, such as ClimGen, WeaGeats and Meteonorm [49]. The historic and future climate data in this study was acquired in EPW format by using the Meteonorm weather generator, to produce Typical Meteorological Years (TMY) [40]. Hourly climate values were generated for two emission pathways (RCP4.5 and RCP8.5) using measured data from the Gothenburg weather station. Since the climate data is based on a typical year, the occurrences of extreme hot years, extreme cold years or extreme weather such as heat waves are not included. As shown in Table 4, annual and peak cooling demand, as well as number of overheating hours and maximum indoor temperature were modelled based on the TMY 2018, and TMYs for 2030 and 2050 following RCP 4.5 and RCP 8.5. A summary of the average monthly temperatures of the different climate scenarios is shown in Fig. 1.

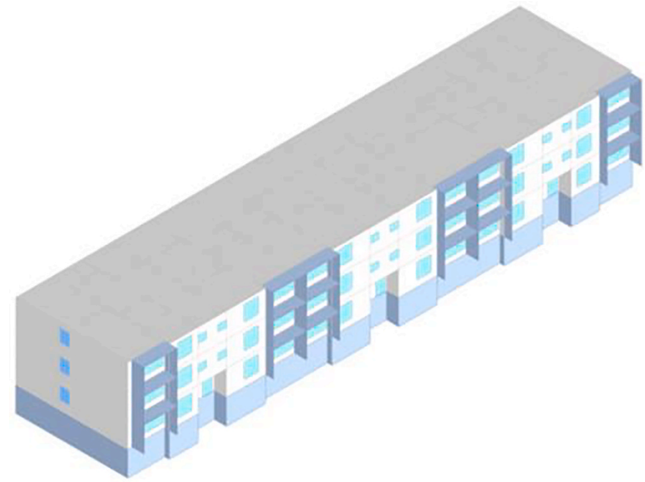

Fig. 2. Energy model of the case study building.

Table 5
Key input data for the energy simulation model.

Description	Parameter	Unit	Comment
Occupancy			
2-bedroom apartment	2.18	people	[43]
3-bedroom apartment	2.79	people	[43]
Occupancy schedule	14	hrs/day	[43]
Occupancy load	80	W/person	[43]
Equipment load	2.4	W/m^2	[43]
Natural ventilation	0.5	l/sm^2	[43]
Schedule – Cooling period	6	hrs/day	[43]
Heating setpoint			
Apartments	22	°C	From case study
Basement	17	°C	From case study
Cooling setpoint	26	°C	[21]

2.4. *Energy assessment*

For the first part of the environmental assessment energy demand

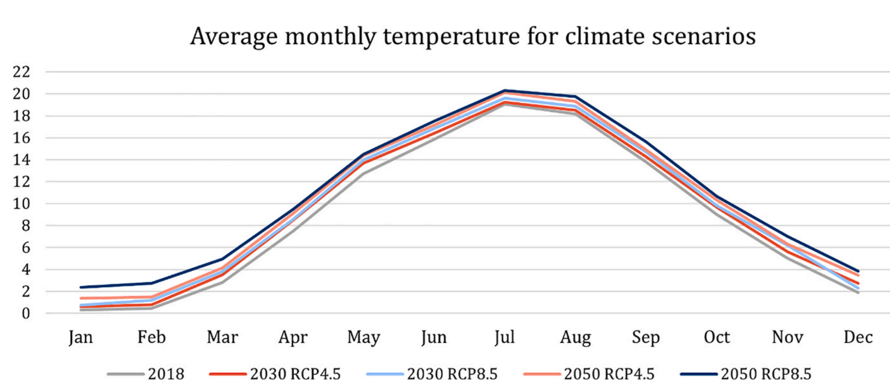

Fig. 1. Average monthly temperature in the different climate scenarios.

Table 6
Energy model input data for the different cases.

Cases	Wall U-value (W/m^{2}K)	Infiltration (l/sm^2)	Window U-value (W/m^{2}K)	Window G-value	Door U-value (W/m^{2}K)	Solar Reflectivity Wall	Solar shading	Natural Ventilation
AS-BUILT	0.319	1.1	2.8	0.75	2.5	0.3	No	No
RENO	0.219	0.7	1.4	0.6	1.2	0.3	No	No
1 – INS	0.123	0.7	1.4	0.6	1.2	0.3	No	No
2 – GLZ	0.219	0.7	0.9	0.45	1.2	0.3	No	No
3 – REF	0.219	0.7	1.4	0.6	1.2	0.7	No	No
4 – SHAD	0.219	0.7	1.4	0.6	1.2	0.3	Yes	No
5 – NV	0.219	0.7	1.4	0.6	1.2	0.3	No	Yes
6 – COMB	0.123	0.7	0.9	0.45	1.2	0.7	Yes	Yes

simulations were carried out by using well established modelling tools. The spatial model of the case study was created within the Rhinoceros/Grasshopper software environment. Weather data as well as the properties of the thermal envelope, schedules, solar shading, occupancy, equipment and heating and cooling setpoints was added to the spatial model using the Ladybug and Honeybee plugins. The Honeybee plugin was employed to link the EnergyPlus simulation engine to the resulting energy model. EnergyPlus is an open-source simulation engine developed and funded by U.S. Department of Energy (DOE), widely used for compliance and research [16]. The energy simulations were made using a bottom-up heat balance model, with climate and building information as text file inputs. The modelled geometry was based on blueprints from the planned renovation, see the energy model geometry in Fig. 2. Key input data is presented in Table 5.

Since a validation of the modelled data against measured data was difficult due to the use of a Typical Meteorological Year as climate boundary conditions, the model was instead calibrated through a comparison of the simulated heating demand per meter square floor area to the measured consumption of a reference building in Uddevalla. The reference building is a multi-family residential building in the same area, built at the same time and with similar construction, size and layout as the case study building. The reference building has already been subject to renovations and the energy use due to heating was monitored before and after. The variation of heating demand per square meter in the cooling season, i.e., May to September, for the model compared to the reference building in the renovated case was below 15 %.

EnergyPlus was used to simulate annual and peak cooling demand, overheating hours and maximum indoor temperature during peak conditions. The windows were modelled as EnergyPlus Simple Window Model objects that only requires G-value and U-value as inputs, while for each case wall composition followed the detailed cases' descriptions in Appendix III. The annual cooling demand was assessed for the whole building, whilst the overheating hours, peak cooling demand and maximum temperature during peak conditions were assessed for the most critical apartment. Internationally, the definition of an overheated apartment varies, where the upper temperature limit for thermal comfort varies from 26 °C to 28 °C depending on geographical context [13,5]; Swedish National Board of Health and Welfare [SNBHW] [44]. This study defines overheating hours in line with the recommendations from Forum for Energy Efficient Construction [21], who states that the temperature should not exceed 26 °C for more than 10 % of the time in the most exposed apartment of a building from April to September in Sweden. The temperature profile was based on the average temperature profiles of the occupied zones, i.e., the living room, kitchen, and bedrooms. Peak conditions for the measuring of maximum temperature were determined by assessing the three hottest consecutive days of the year, including the hottest day of the year. Peak cooling was defined as the maximum amount of cooling power supplied during the simulation period, simulated in hourly steps. See Table 6 for further details on the energy model input data.

2.5. Carbon footprint assessment

The second part of the assessment focused on the estimation of carbon footprint related to materials used for implementing the renovation measures. To aid environmental impact assessments of buildings, Boverket [12] has provided a database of generic climate impact data for commonly used materials in the building industry in Sweden, with average values based on a range of Environmental Product Declarations (EPDs) in the form of Global Warming Potential (GWP) measured in kg CO_2eq with a time frame of 50 years. Other climate impact categories were excluded in coherence with the methodology outlined by Boverket [10]. The carbon footprint of the passive measures was calculated based on the data from the open material database by Boverket [11] and in accordance with the methodology from Boverket [10], the end-of-life or operational phase was not included in the data, i.e., any carbon footprint from maintenance and waste was excluded. No material waste was assumed. In cases where the carbon footprint of a certain product was not available, such as in the case of the triple glazing case and solar shading case, the material of the product has been assessed, therefore excluding any carbon footprint due to added materials for mounting.

Table 7
Overview of the estimated added materials in the different cases.

Cases	Added materials	Area [m^2]	Thickness [m]	Conversion value [kg/m^3, kg/m^2]	GWP [kg CO_2e/kg]
AS-BUILT	–				
RENO	–				
1 – INS	Glasswool, blowing wool, wall	837.4	0.175	30	1.247
2 – GLZ	Floatglass	272.5	0.004	2500	1.781
3 – REF	Paint, acrylic, water-borne for exterior use (color white)	8374		0.1	3.286
4 – SHAD	Aluminium sheet, primary	26.2	0.005	2700	13.177
5 – NV	–				
6 – COMB	Glasswool, blowing wool, wall	837.4	0.175	30	1.247
	Floatglass	272.5	0.004	2500	1.781
	Paint, acrylic, water-borne for exterior use	8374		0.1	3.286
	Aluminium sheet, primary	26.2	0.005	2700	13.177

The materials used in each case are presented in Table 7.

The carbon footprint of the materials was calculated according to Boverket [10] using the following equations:

$$A \times d \times \rho \times GWP_{norm} = GWP_{tot}$$

$$A \times \delta \times GWP_{norm} = GWP_{tot}$$

Where:

A = Area of material [m^2].
d = Thickness of material [m].
ρ = Conversion value [kg/m^3].
δ = Conversion value [kg/m^2].
GWP_{norm} = Normalised global warming potential [$kgCO_2/kg$].
GWP_{tot} = Total global warming potential [$kgCO_2$].

2.6. Carbon efficiency

The carbon efficiency indicator was developed to be able to assess the efficiency of renovation measures in jointly reducing cooling demand and materials' carbon footprint. The carbon efficiency is defined as the carbon footprint that corresponds to the reduction of annual cooling energy demand and maximum indoor temperature, calculated for each case and climate scenario. The carbon efficiency for a case is calculated according to the following equations:

$$\frac{GWP_i}{RCD_{an,i}} = CE_{an,i}$$

$$\frac{GWP_i}{RCD_{peak,i}} = CE_{peak,i}$$

$$\frac{GWP_i}{RMT_i} = CE_{t,i}$$

Where:

GWP_i = Global warming potential of measure [t CO_2].
$RCD_{an,i}$ = Reduced annual cooling demand for measure [kWh].
$RCD_{peak,i}$ = Reduced peak cooling demand for measure [kW].
RMT_i = Reduced maximum temperature during peak conditions for measure [℃].
$CE_{an,i}$ = Carbon efficiency annual cooling demand [t CO_2/kWh].
$CE_{peak,i}$ = Carbon efficiency annual energy demand [t CO_2/kW].
$CE_{t,i}$ = Carbon efficiency maximum indoor temperature [t CO_2/℃].

Concerning the reduction in annual and peak cooling demand, the indicators of carbon efficiency $CE_{an,i}$ and $CE_{peak,i}$, measured in t CO_2e per kWh reduced and t CO_2e per kW reduced, was used to evaluate all renovation cases for the RCP4.5 and RCP8.5 climate scenarios in 2018, 2030 and 2050. For the maximum temperature during peak conditions, the carbon efficiency indicator $CE_{t,i}$ was calculated for the RCP4.5 climate scenario in 2050 and for all passive measures, measured in t CO_2e per °C reduced.

3. Results

In this section, the results from the energy simulation are presented, followed by the results of the carbon efficiency calculations and a case comparison.

3.1. Energy performance

The annual cooling demand, peak cooling demand and overheating hours of the eight cases were simulated for RCP4.5 and RCP8.5, and the years 2018, 2030 and 2050, as displayed in Figs. 3-5. For the renovated case, i.e. the base case, the annual cooling demand is 0.46 kWh/m^2 in 2018, and increases by 180—230 % in 2030 and 280–400 % in 2050 depending on the climate scenario due to increased outdoor air temperatures, corresponding to 1.3–1.9 kWh/m^2. The peak cooling demand is 1.2 kW in 2018, simulated as the total demand for the worst performing apartment, and is estimated to increase by 34–98 % corresponding to 1.7 – 2.3 kW by 2050, depending on climate scenario. It should be noted that the annual cooling demand is around 0.9 – 4.3 % of the annual energy demand for heating and cooling for this case study.

For the annual cooling demand performance, the triple glazing and natural ventilation cases are the most effective of the individual passive measures assessed, reducing annual cooling demand with 52–56 % and 24–45 % for the year of 2050 respectively, compared to the base case. The combined case keeps annual cooling demand at the current level in 2050 for the RCP4.5 climate scenario and increases by around 80 % for the RCP8.5 climate scenario, indicating a possible synergy effect when combining the individual measures.

Considering peak cooling demand, the triple glazing case is again the

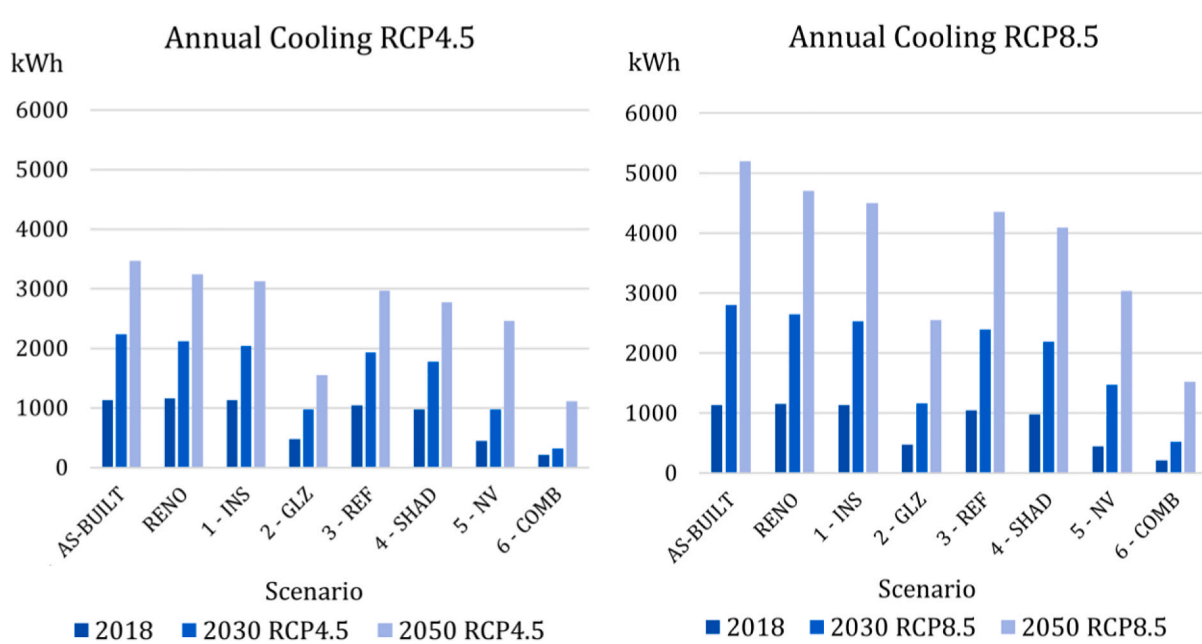

Fig. 3. Total annual cooling demand [kWh] for all cases, for the RCP4.5 (left) and RCP8.5 (right) future climate scenarios, in 2018, 2030 and 2050.

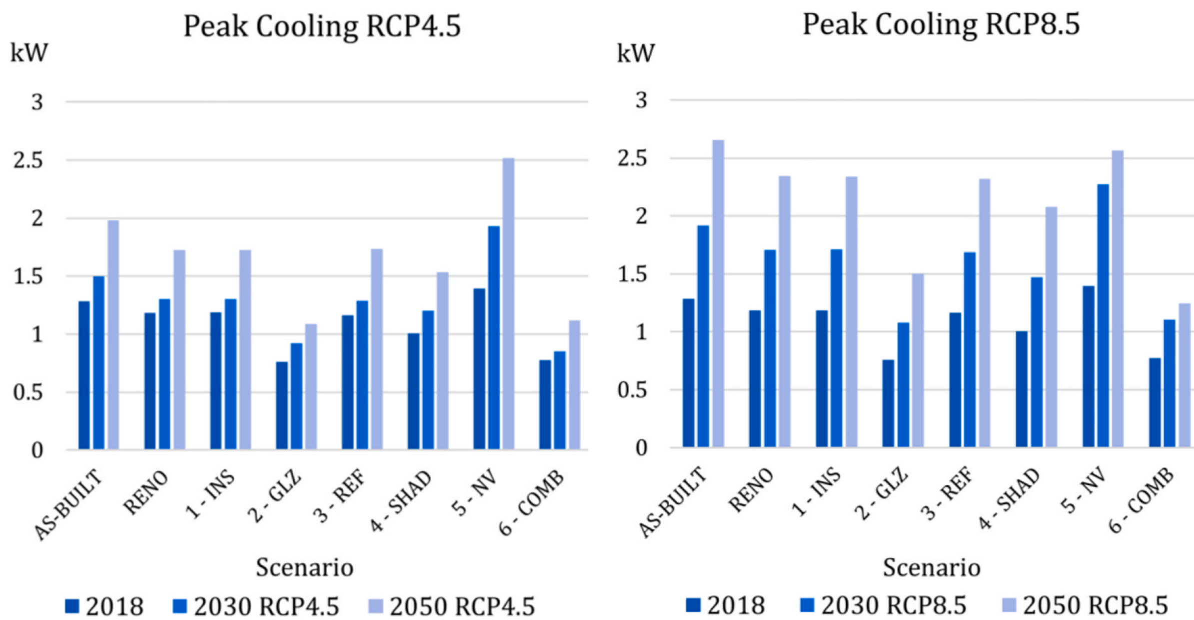

Fig. 4. Total peak cooling demand [kW] for all cases, for the RCP4.5 (left) and RCP8.5 (right) future climate scenarios, in 2018, 2030 and 2050.

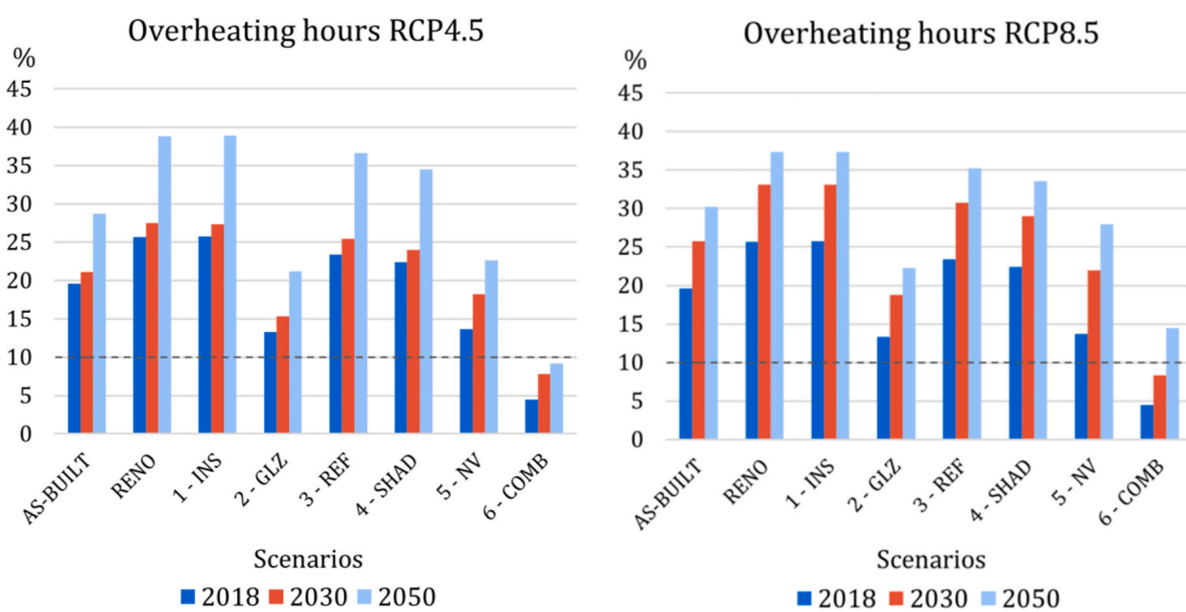

Fig. 5. Overheating hours [%] for all cases, for the RCP4.5 (left) and RCP8.5 (right) future climate scenarios, in 2018, 2030 and 2050. The dashed line represents the threshold for maximum recommended overheating hours.

most effective with a reduction of 36–37 % in 2050 compared to 2018. Moreover, the solar shading case proves to be the second most efficient with the possibility of reducing peak cooling demand with 13 % by 2050 for RCP4.5 and RCP8.5, compared to the base case. The combined case shows little to no synergy effects in most climate scenarios as the reduced peak cooling is very close to the triple glazing case, however, in 2050 for the RCP8.5 it shows a further reduction of 12 %.

The natural ventilation case shows an increase or only slight decrease compared to the base case, ranging from a 25 % increase to a 10 % decrease in peak cooling demand, depending on climate scenario, further discussed in the limitations section. Moreover, the effects from the added insulation and increased solar reflectivity cases are small both in terms of peak and annual cooling demand reduction.

3.2. Overheating hours

The results show that in 2018 the as-built and renovated cases both significantly exceed the 10 % indoor thermal comfort threshold for overheating hours, with calculated overheating hours of 20 % and 25 % respectively. However, it should be noted that case 5 – NV which includes the use of natural ventilation and has the calculated overheating hours of 14 % can be considered as a closer approximation of current overheating conditions. Projecting the future climate data on the baseline case, overheating hours reaches 38 % for the renovated case and 22–27 % including the use of natural ventilation depending on climate scenario. In terms of reducing overheating hours, the different cases show similar efficiencies to the annual cooling demand results, where the triple glazing and natural ventilation are the most effective. The combined case shows a synergy effect which is effective enough to keep

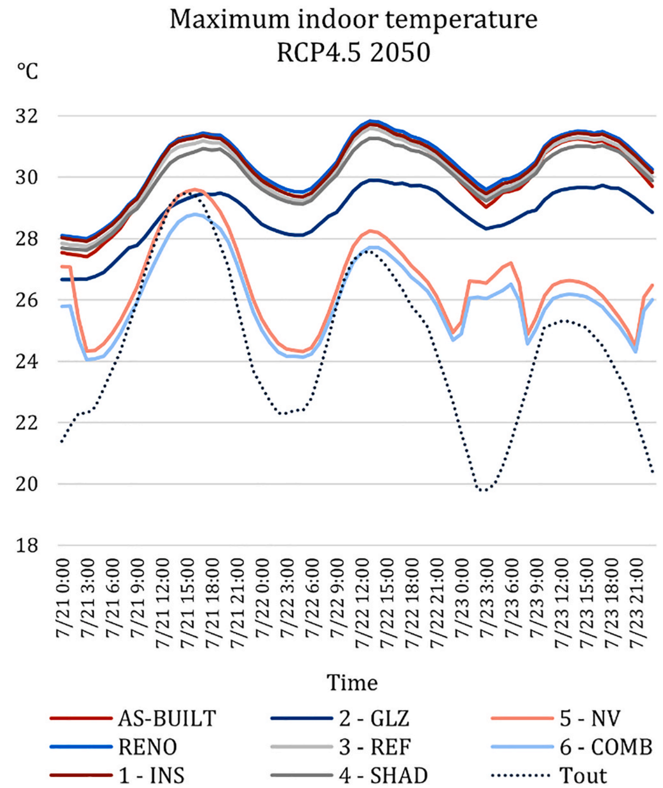

Fig. 6. Temperature profile during hot temperatures, 21st-23rd of July, in 2050 for the RCP4.5 climate scenario. The dotted line represents the outdoor air temperature Tout.

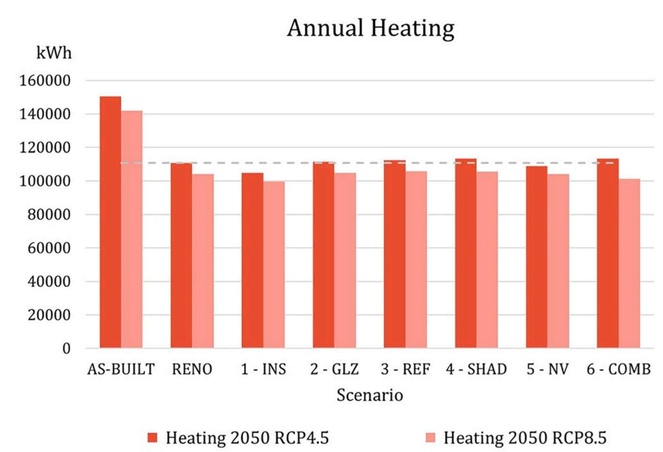

Fig. 7. Heating demand for the assessed measures in 2050, for climate scenarios RCP4.5 and RCP8.5.

overheating hours below the 10 % threshold for the year 2050 in the RCP4.5 climate scenario. Due to modelling limitations, the number of overheating hours as well as the annual cooling demand for the natural ventilation case can be overestimated.

3.3. Maximum indoor temperature

To further assess the thermal performance of the building at high temperatures, the average indoor temperature for the apartment with the worst thermal performance during the hottest three consecutive days of the year was simulated for the RCP4.5 climate scenario in 2050, see Fig. 6. The warmest days of the TMY for 2050 were between the 21st and 23rd of July, reaching a maximum outdoor temperature of 29.5 °C. In

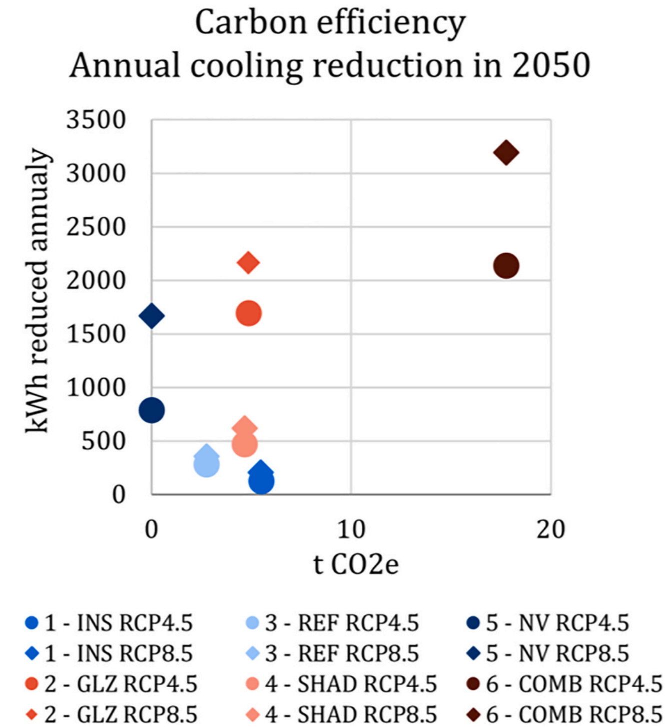

Fig. 8. Carbon efficiency considering annual cooling demand reduction in 2050, for the RCP4.5 and RCP8.5 climate scenarios. The top left area of the chart represents carbon efficient measures, and the bottom right area of the chart represents the most carbon inefficient measures. The bottom left area of the chart represents measures with a relatively small carbon footprint and a small cooling reduction potential, whilst the top right area shows measures which have a high cooling reduction potential together with a high relative carbon footprint.

accordance with previous simulations, the added insulation and increased solar reflectivity cases show a negligible difference. Looking at the maximum average indoor temperature, measured at 2 PM in the afternoon on the 22nd of July, the solar shading option has the potential of reducing the maximum average indoor air temperature with around 0.6 °C, the triple glazing case has the potential to reduce the peak temperature with 1.9 °C, and the natural ventilation case has a reduction potential of 2.2 °C, proving most efficient. In addition, the natural ventilation case shows the lowest peak temperatures during the other days, 21st and 23rd of July. The combined case shows the potential of reducing the maximum interior air temperature below outside air temperature during the hottest day, lowering peak indoor temperature with 2.7 °C to a maximum of 28.8 °C.

3.4. Annual heating demand

In traditional cold climates energy measures for reducing cooling demand can have negative effects on heating demand. For this reason, results for all climate scenarios were also analysed from a heating perspective as shown in Fig. 7. The comparison of the annual heating demand was made to assess the potential increase in heating energy demand associated with each measure. The solar shading option, case 4 – SHAD, showed an increase in heating demand of 1.5 % in 2050 compared to RENO (baseline case). Increasing solar reflectivity, case 3 – REF, presented an increase of 1.3 % compared to RENO case. When measures are combined in case 6 – COMB, heating demand is influenced by the solar shading and thus sees a similar increase. The remaining cases presented no change or a decrease in heating demand.

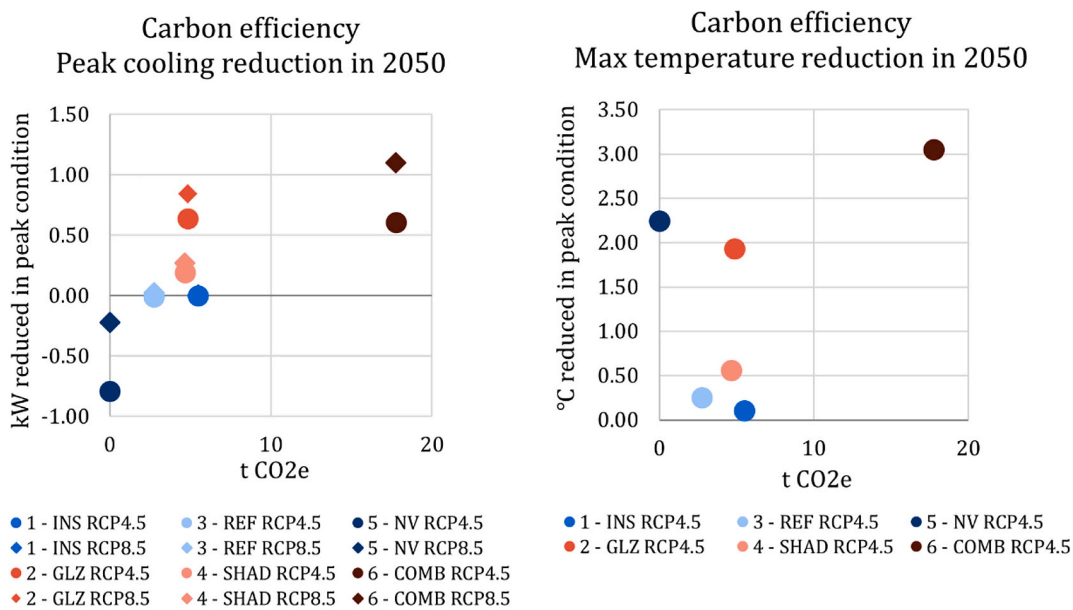

Fig. 9. Carbon efficiency considering peak conditions, represented by peak cooling demand reduction (left) in 2050, for the RCP4.5 and RCP8.5 climate scenarios, and maximum temperature reduction (right) in 2050 for the RCP4.5 climate scenario.

3.5. *Carbon efficiency*

The carbon efficiency results for annual cooling reduction are presented in Fig. 8. The carbon efficiency for the annual cooling demand and peak cooling demand indicators is presented as the difference in demand compared to the base case, i.e., the renovated case (RENO), together with the carbon footprint of the material used for the different measures assessed. Additionally, the indicator of carbon efficiency for the maximum temperature during peak conditions indicator is presented as the difference in maximum temperature compared to the base case, together with the carbon footprint.

The carbon efficiencies depending on annual cooling reduction potential show that the natural ventilation and triple glazing cases are the best performing alternatives. For the RCP4.5 scenario, the triple glazing case is more than twice as effective compared to the natural ventilation case in terms of reducing annual cooling, whilst the difference is smaller in the RCP8.5 scenario. It should be noted that due to the modelling limitations described in section 2.2.6 and the effects of which is further discussed in section 4.1, the efficiency of natural ventilation might be underestimated. As the natural ventilation option had no associated carbon footprint compared to the mid-range carbon footprint of the triple glazing case, it can be considered more carbon efficient. The combined case has the highest efficiency in cooling reduction, however, there is a large trade-off in terms of carbon footprint. Solar shading, added insulation, and increased solar reflectivity have a similar carbon footprint to the triple glazing option but since they are associated with a worse energy performance the carbon efficiency is lower.

The carbon efficiency of the peak cooling demand and maximum indoor temperature reduction is shown in Fig. 9. The results show that the natural ventilation option does not decrease peak cooling demand, however, it is very effective in reducing maximum indoor temperatures during hot days. Furthermore, the increased solar reflectivity and added insulation cases have no effect in reducing peak cooling demand or maximum indoor temperature, and the inefficiency proves even greater considering the carbon footprint associated with the options. The solar shading and triple glazing options both show a potential to reduce peak cooling loads, and the triple glazing option is more efficient due to a larger peak cooling reduction with similar carbon footprint. For the RCP4.5 climate scenario, the combined case shows no greater potential in reducing peak cooling demand than the triple glazing option, and since it is associated with a substantially larger carbon footprint, the results indicate that the combined case is an inefficient solution. The efficiency is greater in the RCP8.5 scenario.

Overall, the triple glazing and the natural ventilation measures prove to be the two most carbon efficient solutions in reducing annual energy cooling demand, overheating hours and maximum indoor temperature during hot days. The case combining all five passive cooling measures shows the greatest efficiency in cooling demand and indoor temperature reduction; however, this case is found to have the largest carbon footprint, making it a seemingly carbon inefficient option in certain aspects. On the other hand, the combined case is the only assessed option which keeps the overheating hours below or close to below 10 % in 2050. Case 1 – INS, (added insulation), and case 3 – REF, (increased solar reflectivity), were found the most carbon inefficient cases. Implementing solar shading (case 4 – SHAD), has a higher efficiency in reducing annual cooling demand, overheating hours, peak cooling as well as indoor temperature during hot days compared to case 1 and case 3 despite a similar carbon footprint.

4. Discussion

In this study, a methodological framework for calculating carbon efficiency was developed to include the carbon footprint of climate adaptation measures in the assessment of residential buildings' renovation. The results of the integrated assessment show a large difference in carbon efficiency between the investigated passive measures, indicating that the material carbon footprint of the considered options is relevant to support the selection of the most carbon efficient measures.

Previous studies suggest that natural ventilation is an effective method of cooling also in future climate scenarios, however, the level of efficiency differs between studies. Nik and Kalagasidis [36] and Hosseini et al [25] both suggest that natural ventilation is an adequate measure to completely mitigate the increased cooling demand by 2090 and 2070 respectively, both using climate data projected from regional climate models. The results of this study suggest that natural ventilation is effective, however, needs to be combined with other passive measures to fully mitigate the increased annual and peak cooling demand. The discrepancy in results can be explained by the different methodologies used, as well as climate data sourcing and building type assessed. Dodoo and Gustavsson [14] also suggest that a combination of solar shading and natural ventilation is nearly sufficient to mitigate the increased cooling demand in 2050 for all climate scenarios. Moreover, Tettey et al [45] and Tettey and Gustavsson [46] suggest that a combination of BAT of appliances, improved envelope and solar shading has the potential of almost eliminating the increased cooling demand over the next century for the RCP4.5 scenario, however, not for the RCP8.5 scenario.

These results, suggesting that a combination of measures is needed to mitigate the increased cooling demand, is in line with the results of this study, however, the incorporation of the carbon efficiency indicator in this study shows that the combination of measures has a significantly lower efficiency when considering carbon footprint. In fact, when considering the carbon footprint of measures, natural ventilation is the most efficient method of reducing cooling demand. The carbon efficiency is the second highest for triple glazing, an improvement measure not typically assessed by itself in previous studies. Solar shading, suggested as an effective passive cooling measure by previous studies, has a distinctly lower carbon efficiency in comparison but is still amongst the three most carbon-efficient solutions.

While this study has compared traditional passive cooling solutions that can be applied at the building level, a larger set of passives measured should be tested through this integrated assessment approach. For example, studies suggest that urban design solutions, such as green and blue cooling infrastructure or the application of phase change materials, can contribute to thermal comfort improvements in outdoor and indoor environments, resulting in higher building energy efficiency [6,22]) . From another perspective the technological advancement in sustainable cooling systems and their combination with renewable energy sources is making active cooling solutions energetically more efficient [1,38] . Integrated environmental and energy assessments should further be used to evaluate a larger range of solutions and offer multiple efficient options to decision-makers.

Additionally, this study confirms general patterns of increased overheating hours and annual cooling demand in future climate conditions. Previous studies by Tettey and Gustavsson [46] and Tettey et al. [45], that simulated total overheating hours in future climate scenarios, had found overheating hours in the range of 25–36 % and 16–22 % by 2090 respectively. However, the results of the modelling in this study indicate overheating hours between 24 % and 38 % with a warmer climate scenario already by 2050, suggesting a more severe exposure to high temperature in a shorter time span. Differently, the relative increase in annual cooling demand found in this study (280–400 % by 2050, corresponding to 1.3–1.9 kWh/m^2 by 2050) is slightly lower compared to previous studies by [15], and [25] (33–510 %, corresponding to 1–10 kWh/m^2 by 2090); while peak cooling demand increase observed in this study (of 34–98 % by 2050) has a smaller range than the one found in studies by [14], and [25] (14–290 % by 2100). These cooling demand and peak cooling demand values are however difficult to compare to previous research results due to the differences in timespan, calculation methods and the variety in building typologies.

This region, as others generally characterised by cold climate, is going to experience warmer temperatures during summer periods. On this Swedish case study, passive cooling measures traditionally developed in hot-arid regions may increase heating and electricity demand during winter months. Despite this study shows that the increase in heating demand for the majority of the measured applied is below 1.5 % it is necessary to reflect on the benefit of integrated assessment approaches and the potential of introducing air and light quality assessments to further offer holistic approaches to complement the cooling and environmental assessment components.

4.1. Limitations

The results of the integrated assessment show a large difference in carbon efficiency between the available passive measures. However, a few limitations of the study are related to the method developed for the integrated assessment. First, regarding the material carbon footprint assessment, no material waste was assumed, which is not representative of reality. Secondly, there was no available data for the specific building component for the triple glazing and added solar shading cases, meaning the carbon footprint was based merely on the material use. This might have led to an underestimation of the carbon footprint of these two alternatives, since carbon footprint associated with the production and transportation of the component is excluded, as well as the impact from any other materials used, e.g., for mounting. However, the assessments of carbon footprint associated with building materials and components are still under development, and the results are in accordance with the climate declaration legislation currently in practice.

The results of the maximum temperature during peak conditions and the peak cooling demand are contradictory for the natural ventilation case, since the reduction potential in peak cooling demand is small or negative whilst the reduction potential for maximum indoor air temperature during hot days is large. This is likely due to the modelling limitations introduced in section 2.2.6, suggesting that when simulating peak cooling, the opening of windows occur when the outside air temperature is warmer than the inside air temperature, leading to a rapid warming effect. This could be avoided by opening windows during the night to precool the space and consequently reduce the peak cooling, or by keeping windows closed during the day to theoretically achieve the same peak cooling demand as in the renovated case. However, manually operated natural ventilation will perform inconsistently due to the dependence on occupancy behaviour. For instance, residents may not occupy the space at optimal hours to control the opening and closing of windows or have the desired knowledge to optimally control the opening and closing of windows. Other aspects that suggest an inconsistent performance of natural ventilation implemented on a larger scale is for instance the risk of compromised air quality, noise and safety. Considering the many examples of limiting factors to an optimal implementation of natural ventilation controlled manually the inconsistent results is still relevant for the comparison of passive cooling measures, and the discrepancy in results illustrates the importance of an informed implementation of natural ventilation.

Due to the identified modelling limitations of the natural ventilation case and considering that an increase in peak cooling demand due to the use of natural ventilation is contradictory to previous research, the natural ventilation option is estimated to be one of the most efficient cases also during peak conditions in accordance with the maximum temperature simulation results. Moreover, if natural ventilation is not an available option to the residents during night-time due to for example safety or noise, the implementation of other adaptation measures becomes increasingly important in a future climate scenario to sustain thermal performance.

For the case under study as for a large number of buildings to retrofit, assumptions are needed for the energy model in case of unavailable measured data. For example, infiltration rate was estimated and then calibrated though comparison to a reference case. According to the building owner, the infiltration rate varies a lot between individual apartments, which makes an estimation of an average difficult, however after the calibration the applied infiltration rate is clearly within the span of measured infiltration rates in flats of similar building years. Moreover, any calculated U-value for the constructions could deviate from the current building performance, especially since the building has been exposed to different weather conditions for over 50 years. The window construction is specified as a simplified component in the energy model to be more broadly representative of different options, however, this could impact the results since no material layers are specified and the heat exchange calculations in the simulation engine therefore could differ depending on type of window frame, glass pane and any gas that could be used for insulation. The extra insulation in the wall has been added into the existing insulation layer, i.e., the middle of the wall, whilst in real life the insulation would be placed either on the interior or the exterior of the existing wall. This is a theoretical simplification to keep the surface material properties of the base case and not present a case that is affected by a particular type of construction. Due to lack of measured weather data for the location of the case study and reference building, the model validation options were limited. A calibration of the infiltration rate was made to fit as closely as possible to the real case, which was within 15 % variation of the annual heating load, however, future studies should aim to monitor the performance of interventions by measuring also indoor and outdoor temperature together with heating and cooling consumption.

According to the results, the solar shading case is a rather inefficient option, at least in comparison with natural ventilation or the implementation of triple glazing. However, the efficiency of solar shading largely depends on the design and placement. Although it is outside the scope of this study, the solar shading alternative might have performed better if a solar shading design optimisation was performed. For instance, the current type and placement does not effectively reduce the solar radiation when the sun is at a low angle, i.e., during morning or afternoon hours. The solar shading could also be optimised by using a seasonally variable option, to eliminate the increased heating demand.

Finally, the uncertainties regarding the projected climate data are addressed. There are large uncertainties in climate models, such as the extent of future GHG accumulation, the climate's response to GHG accumulation and the condensation of data to representative climate models, implying that results based on climate data projection should not be considered as definite but rather be viewed as an indicator for future trends. Furthermore, since the results are based on Typical Meteorological Year, potential peak and annual cooling energy demand for unusually hot years or heat waves are disregarded. If there is a heatwave, outdoor air temperatures are likely to rise above the maximum temperature of the data used in this study, which could particularly affect the results regarding energy performance during peak conditions. Further research is recommended to assess energy performance and indoor thermal performance during extreme weather conditions. Additionally, this study did not assess the coupling of selected compatible measures and did not include active cooling measures as well as the potential effect of urban microclimate. A further exploration of different combinations of measures is recommended as a development of the study.

5. Conclusions

This study assessed the carbon efficiency of passive cooling measures by exploring potential synergies between cooling demand reduction and carbon footprint in building renovation processes. Natural ventilation measures show a significant synergy between low carbon footprint and high potential of annual cooling demand reduction and maximum temperature reduction during peak conditions, as the option has no carbon footprint. However, the implementation heavily affects the cooling demand reduction potential of the measure and if correct implementation cannot be ensured, alternative adaptation measures should be considered. When accounting for the carbon footprint and cooling demand reduction potential, triple glazing and solar shading proved to be among the most efficient solutions. The study also found that combining multiple passive cooling measures results in the highest cooling demand reduction for all climate scenarios and is the only option which keeps overheating below the 10 % threshold in 2050 for the RCP4.5 climate scenario, yet, since the option is associated with the largest carbon footprint due to the carbon footprint of materials used for the measure implementations, the carbon efficiency is low.

Overall, results showed that the carbon footprint and energy performance varied greatly between different passive measures, and that the integrated evaluation method has the potential to aid decision-making processes related to adapting existing buildings to climate change, to improve thermal performance whilst avoiding increased energy demand during the cooling period as well as increased carbon footprint. The study contributes with novel indicators to an integrated assessment method, through the combination of a climate and energy model with a carbon footprint assessment to evaluate the carbon efficiency of passive cooling renovation measures. By including carbon footprint in the assessment, the study suggests a broader perspective when considering climate change adaptation measures and demonstrates how integrative assessment methods can support decisions to synergically support decarbonisation while preparing buildings for a warmer climate.

CRediT authorship contribution statement

Hedda Egerlid: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Xinyue Wang:** Writing – review & editing, Supervision. **Liane Thuvander:** Writing – review & editing, Writing – original draft, Supervision. **Daniela Maiullari:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2025.115502.

Data availability

Data will be made available on request.

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