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# Modelling the effect of passive cooling measures on future energy needs for the Austrian building stock

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ABSTRACT

Driven by climate change, many studies project strong increases in space cooling demand in the coming decades. Passive cooling techniques showed promising results in regional-level models to counteract such increases but have hardly been investigated on a country-level. Therefore, we modelled the potential impact of selected representative concentration pathways (RCP) as well as passive cooling measures (shading, night ventilation) and sufficiency measures (higher indoor temperature) on the space cooling demand of the Austrian building stock. Assuming 100% technology saturation, cooling demand increased from 12 TWh to 19 TWh between 2017 and 2050 under RCP4.5 and 28 TWh under RCP8.5, with residential buildings accounting for the majority of this increase. Up to 60% of the energy demand increase was attributable to climate change. Ambitious implementation of the investigated measures reduced space cooling demand in 2050 by 68% to 73% and completely counteracted the increase in cooling demand. Shading proved particularly effective, reducing space cooling demand by roughly 11 TWh in 2050, followed by sufficiency measures (5 TWh) and night cooling (2.5 TWh). This shows that results from regional-level studies on the effectiveness of shading and night cooling for mitigating space cooling demand also upscale to a country-level in a temperate climate.

## 1. Introduction

Space cooling is the fastest growing form of energy use in buildings and is expected to have a significant share on the overall energy consumption in the near future [1]. Between 1990 and 2016, global energy consumption for space cooling more than tripled and already accounted for over 2020 TWh (6%) of final energy demand in buildings with a 3% annual rise over the last 30 years and no signs for a reversal of this trend [1]. Looking at the European building stock, Werner [2] estimated an annual cooling demand (consumption) of over 1100 TWh per year for the entire EU-27 + UK, considering a 100% technology saturation and Kranzl et al. [3] projected an increase in cooling demand of at least 16% until 2030 compared to 2020 in EU-27. Magnitudes of increases differ quite a lot between individual countries though. For example, Asimakopoulos et al. [4] projected an increase of cooling energy needs in Greece of up to 250% until 2100. In Swiss service sector buildings, Li et al. [5] projected an increase in cooling demand (consumption) of 400% up to 600% by 2050. In the German building sector, Olonscheck et al. [6] found an increase of cooling energy demand (consumption) of up to 235% until 2060 and Berger et al. [7] found an increase between 28% and 98% until 2050 in Austrian office buildings. Such increases are especially pronounced in urban environments, where the used materials and structure enhance summer temperatures, leading to so-called urban heat islands and increasing the cooling demand by a significant amount [8]. In this context, the implementation of nature-based solutions (NbS, e.g. trees for shading, green facades/roofs for indoor cooling) are gaining importance and attention [42].While climate change is probably one of the main drivers of increasing cooling demand, Thibaut & Delmastro [9] also described higher diffusion rates of technologies resulting from higher affordability as contributors and Silva et al. [10] mentioned higher window-to-wall ratio, higher thermal insulation and increased air-tightness in buildings as additional causes of rising cooling needs as well. Unless the needed energy is provided through renewable energy sources, these increases in cooling demand and the resulting use of

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cooling devices will amplify anthropogenic climate change.

### 1.1. The role of passive cooling

Well-designed passive cooling methods could greatly reduce space cooling demand [10], or even diminish it in some regions [11]. However, many passive cooling methods require either substantial construction measures, are suited best for either arid or humid climates, or suffer from other constraints, making a widespread use in Europe difficult [12–14]. Especially night ventilation and shading are often subjects of research, probably due to their relatively easy implementation but also high saving potentials. For example Kuczyński et al. [15] found a decrease of indoor temperature by 6.3 K during night and 7.4 K during daylight in a temperate climate building when combining night ventilation and external shading with thermal mass. Taleb [16] tested the effectiveness of numerous passive cooling measures for reducing the cooling demand in buildings and identified natural ventilation, shading and double glazing of windows as highest potential measures for demand reduction in buildings in hot arid climates. Zwiehoff [17] reported similar results for an average single-family house in a temperate climate.

Effectiveness of night time ventilation highly depends on regional conditions, being much more effective in the north than in the south [18], but when combined with external shading, it is still able to significantly reduce energy demand and increase thermal comfort in Mediterranean climates as well [19]. However, this effectiveness for central and southern regions might diminish in the future due to changing climate conditions [20]. Effectiveness of shading devices highly depends on several factors like location, louver inclination angle, or window area. In regions with lower solar radiance and ambient temperature, such devices could even lead to an increase of total energy demand if used all year long [21]. But at least in Europe we are still lacking literature on the energy saving potential of passive cooling measures on a national level as most studies focused on individual buildings or regions. Indications that results for single buildings may scale up on higher levels came from Silva et al. [10], who modelled passive cooling measures for a representation of the Swiss residential building stock and found a saving potential of shading and ventilation measures of 84% until 2050. Still, more studies are needed to verify those results and see if they also apply to other regions while utilizing other methods as well.

### 1.2. Current study

The goal of this paper is to extend those results to the Austrian building stock and assess the climate change related increase of space cooling energy demand until 2050 and the respective saving potential of passive cooling and sufficiency measures. Literature confirms shading, night ventilation, and glazing as effective measures to reduce cooling demand. As double glazing is oftentimes already implemented as a measure for heating demand reduction, the focus of this study has been on shading and night ventilation in addition to increasing indoor set temperature. Utilizing the Invert model [22], we simulated the cooling needs of the Austrian building stock until 2050. Effects of climate change is simulated using representative concentration pathway (RCP) 4.5 and 8.5 climate scenarios, selecting climatic years according to specific cooling related criteria. Assuming that 100% of cooling energy needs are met as a baseline variant and without addressing the decision calculus of building owners, the evolution of the building stock under exogenous assumptions are simulated, broadly consistent with the goal of decarbonization in terms of energy demand, such as a thermal renovation rate of 2.5% [23].

## 2. Methods

### 2.1. Building stock model

We utilized the Invert building stock model, which follows a dynamic bottom-up approach and considers parameters such as economic incentives, regulatory instruments or technological progress to simulate the impact of technology choice on future energy demand and energy consumption for space heating, cooling and hot water consumption for various scenarios and countries [22,24]. The Invert model uses a quasi-steady-state approach for its energy need calculations where the same indoor temperature is used for all relevant components (e.g. air, wall surface temperature, indoor surface temperature of windows) as well as a monthly energy balance approach. This approach differs from the more commonly used hourly balance approach but allows us to simulate the entire building stock of a given country, which would otherwise require significant computation time and power. Zangheri et al. [25] assessed the models validity by modelling heating and cooling energy needs of different buildings and climate zones (including Vienna) using the hourly EnergyPlus model and the monthly Invert model. While the Invert model tended to slightly underestimate cooling energy needs in temperate climate zones compared to EnergyPlus, no systematic errors were observed, indicating that deviations likely result from differing building and building-usage formulations as well as the complexity of the models and the parameters (e.g. climate data, solar irradiance, g-values, shading and ventilation dynamics) [22,25]. Further analyses conducted for this study showed minor deviations in the heat gains and heat losses between Invert and EnergyPlus for single family homes (Fig. S1) as well as multi-family homes (Fig. S2). These deviations cancelled each other out though, leading to very similar results in both Invert and EnergyPlus and underlining the implication that deviations between the models may stem from differing definitions of energy transmittance parameters and strengthening the validity of our monthly balance approach. A detailed comparison of model parameter outputs can be found in Table S1.

### 2.2. Building stock data

Building stock data is built upon the 2011 registry census conducted by Statistik Austria [26,27]. Data on energy carriers and number of buildings were updated with the energy-related Austrian micro census 2016 [28]. Detailed descriptions regarding building stock specifications and assumptions concerning the development of the building stock can be found in [22,29]. A summary of major building stock parameters can be found in Table S2 and a summary of cooling demand including and excluding internal gains can be found in Table S3. We uploaded a csv-file with even more detailed information regarding our baseline building stock data to *open science framework* under [30]. Energy demand is calibrated by national energy statistics [31] and cooling demand is calculated according to [32].

### 2.3. Climate scenarios

We used numerical global climate models (GCMs) to estimate future climate conditions incorporating all components of the climate system through coupled “sub-models” (e.g. ocean model, atmospheric model, ice sheet model, etc.). Therefore, changes in one component directly affect all others as well, which is crucial for climate projections as provided through the coupled model intercomparison project CMIP [33]. We applied regional climate models (RCMs) which can drastically decrease the coarse spatial and temporal resolutions of GCMs of roughly 100 km and 6 h to only 1 km and 1 h. Thereby, regional specifics such as land use or topography as well as physical processes of smaller scales (e.g. turbulence, convection,…) are better covered. As climate scenarios, we used two RCP scenarios, which cover different evolutions of greenhouse gas emissions and land use changes until 2100 [34]. RCP4.5 represents an increased radiative forcing of 4.5 W/m$^2$ until 2100 and corresponds to a scenario with relatively successful global climate policies where emissions peak around 2040 [35]. RCP8.5 represents a future with steadily rising emissions due to very limited climate mitigation measures, which results in a radiative forcing of 8.5 W/m2 by 2100 [36,37].

Climate data was simulated using the RCM RAMO [38], which has been bias corrected based on Vrac et al. [39]. This model is part of the clim4energy dataset and based on the EC-Earth (GCM) parent model, generated within the EURO-CORDEX set-up [40] with a spatial and temporal resolution of 12 km and 3 h. As climate model years rather reflect general climatic conditions (e.g. position of the sun, CO$_2$ emissions, etc.) instead of an explicit calendar year, we used the most representative climate data within a ±5 year time period of the reference year (e.g. 2020 = 2016 – 2025) as observation year. For both the RCP4.5 and RCP8.5 scenario, we modelled daily temperatures for all Austrian municipalities. Weighted monthly mean temperatures were then used as model input for Invert. Distribution of weighted weekly and monthly temperatures for summer months can be seen in Fig. 1 (for the whole year see Fig. S3).

Additionally, cooling degree days (CDDs) were extracted from the weighted moving average temperature of Austria with the population of each municipality as weight. The number of CDDs was calculated using the definition from Eurostat [41], according to which a mean daily temperature threshold of 24 °C is set. When the mean temperature of a given day exceeds this threshold, CDDs are calculated according to Eq.1.

$$CDDs = \begin{cases} \sum_i T_m^i - 21^\circ C, if T_m^i \geq 24^\circ C, \quad where\ T_m^i = mean\ air\ temperature\ of\ day\ i \\ 0,\ otherwise \end{cases} \tag{1}$$

When comparing CDDs (Table S4) and weighted mean temperatures (Table S5, Fig. S4) between all municipalities and only those with a population >20.000 people (cities), the latter shows consistently higher

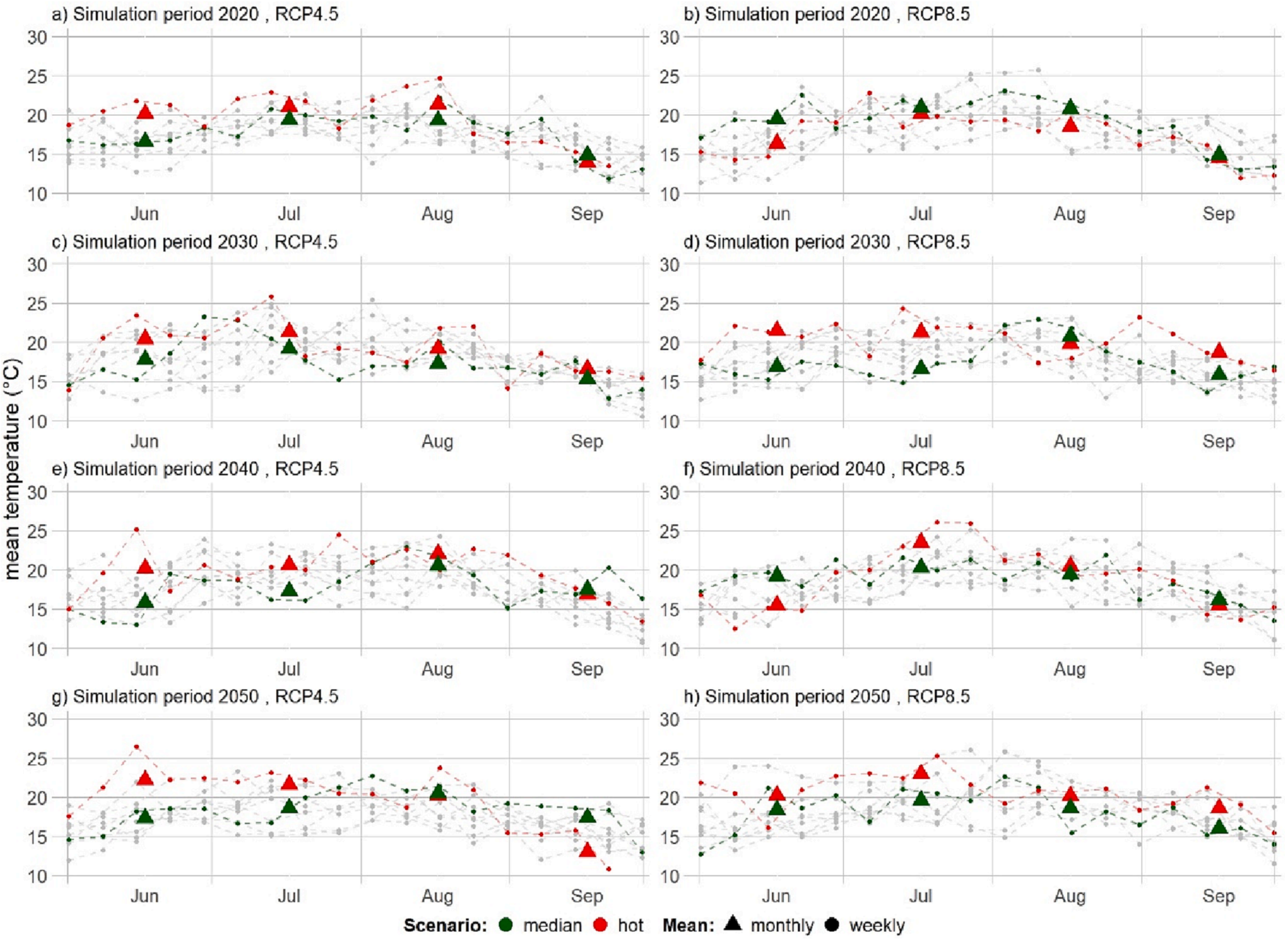

**Fig. 1.** Weekly mean temperatures (dashed lines with dots) from June to September in all Austrian municipalities for each year of each simulation period and climate scenario and monthly mean temperatures (triangles) for each selected hot and median year for each simulation period and climate scenario. Mean values were weighted by population of the respective municipality. Red line indicates the selected year for the 'Hot' scenario, green line indicates the selected year for the 'Median' scenario. For the selection of years for the median and hot scenario, rolling means were used. Thus, the average weekly temperatures not necessarily reflect those scenario selections. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Selected years for each climate scenario and simulation period along with the respective number of CDDs of all Austrian municipalities and the weighted average outdoor temperature during July and August as the most impactful months for space cooling.

| Simulation period (Simulation years) | RCP4.5 | | RCP8.5 | |
|---|---|---|---|---|
| | Median year (CDDs[1]/°C[2]) | Hot year (CDDs[1]/°C[2]) | Median year (CDDs[1]/°C[2]) | Hot year (CDDs[1]/°C[2]) |
| 2030 (2026–2035) | 2030 (47/17.5) | 2035 (110/19.5) | 2027 (52/17.9) | 2026 (137/19.8) |
| 2040 (2036–2045) | 2038 (54/18.2) | 2042 (127/20.5) | 2042 (56/19.1) | 2044 (133/21.2) |
| 2050 (2046–2055) | 2055 (42/19.0) | 2054 (173/20.1) | 2048 (58/18.4) | 2049 (140/20.7) |

[1] Cooling Degree Days (CDDs) of all Austrian municipalities for the respective year.
[2] Weighted average outdoor temperature for all Austrian municipalities during July and August in °C.

CDDs and temperatures, although the spatial resolution (12.5 km) is only sufficient to capture Vienna and Graz properly. Still, this shows the impact of the built environment which would probably be even more prominent if other Austrian cities were sufficiently captured as well. As this was not subject of the current study, we did not investigate further on this matter.

Using calculated CDDs, we identified a reference and a worst-case condition for each RCP scenario and observation year. The reference condition (“Median” scenario) corresponds to the year whose CDDs represent the median of the annual CDDs of the respective ten-year period. The worst-case condition (“Hot” scenario) corresponds to the year with the highest number of CDDs in any 7-day period. Details on selected observation years are listed in Table 1.

### 2.4. *Passive cooling and sufficiency measures*

We implemented shading of windows based on a top-down approach as specified in [32]. This Austrian energy needs calculation norm does not directly consider specific shading schedules but provides empirical parameters which specify the typical reduction of solar radiation passing the shading device, depending on the shading device type (e.g. external louvres or blindes, internal solar reflection foils, etc.) and the activation scheme: manually or time-based activation versus radiation controlled. Assuming vertical windows, shading efficiency is set to 63.2% for all directions (based on [32], p.40ff). This shading efficiency is derived on the assumption that radiation-controlled external louvres are used. Thus, we consider the best shading option provided by the applied calculation procedure. The share of window area that use some kind of shading device varies between scenarios (see Table 2) and is assumed to be equal for all directions. Further we assume a g-value of 0.7, which is at the higher spectrum of light permissibility of windows currently installed in Austria (nowadays, windows often come with a g-value around 0.4 – 0.55 but can even be as low as 0.25). Our scenario thus represents a rather pessimistic case without much solar protection in windows. Higher shading efficiency could not only be accomplished through ambitious diffusion of advanced shading equipment (radiation controlled external shading devices) but also through windows with lower g-values (e.g. triple glazed windows or solar radiation blocking layers), both of which require substantial alterations of buildings. Therefore, we tied shading measures to a renovation rate of 2.5%. Night cooling describes the cooling of the building by increased air circulation during night (e.g. opening windows). Our baseline air exchange rate of 0.5ACH in residential buildings rather reflects natural ventilation including air infiltration. The temperature measure describes higher indoor temperatures and accordingly decreased use of active cooling devices (e.g. adapted clothing habits). Both the temperature and night ventilation measure were implemented instantly and for the entire building stock as they mostly require behavioural changes.

Parameters for these three measures were varied in three distinct scenarios (High, Medium, Low). The ‘High’ scenario describes a high cooling demand scenario with minor or no implementation of passive cooling measures, while the ‘Low’ scenario describes a low cooling demand scenario with an ambitious implementation of passive cooling and sufficiency measures. The ‘Medium’ scenario describes an intermediate scenario. The three variants are simulated for all four climate scenarios (for scenario parameters see Table 2).

### 2.5. *Effects of individual passive measures*

In addition to the bundled measures scenario described above, we considered an individual measure scenario (IMS), in which the individual impact of all three passive cooling measures and of the climate change scenarios is assessed. For this scenario, extensive shading, as well as night cooling and a high indoor temperature according to the low variant in the combined measures scenario is assumed (see Table 2). To account for interactions between measures, we calculated the difference in energy demand between various simulation permutations where all measures are systematically in- and excluded according to Eq. (2).

$$E_{impact\ i} = \frac{1}{3}\Big((E_i - E_{Baseline})_{excl.\ climate} + (E_i - E_{Baseline})_{incl.\ climate} + (E_{Total} - E_{Totalexcl.\ i})_{incl.\ climate}\Big)$$

$$i \cdots measure \quad i \in \{shading,\ temperature,\ night\ ventilation\} \tag{2}$$

$E \cdots$*Cooling energy needs of a given scenario*

E.g. for shading the permutations are: constant climate and no measures vs. constant climate and shading implemented, climate change scenario and no measures vs. climate change scenario and shading implemented, and climate change scenario and all measures implemented vs. climate change scenario and all measures except shading implemented. To extract main effects, the mean of the difference

**Table 2**
Parameters for shading, night cooling and indoor temperature as well as the used climate scenario for each High, Medium, and Low model scenario. The parameters for the Baseline are equal to the ones used in the high scenarios but with constant climate. The parameters of the individual measure scenario (IMS) are equal to those used in the low scenario but with RCP8.5 – Hot as climate scenario.

| | High/Baseline | Medium | Low/IMS |
|---|---|---|---|
| Shading[(a)] | 40% | 50% | 80% |
| Night cooling Residential buildings (1/h) | 0,5 | 1,5 | 2,5 |
| Night cooling non – residential buildings (1/h) | 1,2 | 1,5 | 2 |
| Temperature office buildings | 22 °C | 25 °C | 26 °C |
| Temperature non-office buildings | 24 °C | 25 °C | 26 °C |
| Climate | RCP scenario/Constant climate | RCP scenario | RCP scenario/RCP8.5 – Hot |

Note: parameter definitions for shading, night cooling and temperature are given in section 2.3. (a) only applies to renovated buildings.

between those three pairs was calculated. Main effects of climate change scenarios were calculated as the difference between a constant climate scenario with no measures and a climate change scenario with no measures implemented. A different calculation approach for the effect of climate change was used as we aimed to estimate these effects without additional passive cooling measures. This process was repeated for all measures and all climate change scenarios.

## 3. Results & discussion

### *3.1. Effects of bundled measures*

In the modelled period, space cooling demand increases significantly from close to 12 TWh in 2017 (baseline) to over 19 TWh (RCP8.5 – median) up to 28 TWh (RCP8.5 – hot) in 2050 if only minor passive measures are implemented (High scenario). More ambitious measures (Low scenario) could reduce this cooling demand by roughly 70% to 6 TWh in the RCP8.5 – median scenario and to approximately 9 TWh in the RCP8.5 – Hot scenario, which would even lead to a space cooling demand that is 25% lower than the baseline 2017 demand (see Fig. 2). Similarly, the RCP4.5 Hot scenario shows a 68% saving from 25 TWh to 8 TWh and the RCP4.5 Median scenario even shows a 73% saving from 22 TWh to 6 TWh. Thus, a significant influence of climate change on the effect of the measures themselves does not seem to exist. In residential buildings alone, our results suggest a saving potential in cooling demand of 82% until 2050. This result is in line with those of Silva et al. [10] who found a saving potential of 84% in the Swiss residential building sector in a similar climate scenario, but only included shading and night cooling as passive cooling measures.

Noticeably, we observed a decrease in cooling demand for the RCP8.5 – Median scenario between 2040 and 2050 and generally lower cooling demand than in the RCP4.5 scenarios. This is quite surprising as the lowest cooling demand would have been expected in the more optimistic RCP4.5 – Median scenario. As seen in Fig. 1, the average summer temperature (which is the most relevant time period for space cooling) for the model period 2050 is lower for RCP8.5 – Median than for the other scenarios and also lower compared to the 2040 period of the same scenario. The same trend cannot be seen for the CDDs, indicating that our climate scenario modelled many days slightly above the threshold for CDDs described in Eq. (1), leading to a high number of CDDs but still comparably low overall temperature.

Looking at individual building categories, the majority of the cooling demand in the High scenario stems from residential buildings (61% – 64% depending on the climate scenario, see Fig. 3). Moreover, single-family homes (SFH) required more cooling energy than multi-family homes (MFH) and are a bit overrepresented considering their share in total floor area in the building stock whereas MFHs are slightly underrepresented (Table S6). In our model, residential buildings also profit most from passive measures as their share in cooling demand decreases significantly while the share for most other building categories increases slightly. Healthcare buildings (e.g. hospitals) profited less from passive measures as their share on cooling demand doubles to 24% from the High to the Low scenario, even though making up less than 7% of the total floor area of the building stock. These findings highlight the importance of residential buildings and especially SFH in future energy planning and also the importance to increase energy efficiency in healthcare buildings.

### *3.2. Impact of individual measures*

The analysis of individual measures shows an increase in space cooling energy demand to around 28 TWh in 2050 in the worst case

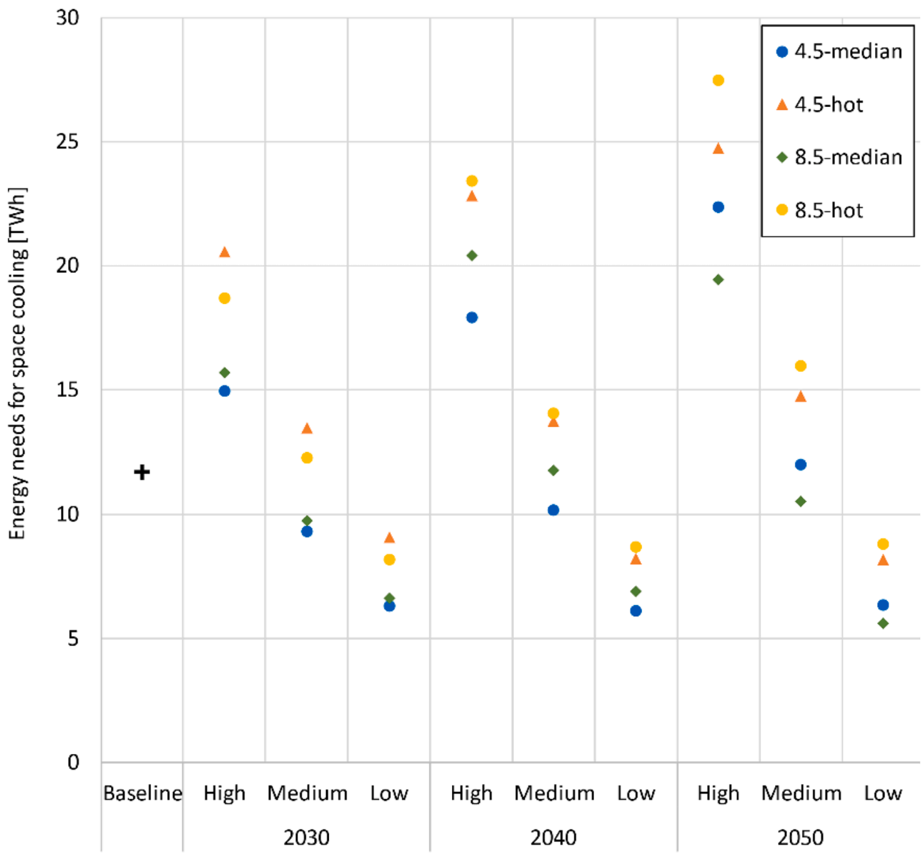

**Fig. 2.** Energy needs for space cooling in various passive measures scenarios as well as no increase in passive cooling measures. Comparison of all RCP climate change scenarios.

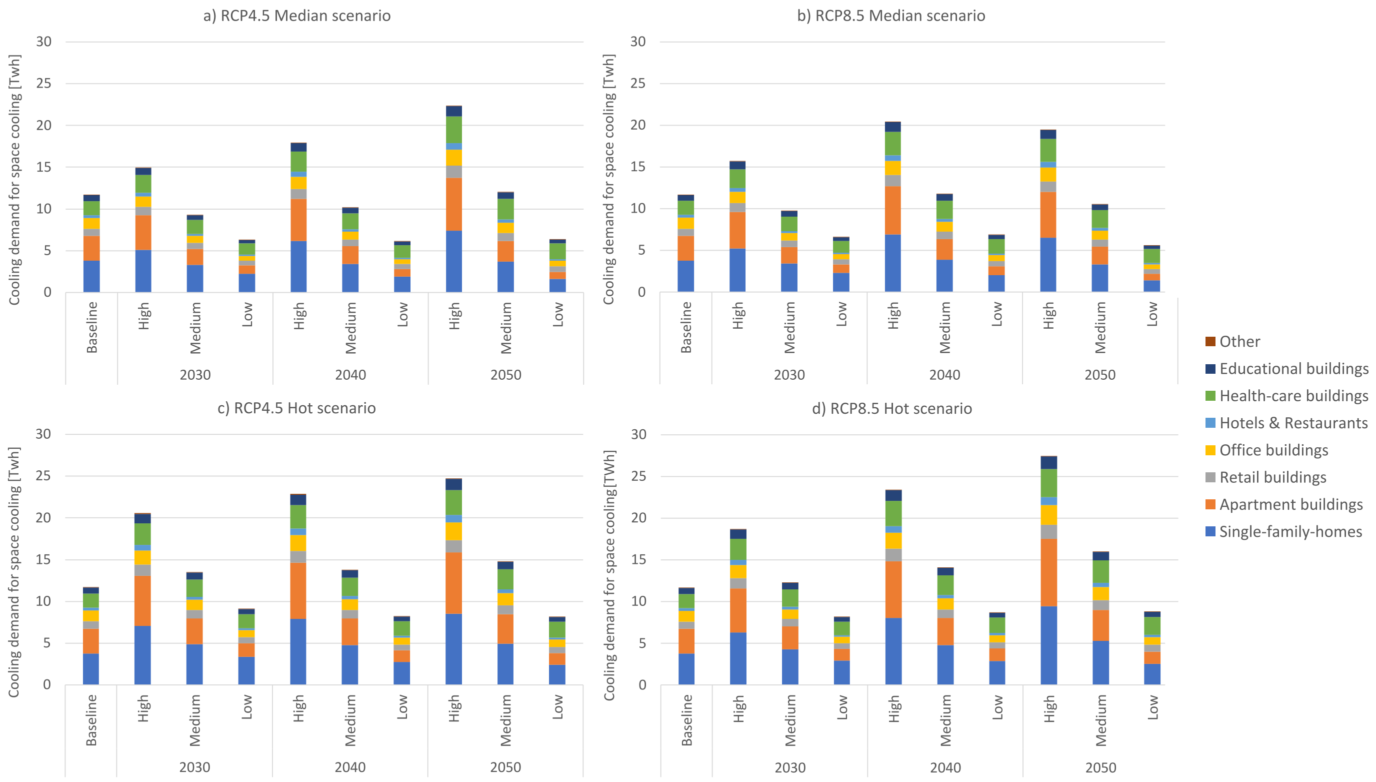

**Fig. 3.** Energy needs for space cooling in 2050 by building category for the (a) RCP4.5 median climate change scenario, the (b) RCP8.5 median climate change scenario, the (c) RCP4.5 hot climate change scenario and the (d) RCP8.5 hot climate change scenario.

RCP8.5 – Hot scenario, consistent with the results from the combined measures scenario. 60% of the increase since 2017 and 30% of the total space cooling demand (10 TWh) is attributable to climate change (Fig. 4). Increases in the base cooling demand can be explained by higher diffusion rates of active technologies and renovation measures disadvantageous for space cooling [9,10]. As expected, the impact of our climate models (together with the overall cooling demand) decreases for the more optimistic climate models (e.g. 20% in RCP4.5 – Median). Main effects of passive cooling measures are relatively stable between scenarios, indicating independence of our measures from our climate models. In the long term, shading provides the greatest savings potential between 10 and 12 TWh in 2050 against just over 2.5 TWh for night cooling and just over 5 TWh for increased indoor temperature. It is striking that the effects of shading increase by over 170% from 2030 to 2050, underlining the importance of consideration of shading for future renovation measures. It should also be noted though, that shading measures could also be linked e.g. to window replacements or be carried out as separate measure, which could lead to faster diffusion of shading devices compared to the overall renovation rate. The effects of night cooling and higher indoor temperature remain almost unchanged over observation years due to our instant implementation of the measures for the entire building stock. This also means, that our saving estimates for those measures must be considered as upper bound of theoretical potentials. Real savings from these measures will probably be quite a bit lower especially for night cooling which suffers from additional barriers and investments from for example traffic noise, or requirements for control and security systems to open windows. Still, these results show a very high short-term saving potential that, in theory, could be utilized instantly.

Interestingly, the lowest cooling energy demand in 2050 is observed in the RCP8.5 – Median scenario instead of the more optimistic RCP4.5 scenarios. As discussed above already, this might be due to a lower average temperature over the summer months (Table 2) in the 2050 period. This is not so unlikely as the impact of the different emission scenarios on the local temperature are quite similar until 2050 due to the inertia of the climate system. Furthermore, RCP8.5 – Median has an even larger total cooling demand for the observation year 2040 than 2050 due to a three times higher effect of climate change, even though the number of CDDs and the maximum temperature is higher in 2050. One potential explanation stems from our climate data. Our model showed higher mean temperatures during summer months (June – September) for the simulation period 2040 (18.1 °C) than 2030 (17.4 °C) and 2050 (17.5 °C) in RCP8.5. This can result from prolonged stationary weather conditions or less intensive heat waves that are not uncommon for climate models. In our other scenarios (RCP4.5 – Hot/Median, RCP8.5 – Hot), average summer temperatures (which are the main driver of cooling demand) are steadily rising over simulation periods, resulting in the increasing effect of climate change. However, it remains uncertain to us if the increase in mean summer temperatures of 0.6 °C can solely explain tripling effects of climate change on cooling demand. Our method to extract the main effects also led to some averaging errors (see Fig. 4). The errors are negligible in size though and don't show a clear pattern, indicating that they are random noise.

## 4. Conclusion

Some drivers, such as an increasing spread of active cooling technologies or climate change lead to increasing cooling energy demand. Passive measures can be implemented on the building side to counteract these drivers. To our knowledge, this is the first study that modelled the effects of passive cooling and sufficiency measures on cooling needs for the entire Austria building stock. We utilized the Invert model describing the current building stock and possible future scenarios in a disaggregated manner. Climate models were calculated using the regional atmospheric climate model RACMO [38], representing the climate scenarios RCP4.5 and RCP8.5, from which we derived a *hot* and *median* case for every 10 year period until 2050 and investigated the effects of reduced solar gains by shading, higher air exchange rates by

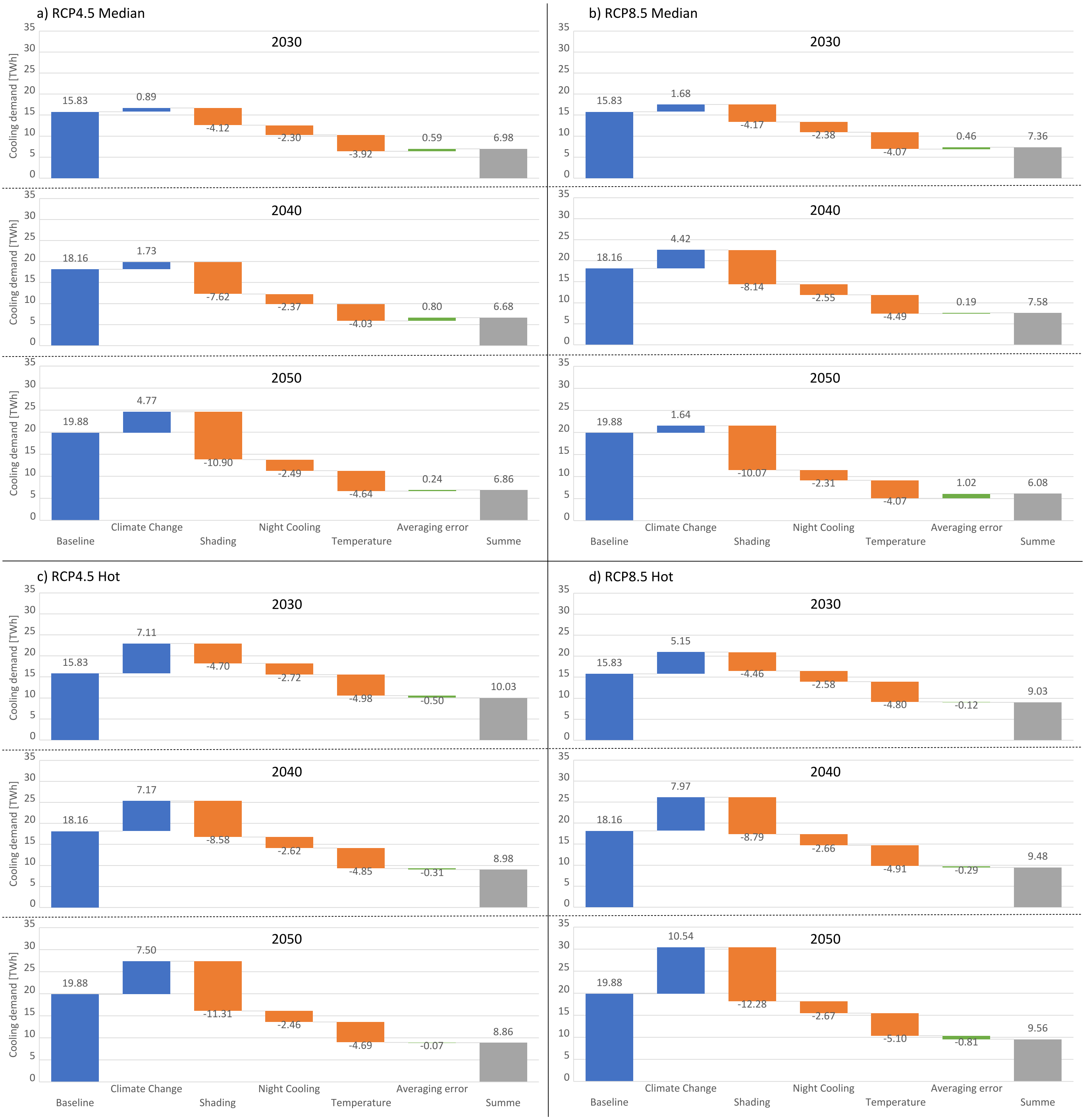

**Fig. 4.** Influence of climate change, passive measures and interaction of these on the cooling demand for space cooling in the scenario (a) RCP4.5 – Median, (b) RCP8.5 – Median, (c) RCP4.5 – Hot and and (d) RCP8.5 – Hot.

night cooling and decreased active cooling by higher indoor temperatures.

- Under the assumption of 100% technology saturation, our results suggest an increase of cooling demand in the Austrian building stock between 150% and 230% until 2050 if only minor passive cooling measures are implemented. Ambitious passive cooling and sufficiency measures could reduce demand by 68% to 73%, resulting in a stagnation of the energy demand for space cooling between 2030 and 2050.
- Residential buildings were responsible for 64% of the cooling demand in buildings. Their cooling demand could be reduced by up to 82% in ambitious scenarios which is in line with other literature investigating passive cooling measures in comparable climates and building stocks (e.g. [10]). These findings underline the importance of the residential building sector for future energy transition and policy considerations.
- Shading proved to be particularly useful, reducing cooling energy demand by up to 12 TWh in the long term and thus should be considered in future renovation measures. We consider the implementation of shading devices on 80% of windows in the high

efficiency scenario through ambitious, but also realistic. Our light permissibility assumptions were rather pessimistic, meaning that real savings could be even higher.

- While the effect for night cooling and increased indoor temperatures is much smaller than for shading, those measures still showed a maximum theoretical saving potential of 2.5 TWh (night cooling) and 5 TWh (higher indoor temperature) and could prove valuable as they seldom require any investments but could be implemented instantly through behavioural adaptations only. Especially for night cooling, effects could diminish for other climatic regions though.
- Other passive measures can be implemented as well but were not investigated in this paper (e.g. other surface and building materials, green roofs, urban green spaces). However, the effect of these NbS is not instantly available as the green infrastructure needs time to develop.

## 5. Limitations

We used a monthly-balance approach for energy modelling which is often less accurate than the more common hourly approach used in EnergyPlus for example. Still, we consider the deviations between the Invert model and hourly building simulation approaches presented above sufficiently small to draw valuable conclusions from it.

Our results' applicability to regions outside central Europe is also uncertain as the effectiveness of passive measures can depend on climatic conditions. More studies considering the entire building stock of other countries and especially other climatic regions should follow. Effectiveness may even change with progressing climate change, calling for studies evaluating passive cooling measures under future climate conditions in specific regions. Other passive cooling methods like cool roofs, thermal mass or nature based solutions may appear to be more efficient under such considerations but were not considered in this study.

## CRediT authorship contribution statement

**Lukas Mayrhofer:** first author, model set-up, formal analysis, writing. **Andreas Müller:** conceptualization, model set-up, model comparison, formal analysis, writing – model description. **Marianne Bügelmayer-Blaschek:** preparing climate change scenarios, writing – description of climate scenarios. **Malla Aadit:** literature screening, result comparisons, writing - Introduction. **Lukas Kranzl:** corresponding author, conceptualization, formal analysis, writing.

## 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.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2023.113333.

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