Analysis of the predicted effect of passive climate adaptation measures on energy demand for cooling and heating in a residential building

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Abstract:

Both new and existing buildings need to be adapted to climate change, in order to keep providing a comfortable and healthy indoor climate. Preferably, the adaptation measures applied at the building level scale do not require additional energy (i.e. passive measures). Previous studies showed that passive climate change adaptation measures can have a positive effect on thermal comfort in summer and its shoulder seasons in non-air-conditioned residential buildings. In this paper, the effect of these passive climate adaptation measures – applied at building component level – on the cooling and heating energy demand of a terraced house is analyzed using building energy simulations. It is shown that for this particular case the required cooling energy can be limited to a large extent (59-74%) when external solar shading or additional natural ventilation is applied. In addition, it is shown that for a well-insulated terraced house the energy cost for heating is not strongly affected by the application of passive climate change adaptation measures.

Keywords: building energy simulation; climate change adaptation measures; dwellings; heating and cooling energy; building performance; future climate

Highlights

- Influence of passive climate adaptation measures on cooling/heating demand.
- Analysis for both an average current climate and an estimated future climate.
- Building energy simulations for a terraced house with different insulation values.
- The required cooling energy can be limited to a large extent by passive measures.
- External solar shading and additional natural ventilation show best performance.

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1. Introduction

The main conclusions in the reports by the Intergovernmental Panel on Climate Change (IPCC) that have been published in the last decade are clear: climate change is unmistakably occurring. In the latest report by the IPCC it is stated, for example, that the global average land and ocean surface temperature has increased with 0.85°C (0.65-1.06°C) from 1880-2012 [1]. In addition, it is reported that it is 'likely' that the frequency of heat waves has increased in large parts of Europe, Asia and Australia. Furthermore, in the Northern Hemisphere the 30-year period from 1983-2012 was 'likely' the warmest period in the last 1400 years [1].

In the Netherlands, climate change will most likely lead to a continuous rise of temperatures, resulting in milder winters and hotter summers with more heat waves during the summer [2]. While the occurrence of mild winters will decrease the energy demand for heating, the increasing number of hot summers can lead to problems regarding thermal comfort and health of building occupants, and to an increase of energy use in buildings with active cooling systems (e.g. [3-7]). If active cooling is applied in order to prevent people against excessive exposure to high indoor air temperatures, it is important to minimize the energy use for this purpose as much as possible. Otherwise, the use of active cooling systems will result in an increase in the use of fossil fuels, the emission of CO_2, and a further acceleration of climate change in the future. In a recent report on the impact of climate change on buildings it is stated that the global energy demand for air-conditioning in buildings is expected to increase from nearly 300 TWh in 2000 to 4000 TWh in 2050, if no additional mitigation policies are undertaken [8,9]. Maintaining a healthy and comfortable indoor environment without using excessive amounts of energy should be the goal when designing a new building, now and in the future. However, a too strong focus on only one of the aforementioned aspects might lead to a deterioration of the other aspect (e.g. [3]).

Although the majority of the residential buildings in the Netherlands and in many other North-Western European countries are typically neither equipped with an air-conditioning system, nor with other active cooling systems to reduce the indoor air temperature in hot periods [10,11], the presence of small air-conditioning systems to cool one or more rooms of a house appears to be growing [12-14]. In a EU report by Capros et al. [12] it is stated that the use of active cooling in residential buildings is limited in Europe, but will grow "at a fast pace" and will attain a share of almost 2% of the total energy use in residential buildings in Europe in 2030. Wu and Pett [13] reported that 10% of the non-domestic building floor area and 0.5% of the domestic building floor area in the UK was cooled in 2006. However, they also stated that the growth in the domestic sector will be the fastest, and that the carbon emissions from these additional cooling efforts will overweigh the reduction in carbon emissions due to a decrease in heating demand in the UK in the future due to the changing climate [13]. Finally, they mentioned that air-conditioning units are often purchased in periods of distress (e.g. during heat waves) and that afterwards the air-conditioning will be used whenever the temperature will rise, even when the temperatures are lower than the ones that caused the distress and initiated the purchase, which will lead to an excessive use of the cooling systems [13]. Aebischer et al. [14] indicated the growth of the energy demand for cooling in Europe, due to – among others – climate change, higher internal loads, application of large glass facades (i.e. higher solar heat gains), higher thermal insulation values, and an increase in thermal comfort standards and expectations (e.g. resulting from air-conditioned cars, trains and public spaces). As indicated also by Wu and Pett [13], in large parts of Europe (moderate climates) the cooling energy demand will be outweighed by a reduction in the heating demand [14]. However, the yearly total amount of CO_2 emission can increase, depending on the percentages of cooling and heating in a specific country, and on the CO_2 intensity of the heating fuels and electricity that are supplied to the buildings [14]. As indicated in the aforementioned publications, the application of (ad-hoc) energy-consuming measures to avoid indoor overheating should be stopped or at least limited, to avoid an increase of energy use and CO_2 emission in the built environment in the near future. Previous studies have shown that passive climate change adaptation measures can significantly reduce the number of overheating hours in – among others – residential buildings that are not equipped with air-conditioning or active cooling systems (e.g. [15-21]). Note that none of these studies mentioned here assessed the influence of passive climate change adaptation measures on the energy demand for cooling, when an active cooling system would be present.

In this study, the cooling and heating demand of a residential building are analyzed, after which the effect of a range of passive climate change adaptation measures is assessed with respect to both the energy demand for cooling and heating, and for the total energy demand. This study is performed for a typical Dutch terraced house. The simulations are conducted for an expected future climate year, and a selected number of simulations has been conducted for an "average" climate year. A passive measure is defined in this study as a measure which does not use energy once it has been implemented. The following passive climate change adaptation measures are analyzed in this paper: (i) increased thermal resistance; (ii) changed thermal capacity; (iii) increased short-wave reflectivity (albedo value); (iv) vegetation roofs; (v) solar shading; and (vi) additional natural ventilation (see Table 1). In addition, the

combined effect of several passive climate change adaptation measures is assessed. Dynamic thermal simulations using EnergyPlus [22] are performed to analyze the effect of the different measures on the yearly energy demand for heating and cooling.

The research was conducted within the Climate Proof Cities (CPC) research consortium, which was one of the research consortia investigating the climate vulnerability of urban areas and the development and effectiveness of climate change adaptation measures [21,23-35]. The methodology will be addressed in Section 2, after which the results of the dynamic thermal simulations will be presented in Section 3. Section 4, (discussion), Section 5 (conclusions), and Section 6 (future work) conclude this paper.

2. Methodology

Dynamic thermal simulations are performed with EnergyPlus to assess the performance of the different passive adaptation measures. EnergyPlus consists of three basic components: (1) a simulation manager, (2) a heat and mass balance simulation module, (3) a building systems simulation module [36]. The development of EnergyPlus is funded by the Department of Energy (DOE) of the US and has been validated extensively in the past (e.g. [37-40]). In addition, the authors have performed several successful comparisons of EnergyPlus results with data from the Building Energy Simulation Test (BESTEST). More background information on EnergyPlus and validation tests can be found in [22,36-42].

2.1. Building description

The building geometry of the terraced house is based on an example terraced house in the Netherlands as defined by Agentschap NL [43]. It has one zone for the living room (ground floor), one zone for the bedrooms (first floor), and a third zone, which consists of the attic. It is assumed that four occupants are present in the terraced house; two adults and two children. The simulations are conducted for four different orientations of the facade in which the entrance is situated (0°, 90°, 180°, 270°), enabling an assessment of the influence of window orientation in combination with solar radiation.

The ground plans and building facades are depicted in Figure 1. The three floors of the building each have a surface area of 45.5 m^2, and the total net indoor volume is about 348 m^3. Two sides of the building are exposed to the ambient conditions; adiabatic conditions are assumed for the two other sides that share an internal wall with adjacent terraced houses.

Residential buildings in the Netherlands are very often heavy-weight buildings, i.e. concrete and stone materials are used for the floors and both sides of the cavity walls. Therefore, the base case building is also a heavy-weight building. The insulation values of the base case building are in accordance with the building regulations in the Netherlands in 2012 [45]. In addition, simulations have been performed for a lower value of the thermal resistance of the building envelope, which corresponds to a building built in the 1970s (i.e. named RC04). These simulations are performed to assess the cooling and heating energy demand for older buildings compared to new buildings. Table 2 provides an overview of the construction details of the base case building, whereas Table 3 provides this information for the building from the 1970s. Note that the range of passive climate change adaptation measures is only applied for the base case building.

The building is conditioned using an all-air system with a heating coil and a direct expansion cooling coil. Note that an all-air system, and, as mentioned before, air-conditioning or active cooling systems are not commonly applied in residential buildings in the Netherlands, and also not in several other North-Western European countries [10,11]. However, the aim of this study is to provide an insight in the amount of energy that would be used, and thus could be saved, when residents do apply air-conditioning systems in their houses, either in the Netherlands, or other countries in a similar climate. No shading devices are present in the base case situation, which is currently common for newly built residential buildings in the Netherlands. The all-air system that is present ensures a constant ventilation flow rate of 0.7 dm^3/sm^2 [44]. The infiltration flow rate is set to 0.2 ACH [45]. Note that the adaptation measure regarding natural ventilation (NV) assumes that windows will be opened to allow ventilative cooling when the indoor temperature is higher than the outdoor temperature, which therefore results in an additional airflow on top of the basic ventilation flow rates as mentioned above.

Table 4 lists the air temperature heating setpoints (based on [46]), and the cooling setpoint is set to 24°C (based on e.g. [45]). Table 5 shows the indoor heat gains for the ground floor (living room) and first floor (bedrooms) (based on [45] and [47]).

2.2. Adaptation measures

The studied passive climate change adaptation measures are listed below. For more detailed information and a literature study on these measures the reader is referred to van Hooff et al. [21].

2.2.1. Thermal resistance

The prescribed thermal resistance (R_C value) for all closed parts of the building envelope should be at least $R_C =$ 3.5 m^2K/W in the Netherlands (U = 0.29 W/m^2K), according to the building code of 2012, and the U value (thermal transmittance) for the doors and windows should be U = 1.65 W/m^2K or lower [44]. As indicated in van Hooff et al. [21] and Aebischer et al. [14], an unwanted effect of increasing insulation levels of opaque and transparent parts of the building envelope during summer (warm days) is the fact that once a high indoor temperature is reached, for example due to solar radiation through the transparent parts (glass) of the building envelope or due to internal heat gains, it will also be maintained for a longer period than in the case of lower thermal resistances. In this study, the effect of two alternative values of the thermal resistance of the closed parts of the building envelope are analyzed: R_C = 5.0 m^2K/W (RC50) (U = 0.2 W/m^2K) and R_C = 6.5 m^2K/W (RC65) (U = 0.15 W/m^2K). Note that the energy demand for a building with low values of the thermal resistance is also calculated (RC04).

2.2.2. Thermal mass

The amount of available thermal mass varies for each building and depends on the material that has been used for the different building components. A distinction can be made between heavy-weight buildings (> 85 kg/m^2), and light-weight buildings (< 20 kg/m^2), referring to the amount of thermal mass that is available for thermal storage per visible surface area (either a wall, a floor or ceiling, adjacent to indoor air) (e.g. [45]). As mentioned in Section 2.1 most residential buildings in the Netherlands are heavy-weight buildings due to the use of concrete, brick, and other heavy building materials. Therefore, the base case building is a heavy-weight building. In the alternative case (TM_low) the amount of thermal mass is reduced by assuming that the inner leaf of the building envelope consists of wooden sheets instead of limestone, and the ceilings consist of a wooden construction instead of concrete. Therefore, this is the inverse of adaptation. Nevertheless, it serves to illustrate the effects of thermal storage on energy use.

2.2.3. Short-wave reflectivity

The short-wave reflectivity (albedo value) of a surface determines the fraction of incoming short-wave radiation that is being reflected. In the built environment, common values for the short-wave reflectivity are about 0.3 for red brick materials and roof tiling [48]. This value for the short-wave reflectivity is taken for the facades and the roof in the base case, and as an alternative case this value is increased to 0.8 (SWR08), which corresponds to short-wave reflectivity values from literature [48].

2.2.4. Vegetated roofs

Extensive vegetated roofs are added to the building (VR), since this type of vegetated roof has less implications for the roof construction and can therefore be more easily applied on new and on existing buildings. Extensive vegetated roofs can be distinguished from intensive vegetated roofs; it can be assumed that extensive roofs generally have vegetation lower than 0.15 meter and intensive roofs have vegetation higher than 0.15 meter [49] (and are therefore heavier and more demanding for the roof construction). The height of the vegetation is taken equal to 0.1 meter, which represents the height of sedum plants, which are often used as extensive roof vegetation. The Leaf Area Index (LAI) is set to 5. Scurlock et al. [50] defined the LAI as the functional vegetated leaf area of the canopy (m^2)

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per area of ground (m^2). A LAI value of 5 is relatively high, but it is chosen to assess the upper bounds of the effects of an "ideal" extensive vegetated roof.

2.2.5. Solar shading

Solar shading is not yet commonly applied in residential buildings in the Netherlands and surrounding countries. In this study it is assumed that all the windows on the east, south and west facade of the building are equipped with automatic vertical exterior solar shading devices with a solar reflectivity of 0.9. The threshold for lowering the solar shading is set to a zone air temperature of 21°C and a simultaneous occurrence of solar radiation on the window (beam and diffuse) of 150 W/m^2 or more (e.g. [51]). By setting a double threshold, i.e. a minimum indoor air temperature in addition to the solar radiation limit, solar irradiation can be optimally utilized to reduce the building heating demand in the heating season.

2.2.6. Natural ventilation

Addition natural ventilation by opening windows can be seen as a passive adaptation measure. Therefore, it is assumed that the windows in the base case are closed throughout the day. In this study it is assumed that the windows will be opened above a threshold indoor air temperature of 23°C. An additional requirement is that the indoor air temperature should be higher than the outdoor air temperature in order to prevent an undesired increase of the indoor air temperature. The opening area of the windows is indicated by the triangular shapes in the windows in Figure 1. The windows will be systematically and automatically opened when the given thermal criterion is met, irrespective of the time of the day.

2.3. Weather data

The weather data that has been used are those measured in De Bilt, the Netherlands, during 2006, which was a much warmer year than normal with several heat waves during the summer, and can therefore be seen as a representation of a climate year with a summer period that will be more common in the future [52,53]. The winter in 2006 was slightly warmer than the average winter in the past 20 years; the total number of heating degree days [47], determined with a base temperature of 18°C, for the average and future climate amounts 2895 and 2751, respectively [52,54]. In Section 3.1 a comparison is made between the predicted energy demands for heating and cooling using weather data for an average climate year and for a future climate year. Please note that the aim of this study is not to provide absolute values of the heating and cooling demand for a future climate, but to provide insights in the energy demand for cooling, and in possible synergy effects and conflicts when passive adaptation measures are applied with respect to the heating, cooling and total yearly energy demand.

2.4. Additional simulation parameters

The dynamic thermal simulations are conducted using six time steps per hour, as recommended by EnergyPlus [41]. The number of time steps per hour is increased to 60 for the simulations with the vegetated roof, as recommended by EnergyPlus [41], to improve the numerical solution of the zone heat balance model and to obtain more accurate results. The ground temperature at a depth of 1 m is taken equal to 10°C, and the ground reflection is set to 0.2. The surface convection algorithms used for the interior and exterior building surfaces are TARP and DOE-2, respectively (e.g. [55]). To incorporate the (natural) ventilation flow the airflow network included in EnergyPlus is used. The wind pressure coefficients to calculate the volume flow rate have been obtained from Liddament [56]; wind pressure coefficients for a building surrounded by obstructions equal to the height of the building under study are used.

2.5. Performance indicators

The performance of the climate change adaptation measures is assessed based on (1) yearly energy demand for cooling (kWh/m^2); (2) yearly energy demand for heating (kWh/m^2); (3) yearly total energy demand (kWh/m^2). The yearly energy demand for cooling and heating is based on the temperature setpoints as mentioned in Section 2.1.

3. Results

3.1. Average climate vs. future climate

For the base case building and for RC04, RC50 and RC65, a comparison is made of the predicted energy demand determined for the currently used climate year in building energy performance simulations for determining heating and cooling demands in the Netherlands, and for the climate as measured in 2006 [52], which can be considered as a future climate year (certainly with respect to the summer season, and to some extent also for the heating season). The currently used climate year is obtained from NEN 5060 [54] which is based on EN ISO 15927-4 [57]. This climate year is calculated based on the climate of the past 20 years (1986-2005).

Figure 2 shows the results of this comparison. Figure 2a clearly shows a strong increase in the yearly energy demand for cooling averaged over the four orientations when the same building is subjected to the future climate; the increase is around 400% for the poorly insulated building (RC04) and slightly less than 200% for the other three cases. The amount of energy for cooling is the lowest for case RC04, which can be attributed to the fact that heat can more easily be transferred through the building envelope once it is inside the building due to, for example solar radiation through the transparent parts of the building envelope. This counter-intuitive effect was indicated earlier in a previous study by the authors [21] as well as by Aebischer et al. [14]. Figure 2b shows the yearly energy demand for heating averaged over the four orientations for both the average climate and the future climate. It can be seen that there is a decrease in yearly energy demand, which can be attributed to the warmer winter in the future climate file used for this study (less heating degree days). The decrease is around 8% for all four cases. The total yearly energy demand averaged over the four orientations is depicted in Figure 2c, which shows that the total yearly energy demand tends to decrease, which is the result of a larger decrease in heating demand than the increase in cooling demand.

3.2. Passive adaptation measures

Figure 3 shows the yearly energy demand for cooling in kWh/m^2 for both the base case and for the cases with the different passive climate adaptation measures included. The columns indicate the average value over the four different orientations while the error bars indicate the minimum and maximum value. As indicated in Section 3.1, the terraced house from the 1970s (RC04) with low insulation values has a lower energy demand for cooling than the terraced houses with higher insulation values, i.e. the base case and RC50 and RC65. Applying less thermal mass results in an increase of energy demand of 16% compared to the base case building. This increase in cooling energy demand is the result of the lower amount of thermal storage that is available in both the inner leaf of the external walls and in the inner walls (wooden sheets instead of limestone), as well as in the ceilings (wooden construction instead of concrete). When less thermal mass is present in the constructions which are exposed to the indoor conditions, less thermal storage is available for heat gains from solar radiation and internal heat sources, which will either lead to a higher indoor air temperature if no active cooling would be present (e.g. [21,58-61]), or a higher cooling demand if active cooling is available, as in the current study and as reported in previous studies (e.g. [62-64]). Thermal mass in buildings both delays and reduces peak indoor air temperatures and can thus have a positive effect on the cooling energy demand. Increasing the albedo value of the building envelope to 0.8 (SWR08) decreases the mean energy demand for cooling by 10%, while a vegetated roof (VR) only results in a decrease of 3%. Applying solar shading (SH) and additional natural ventilation (NV) have the largest impact on energy demand for cooling with a decrease of 74% and 59%, respectively. Applying additional natural ventilation and solar shading to a highly-insulated building (RC65_NV and RC65_SH) can reduce the cooling energy demand considerably as well. Finally, it is shown that large differences are present for the different orientations, as a result of the different solar heat gain levels for the four different orientations.

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Figure 4 shows the yearly energy demand for heating in kWh/m^2. Obviously, the poorly-insulated building from the 1970s (RC04) requires by far the highest amount of energy for heating; i.e. 107% more than the base case building. The energy demand for heating of a terraced house from the 1970s (RC04) can be reduced with 57% if one would increase the thermal resistance to R$_C$ = 6.5 m^{2}k/W (U = 0.15 W/m^{2}K). Increasing the insulation values for the base case building (building from 2012) only results in a relatively small decrease of the yearly energy demand of 5% and 8%, for case RC50 and RC65, respectively. A reduction of the amount of thermal mass and an increase of the albedo value result in a very small increase of the energy demand (1-2%), which can be regarded as negligible. The application of an extensive vegetated roof results in a very small decrease of the yearly energy demand for heating (-2%), which can be attributed to the slightly increased value of the thermal resistance of the roof due to the addition of the vegetated roof (soil, etc.). Applying automated external solar shading based on the indoor air temperature (21°C) and on the total solar irradiation on the window (E > 150 W/m^2) does not affect the energy demand for heating much. However, note that automated solar shading that is only controlled by solar radiation on the window will prevent solar radiation from entering the building in the heating season, and will result in a higher energy demand for heating.

Figure 5 shows the total yearly energy demand for heating and cooling, as percentage of the total yearly energy demand for the base case building. The building with low thermal insulation values (RC04) requires 93% more energy for heating and cooling than the base case building, which is due to a substantially higher energy demand for heating (energy demand for cooling is less than for base case building; see Fig. 3). The terraced houses with higher insulation values, RC50 and RC65, have a 4% and 7% lower yearly energy demand compared to the base case house, respectively. The energy demand of a terraced house with a lower thermal mass is 4% higher, and for the terraced house with a higher albedo value it is almost equal, i.e. the advantage in the cooling season is cancelled out by a negative effect in the heating season. The application of a vegetated roof results in a 2% lower total yearly energy demand. Providing additional natural ventilation results in a decrease of energy demand with 5%, and the use of solar shading comes with a decrease of 6% in the total yearly energy demand. Finally, the lowest total amount of energy is used in the terraced house with high insulation values (R$_C$ = 6.5 m^{2}K/W; U = 0.15 W/m^{2}K) in combination with either the application of additional natural ventilation (-12%) or of external solar shading, i.e. -13% compared to the base case. The decrease in energy demand due to an increase of the thermal resistance from R$_C$ = 3.5 m^{2}K/W (U = 0.29 W/m^{2}K) to R$_C$ = 6.5 m^{2}K/W (U = 0.15 W/m^{2}K) is about equal to the decrease in total yearly energy demand when applying external solar shading or additional natural ventilation.

4. Discussion

This paper presented dynamic thermal simulations using EnergyPlus to assess the heating and cooling demand for a terraced house for both a base case building, and for the same building with a range of different passive climate change adaptation measures applied. In Section 4.1 a discussion is presented concerning the application of passive adaptation measures and possible unexpected effects on the total energy demand, depending on the construction year and insulation value of the building under renovation. Subsequently, a discussion on the balance between heating and cooling demands is presented in Section 4.2. Note that the limitations of the current study and directions for future research are listed in Section 6.

4.1. Possible adverse effect of passive adaptation measures on energy demand

Application of passive climate change adaptation measures with the aim to reduce the amount of indoor overheating or the cooling demand should be done only after careful consideration and analysis of the building under renovation, since the effects can differ per building type, construction year, insulation level, etc. For example, increasing the value of the short-wave reflectivity is known to have a positive effect on indoor air temperatures and cooling demand in summer (Fig. 3 and, e.g. [21,65-68]). However, it can also have negative consequences during the heating season since higher short-wave reflectivity values reflect more solar radiation and lead to lower surface temperatures. In van Hooff et al. [21] it was shown that the effect of – among others – changing the short-wave reflectivity value on indoor air temperatures was more pronounced for poorly insulated buildings. The question arises what the net effect will be of a reduction of short-wave reflectivity of a residential building with a low overall thermal insulation value on the total energy demand. To answer this question, additional simulations were performed to assess the influence of the short-wave reflectivity on energy demand in both the heating and the cooling season for

the poorly insulated terraced building (RC04). Figure 6 shows the yearly energy demand for cooling, heating and in total in kWh/m^2 for a poorly insulated building with normal values of the short-wave reflectivity, and with high values of the short-wave reflectivity (0.8) for both the average climate year and the future climate year. It can be seen that the cooling demand is reduced to zero when applying high values of the short-wave reflectivity. However, the energy demand for heating is increased with slightly more than 11%. The total yearly energy demand when higher values of the short-wave reflectivity are applied increases with almost 11% for the current climate and with 8% for the future climate. These results show that careful consideration is needed in the implementation of passive climate change adaptation measures in the design and retrofitting of residential buildings, since certain measures that work well as climate change adaptation measures can have a negative impact on the yearly energy demand, and vice versa. In addition, the total predicted effect of some of the climate change adaptation measures on the total yearly energy demand can depend – among others – on the properties of the building envelope, as illustrated in this section.

4.2. Ratio cooling vs. heating demand

Comparison of Figure 3 and Figure 4 shows that for the Dutch climate, which is a maritime temperate climate according to the Köppen climate classification [69], the energy demand in the heating season is considerably larger, (around 90% of the yearly total) than the energy demand for cooling, which is around 10% of the total yearly energy demand for cooling and heating. However, the percentage of the total energy demand that is associated with cooling will increase in the future due to climate change (milder winters and hotter summers), the urban heat island effect, better insulated and more airtight buildings, etc. (e.g. [14]). Although 10% for cooling appears to be small compared to the 90% for heating, it must be noted that it is shown that passive climate change adaptation measures, such as external solar shading and additional natural ventilation, can almost prevent the use of active cooling in residential buildings and can save roughly 7-8 kWh/m^2 per year (i.e. around 10% reduction of yearly total energy demand), which is still a considerable possible decrease. In fact, these measures result in a decrease of the total yearly energy demand which is almost equally large as the decrease that would be obtained when increasing the thermal resistance of the building envelope from $R_C = 3.5$ m^{2}K/W (U = 0.29 W/m^{2}K) to $R_C = 6.5$ m^{2}K/W (U = 0.15 W/m^{2}K). Furthermore, note that the weather data used in this study provides an indication of future hot summers, but the air temperatures in winter for the future climate year are only slightly higher. Therefore, it is expected that the contribution of the yearly heating demand to the yearly total energy will most probably be lower in the future than calculated in this study.

5. Conclusions

This study presents the results of a computational analysis of the heating and cooling demand of a terraced house and the influence of six different passive climate change adaptation measures at the building component scale on these energy demands. The analysis has been performed using dynamic thermal simulations with EnergyPlus. From this study the following conclusions can be made:

- The energy demand for cooling is the highest for the well-insulated houses without solar shading or additional natural ventilation. Lower insulation levels lead to lower energy demands for cooling. Application of solar shading and/or additional natural ventilation can reduce the energy demand for cooling considerably; with 74% and 59% respectively. When less thermal mass is applied this has a negative effect on the energy demand for cooling, which increases with 16%.
- The energy demand for heating is mainly dependent on the insulation values. Application of passive climate change adaptation measures hardly influences the energy demand for heating; i.e. within 2% of the heating demand of the base case building. The energy demand for the terraced house from the 1970s with low insulation values (RC04) is two times higher than for the other cases.
- The influence of a high albedo values or a vegetated roof on the total energy demand for heating and cooling is negligible; it remains within 2%. A lower thermal mass leads to an increase of the total energy demand of 4%. The total energy demand is the lowest for the well-insulated houses in combination with either solar shading (RC65_SH) or additional natural ventilation (RC65_NV); requiring 87% and 88% of the energy demand by the base case building.

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- Application of external solar shading or additional natural ventilation can result in a decrease of the total energy demand which is equally high as the decrease when one would apply a thermal resistance of $R_C = 6.5$ m^{2}K/W ($U = 0.15$ W/m^{2}K) instead of $R_C = 3.5$ m^{2}K/W ($U = 0.29$ W/m^{2}K).
- Increasing the short-wave reflectivity to 0.8 (SWR08) for a poorly insulated building reduces the energy demand for cooling, but results in an increase of the total yearly energy demand due to the negative effects on the yearly heating demand.

6. Limitations and future work

There are several limitations in this study which indicate directions for future research:
- It would be very valuable if measurement data of the energy use for heating and cooling in residential buildings would be collected in the near future. This data could be used for a more detailed validation study and, moreover, to assess the influence of building users on the energy demand and its spread in residential buildings.
- The study can be extended to include other residential buildings (apartment, detached house, etc.), and other building types, e.g. office buildings, schools, hospitals, which all have their own specific characteristics and heat balances and require an additional analysis.
- Opening the windows and lowering external solar shading appear to be the most efficient measures to reduce the cooling demand in a terraced house when active cooling would be present. However, both measures strongly rely on human behavior since both measures generally require manual intervention by the occupants of a building. This fact results in the possibility that large differences can occur in the expected energy demand reduction and the reduction in practice (e.g. [70,71]). The occupants of residential buildings should have basic knowledge on how to prevent indoor overheating and should be able to apply these preventive measures in an efficient way. An alternative would be the automation of these actions by a detection and control system.
- Only one type of vegetated roof is studied, which does not allow to draw general applicable conclusions from this study. Future work can include a more exhaustive assessment of the effect of vegetated roofs, and possibly also vegetated facades, on heating and energy demand in residential building. Note that a previous study by Ottelé et al. [72] also showed only very little effect of extensive vegetated roofs on the indoor air temperature when applied on well-insulated building envelopes, which agrees with the findings in the current study.
- Only a limited number of climate change adaptation measures is studied, and future studies can extend this number to include evaporative cooling, water roofs, etc. In addition, the effect of these measures on both the energy demand for heating and cooling, and on the outdoor thermal environment can be assessed.
- The study is performed using the Dutch climate, which is a maritime temperate climate according to the Köppen climate classification [69]. The work should be extended to other climates from the Köppen climate classification, and other building and construction typologies that are common in other countries and continents.
- Future work will also consist of an analysis of the different passive climate change adaptation measures for a shorter heatwave period. This study will then focus on the cooling energy demand only.

7. Acknowledgements

8. References

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TABLES

Table 1: Overview of adaptation measures studied.

Adaptation measure	Description	Abbreviation
Increased thermal resistance	The thermal resistance of all external building surfaces is increased to R_C = 5.0 m^2K/W (U = 0.2 W/m^2K) and R_C = 6.5 m^2K/W (U = 0.15 W/m^2K), for RC50 and RC65, respectively. This measure is implemented by increasing the thickness of the insulation layers.	RC50, RC65
Changed thermal capacity	The thermal capacity is lowered, since the base case is a heavy building. The thermal capacity is changed by replacing the limestone inner leaf by an inner leaf of wooden sheeting. In addition, concrete ceilings are replaced by wooden constructions.	TM_low
Increased short-wave reflectivity (albedo)	The short-wave reflectivity value of the external surfaces is increased from the default value of 0.3 to 0.8.	SWR08
Vegetated roof	The default roof constructions are extended to incorporate a vegetated roof with a Leaf Area Index (LAI) of 5.	VR
Solar shading	Exterior solar shading is applied for all windows on the east, south and west side of the facades. The solar shading is automatically lowered when the indoor air temperature is 21°C or higher and when at the same time solar radiation on the window is at least 150 W/m^2.	SH
Additional natural ventilation	Additional natural ventilation is provided by opening (parts of) the windows. The windows will be opened when the indoor air temperature is above 24°C, but only when the indoor air temperature is higher than the outdoor air temperature. The windows can be opened the entire day (24 hours).	NV

Table 2: Overview of construction details for the base case building from 2012.

Element	Details	R_C (m^2K/W)	U (W/m^2K)
External walls	Cavity walls with (inside to outside): Limestone inner leaf, insulation, air cavity, brick outer leaf	3.5	0.29
Internal wall	Limestone wall	-	-
Roof (pitched)	Inside to outside: Wooden sheeting, insulation layer, air cavity, roof tiles.	4	0.25
External floor	Inside to outside: Concrete, insulation	3.5	0.29
Internal floor	Concrete	-	-
Windows	Double pane glazing. Solar transmittance coefficient = 0.7.	-	1.65

Table 3: Overview of construction details for the base case building from the 1970s.

Element	Details	R_C (m²K/W)	U (W/m²K)
External walls	Cavity walls with (inside to outside): Limestone inner leaf, air cavity, brick outer leaf.	0.4	2.5
Internal wall	Limestone wall	-	-
Roof (pitched)	Inside to outside: Wooden sheeting, insulation layer, air cavity, roof tiles.	0.8	1.25
External floor	Concrete	0.17	5.88
Internal floor	Concrete	-	-
Windows	Single pane glazing. Solar transmittance coefficient = 0.7.	-	5.2

Table 4: Temperature setpoints for heating (based on [46]).

	Time interval [hour]		
	06:00-18:00	18:00-23:00	23:00-06:00
Temperature setpoint	19°C	20°C	16°C

Table 5: Heat gains inside the building (based on [45] and [47]).

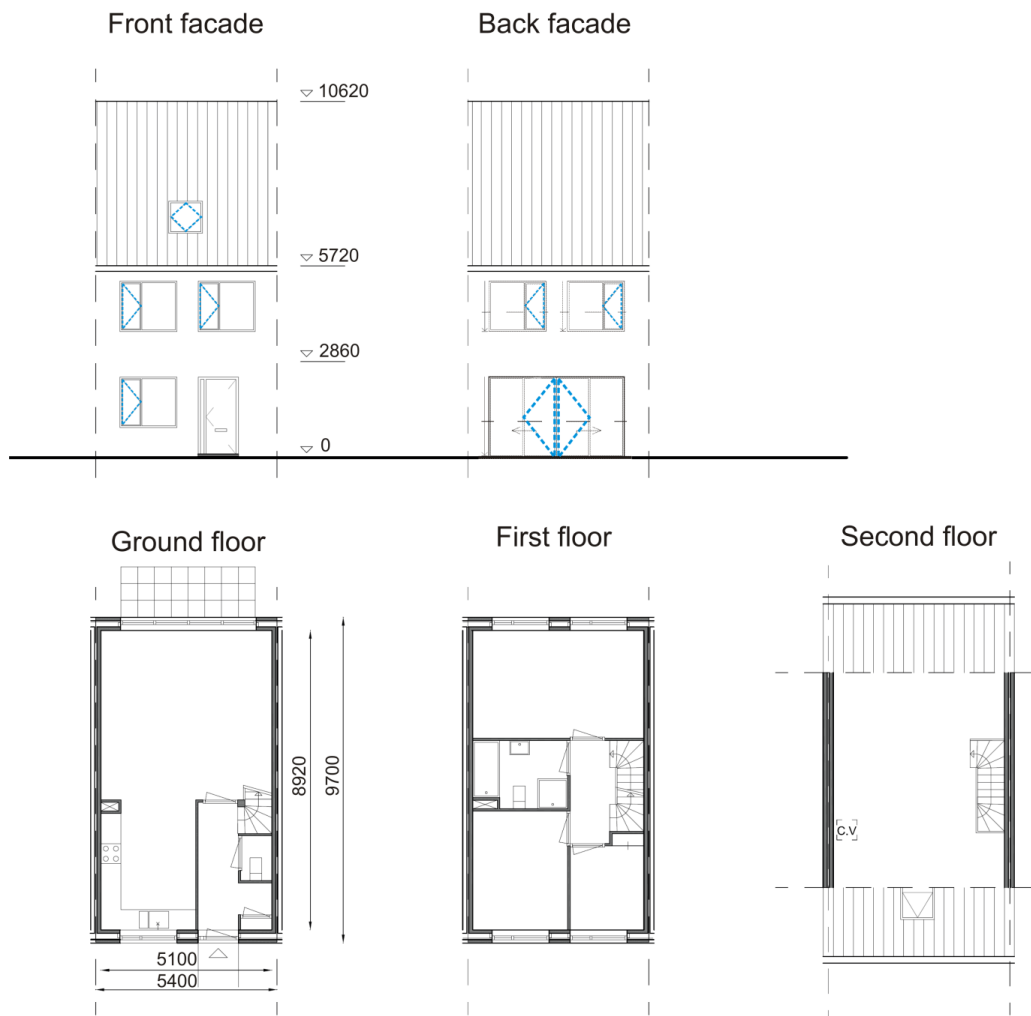| Zone	Heat source	Time interval [hour]			
		06:00-18:00	18:00-19:00	19:00-23:00	23:00-06:00
Living room	Appliances	25 W	100 W	100 W	25 W
	Kitchen	250 W	600 W	250 W	-
	Persons	-	385 W	385 W	-
	Lighting	-	-	15 W/m²	-
Bedrooms	Persons	-	-	-	241 W

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FIGURES

Fig. 1: Facades, floor plans and building dimensions (modified from [44]). Triangles in windows and doors indicate operable windows/doors for the additional ventilation configuration. Dimensions in mm.
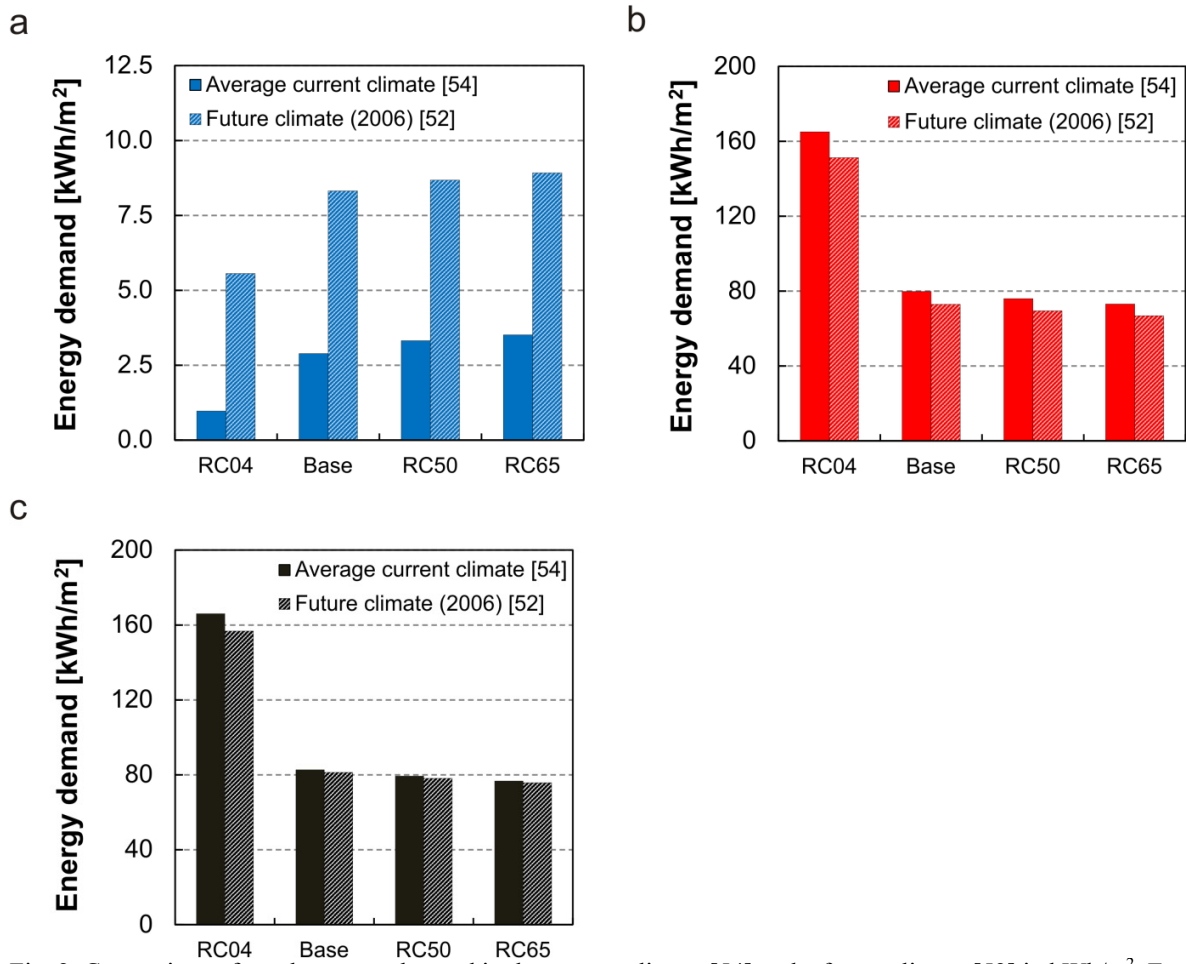
Fig. 2. Comparison of yearly energy demand in the current climate [54] and a future climate [52] in kWh/m^2. Energy demand for: (a) Cooling. (b) Heating. (c) Total.
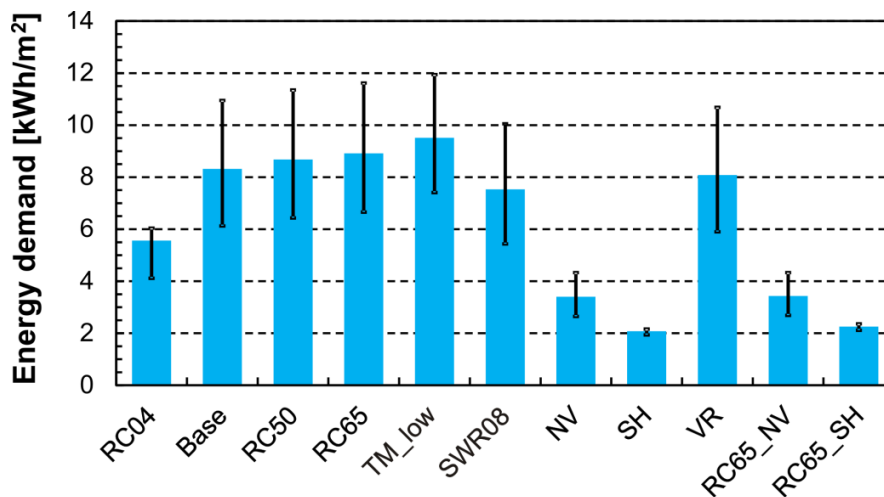

Fig. 3: Yearly energy demand (kWh/m^2) for cooling for the base case building and for the different alternative building configurations. The columns represent the average energy demand over four different orientations, the error bars provide information on the minimum and maximum values.
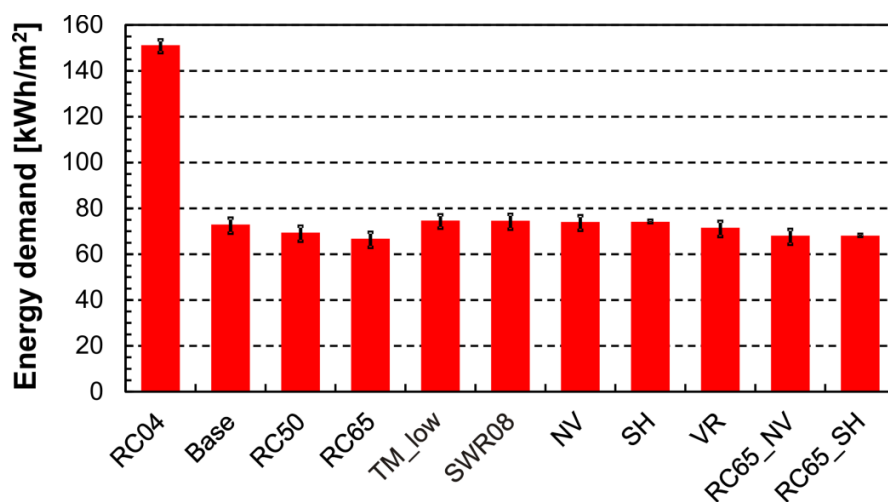
Fig. 4: Yearly energy demand (kWh/m^2) for heating for the base case building and for the different alternative building configurations. The columns represent the average energy demand over four different orientations, the error bars provide information on the minimum and maximum values.
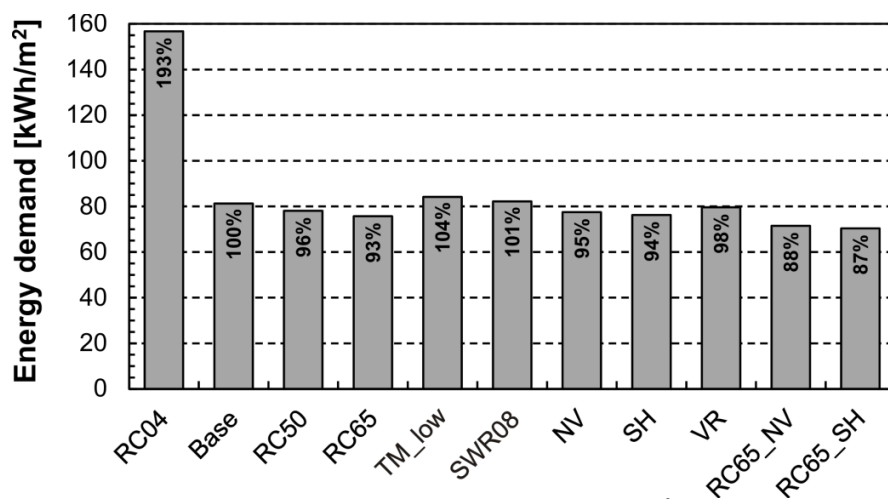

Fig. 5: Yearly energy demand for heating and cooling (kWh/m^2) compared to the base case building (= 100%).
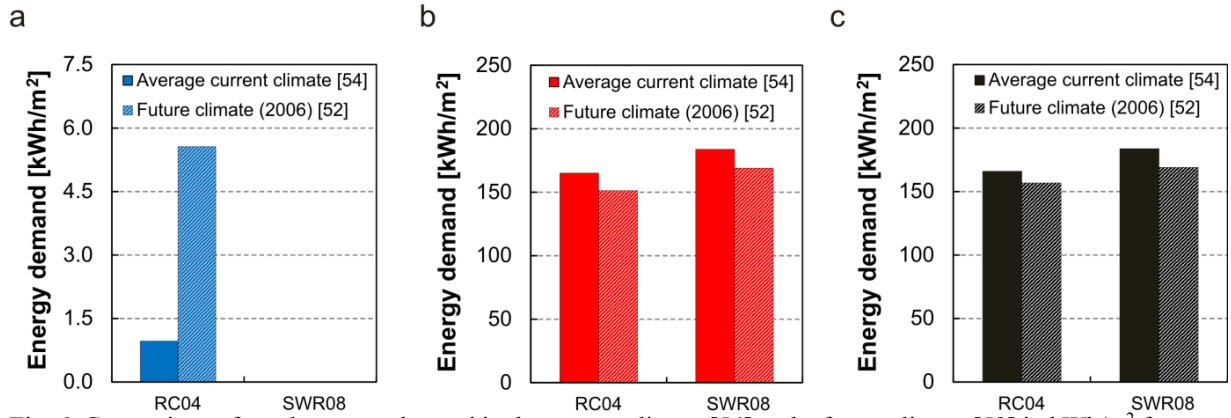
Fig. 6. Comparison of yearly energy demand in the current climate [54] and a future climate [52] in kWh/m^2 for case RC04 and for case RC04 but with short-wave reflectivity values of 0.8. Yearly energy demand (kWh/m^2) for: (a) Cooling. (b) Heating. (c) Total.