Strategy for achieving long-term energy efficiency of European single-family buildings through passive climate adaptation

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HIGHLIGHTS

- Low energy use of single-family buildings can be assured solely by passive design.
- Passive adaptation only partly counterbalances climate change effects on energy use.
- Total energy use will decrease in cold and temperate and increase in warm climates.
- The most effective long-term climate adaptation measure is applying smaller windows.
- New buildings should be designed according to mid-term optima (2020/2050 period).

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ABSTRACT

The presented study aims to clarify the implications of passive design measures on heating and cooling energy use of single-family residential buildings under European representative climates. In order to address this matter, different values of thermal transmittance (opaque and transparent), window to floor ratio, window distribution, shape factor, diurnal heat storage capacity, external opaque surface solar absorptivity and natural ventilation cooling rates were combined in 496,800 building energy models, which were simulated at eight locations. Because buildings are in use for many decades, the energy use simulations were made considering the projected climate change up to the end of the 21st century. The results delivered a set of the most effective passive design measures for achieving low energy use in buildings regarding climate type and period. A lower window to floor ratio was identified as the most universally applicable design measure to counterbalance the projected effect of a warming climate. In contrast, other measures vary according to climate type and studied period. Furthermore, it was concluded that it is difficult to neutralise the projected climate change effects on buildings' energy use, even when applying the best performing combination of passive design measures. However, reasonably low energy use can still be assured solely by passive building design, especially in oceanic, warm, and some temperate climate locations. Therefore, the identified trends in energy use and passive design measures represent the foundation for strategies and guidelines aimed at future-proof energy-efficient buildings.

1. Introduction

The resilience of buildings, especially in the context of climate

adaptation, has lately become a significant issue in the field of building energy efficiency. Energy performance of buildings can be improved by increasing the efficiency of passive (e.g. building shape, building

Abbreviations: HVAC, Heating, Ventilation and Air Conditioning; PV, photovoltaic; IPCC, Intergovernmental Panel on Climate Change; WWR, window to wall ratio (%); SRES, Special Report on Emissions Scenarios; RCP, Representative Concentration Pathways; SHGC, solar heat gain coefficient (-); f_0 , shape factor (m^{-1}); WFR, window to floor ratio (%); W_{dis} , window distribution; U_w , window thermal transmittance (W/m^2K); U_o , opaque envelope thermal transmittance (W/m^2K); DHC, diurnal heat storage capacity (kJ/m^2K); α_{sol} , external surface solar absorptivity (-); NV_c , summer natural ventilation cooling rate (h^{-1} or ACH); Q_{NH} , annual energy use for heating per floor area (kWh/m^2); Q_{NC} , annual energy use for cooling per floor area (kWh/m^2); Q_T , annual total energy use per floor area ($Q_{NH} + Q_{NC}$) (kWh/m^2); ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; EPW, EnergyPlus weather file; IWEI, International Weather for Energy Calculation.

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envelope design, etc.) or active (e.g. HVAC system, PV systems, etc.) building elements and systems. According to Olgyay [1], Almusaed [2] and Košir [3], the bioclimatic design concept is often used to optimise a building's passive elements in order to adapt it to the relevant climate conditions. Through bioclimatic design and the use of passive building design measures, a higher level of building energy efficiency and indoor thermal comfort can be achieved [4,5]. An attractive feature of some passive building measures, such as building orientation or natural ventilation, is that they generate little or no additional costs for the building project during the design and construction. However, for other passive measures, cost-effectiveness analysis should be executed in order to validate their implementation regarding application costs and energy savings. For this reason, the bioclimatic approach is an essential aspect of cost-optimal energy-efficient solutions.

On the other hand, passive building elements are rigid and difficult to modify after the building has been constructed. For example, changes to the building shape, window distribution or glazing area require substantial interventions in the building or its envelope. Therefore, they are challenging to implement and usually costly. Consequentially, passive building elements represent a substantial lock-in risk for buildings if they are not appropriately designed and evaluated in terms of climate and the intended building use.

In general, passive measures can be divided into four main strategy groups: heat retention, heat admission, heat exclusion and heat dissipation [3]. The selection of appropriate passive design strategies should always depend on climate and location characteristics, as emphasised by Szokolay [6], Košir [3] and Pajek and Košir [7]. At this point, it is essential to understand that with the current trend of global warming, many of the bioclimatic measures that used to be a cost-optimal solution at a specific location might no longer be considered as such. To illustrate, with increasing atmospheric temperatures, at some locations, heat exclusion measures (e.g. smaller glazing area, efficient shading, etc.) can become more important than heat admission measures (e.g. large glazing area for passive solar heating) that were better suited for a colder climate of the past. The worrying projected effects of global warming for the 21st century could be compensated, at least to some extent, by appropriate and informed climate-adapted building design, considering the trend of projected climate change.

1.1. Theoretical framework

In order for bioclimatic building design to be effective, climate adaptation towards future climatic conditions must be considered. Skarbit et al. [8] state that the observations and climate models demonstrate that the climate will become warmer and dryer during the current century. However, the extent of the projected change depends on the climate change scenario used in the models. Several scenarios have been introduced by the Intergovernmental Panel on Climate Change (IPCC) [9], covering various global projected technological, demographic, economic, social and political developments. These scenarios can be grouped into SRES (Special Report on Emissions Scenarios) scenarios introduced in the Third [10] and Fourth [11] IPCC's Assessment Reports and the RCP (Representative Concentration Pathways) scenarios from the Fifth [12] IPCC's Assessment Report. At the moment, it is quite uncertain which scenario will eventually unfold, if any [13]. However, observing the projected outcomes of the SRES and RCP groups of scenarios, it becomes evident that until the end of the 21st century, all the scenarios lead to a warmer future climate.

For this reason, weather file "morphing" methods have been developed to produce design weather data for use in building thermal response simulations that account for future climate change. Several examples of these methods, but not all, were presented by Jentsch et al. [14], Arima et al. [15], Belcher et al. [16], Soga [17] and Jiang et al. [18]. Morphing combines the observed weather data with climate change models [16]. For both RCP (e.g. Spinoni et al. [19]) and SRES (e.g. Berardi and Jafarpur [20]) scenarios, building energy simulations

project a decrease in heating demand and increase in cooling demand of buildings. Even under optimistic climate scenarios (e.g. RCP2.6 – projecting a mean global surface temperature increase of 1 °C by the end of the century), the majority of cities will most likely experience a considerably different climate than today [21] or even extreme conditions that are not currently found in any existing major city, as stated by Bastin et al. [22].

Therefore, using projected future weather data is vital for studying climate change impact on buildings, as highlighted by Jiang et al. [18]. An essential view of the problem was presented by Zhou et al. [23], who highlighted that climate change has a geographically heterogeneous impact on the heating and cooling of buildings. Nevertheless, numerous studies have been conducted evaluating building energy performance against the projected future climate, and a consensus has been reached on the increase in cooling and a decrease in heating demand [24]. An example of such a study was presented by Flores-Larsen et al. [25] in Argentina for residential buildings. They showed a considerable decrease in energy need for heating and an increase in energy need for cooling of buildings. In this context, shading, reducing direct solar gains, and natural ventilation were presented as the most effective design measures to counteract the climate change effects. Furthermore, Andrić et al. [26] showed that heating decrease in warm climates was more significant than in cold climates, and Zhai and Helman [27] stated that the total energy use of buildings would increase, predominantly due to the large increase in cooling energy demand. Kishore [28] also drew similar conclusions to the above-stated ones on a case of a typical residential building evaluated under climate change projections for the 21st century under five main climate types of India. It was demonstrated that passive design strategies could reduce the projected annual cooling load by approximately 50–60% for India's residential buildings.

Concerning the passive and active measures applied to a typical Mediterranean residential building under various climate change scenarios, Pérez-Andreu et al. [29] stated that ventilation has the most negligible impact among several design parameters. In contrast, increased thermal insulation and airtightness will have a more significant effect on future energy performance. Similarly, Rodrigues and Fernandes [30] executed a statistical comparison of random two-storey family building geometries with diverse U values for current and future projected climates in sixteen Mediterranean locations. Importantly, they found that in the future further reduction in U values would continue to be a beneficial design measure for several locations. Future energy needs were also estimated by Ciancio et al. [31] for a hypothetical three-storey residential building placed in 19 European cities. They highlighted that heating energy tends to decrease in northern cities while cooling energy use is expected to increase in southern Europe. Gercek and Arsan [32] stated for the case of Turkey that the most critical parameters concerning the energy performance of residential buildings are related to the transparent surfaces of building envelope. In like manner, Harkouss et al. [33] showed that for the current climate, the optimisation of passive design measures, namely window to wall ratio (WWR), U value and glazing type, for generic residential building results in using high levels of thermal insulation under cold and temperate climates (e.g. $U = 0.2 \text{ W/m}^2 \text{ K}$) and lower levels under hot climates (e.g. $U = 0.6 \text{ W/m}^2 \text{ K}$).

In line with the findings mentioned above, Moazami et al. [34] successfully introduced a robust approach to energy performance evaluation under projected climate change. Similarly, Shen et al. [35,36] proposed an optimisation method for building retrofit planning of a campus building in the US under climate change, for which more than a thousand Pareto fronts were obtained using variables as U value, glazing type, natural ventilation and air infiltration level, heating and cooling system efficiency, renewable energy systems implementation, etc. Although climate change effects were not taken into account, numerous studies in the field of building energy use and operation optimisation, presented by Robic et al. [37], Chiesa et al. [38], Gou et al. [39] and Ciardiello et al. [40], have produced encouraging results. In conclusion, the referenced studies emphasise that it is vital to include a large set of

variables to optimise a building's energy performance as the identified critical parameters were certainly location-dependent.

1.2. Knowledge gap identification and study objective

As noted in the literature review, a building envelope's thermal resistance is known to be one of the most efficient and most resilient passive building approaches to reducing energy use in buildings [41,42]. Therefore, it is also quite common for the policymakers to set U values' upper limit for a building envelope and its components. At the same time, the energy efficiency of buildings can be further enhanced by applying additional passive design measures [43], which do not represent such a substantial financial investment as the implementation of a very thick thermal insulation (example of a study aiming at optimum insulation thickness was shown by Raimundo et al. [44]). Besides, Andrea et al. [45] exposed that homeowners are only aware of bioclimatic principles and that effective planning is needed to improve the residential sector's energy efficiency. As exposed by the above-referenced studies, the issue is widely researched. However, studies are typically focused on thermal retrofitting of specific commercial or residential buildings (e.g. Shen et al. [36]), aiming at the optimal specific solution (e.g. Shen et al. [35]), are performed with a limited set of variables (e.g. Robic et al. [37], Košir et al. [46]) or do not concern the climate change effects (e.g. Ciardiello et al. [40]). Therefore, a potential long-term contribution of passive design measures to reducing total energy use for heating and cooling of single-family residential buildings under various European climates is unknown. Accordingly, there is a considerable lack of guidelines and recommendations for implementing appropriate passive design measures concerning the building energy efficiency targets. Overall, the following study aims to present crucial information for the design of climate-adapted and energy-efficient buildings that strive for efficient energy use under current and projected climate conditions. A novel holistic approach was devised, applying a comprehensive parametric study in four climatically different intervals. The effectiveness of passive design measures was evaluated based on the resulting building energy performance. Additionally, the identified energy use trends and the corresponding impact of specific design decisions represent a basis for developing future-proof policy strategies and guidelines in the field of energy-efficient buildings.

2. Methods

The above-exposed knowledge gap was addressed by performing a comprehensive parametric study. The study was focused on the energy performance of single-family detached residential buildings because this building type represents a substantial share of the European residential building stock [47]. Furthermore, such buildings are also particularly suitable for a parametric study because passive design measures might be highly efficient in optimising their energy use due to high interaction with the climate since its thermal response is envelope dominated [48]. Moreover, residential buildings are typically in use for many decades without being substantially remodelled. Therefore, an integral part of the executed study was searching for the best performing sets of passive design measures concerning the projected climate change until the end of the 21st century.

Firstly, 496,800 building models were parametrically defined to achieve the paper's purpose, with each case representing a unique combination of passive building design measures defining characteristics of an individual building. As parametric variables, we chose three different building model geometries, ten values of opaque envelope thermal transmittance, ten values of window thermal transmittance with corresponding SHGCs, nine values of the window to floor ratio, two different window distributions, three different diurnal heat storage capacities, four values of external surface solar absorptivity and nine different summer natural ventilation cooling rates. A total number of 496,800 combinations was reached by combining these values in

distinctive building models. However, an actual number of combinations would be 583,200 but in some building shapes very large south-concentrated window areas cannot be applied due to limited facade area. Then, each model was simulated under the climate of the eight selected locations in Europe given four distinctive periods: an original "present" climate file and three additional climate files considering climate change projections. Overall, this resulted in a total of 15,897,600 simulated cases. The annual energy use for heating and cooling was calculated for each model, and best performing models were identified through a 5th percentile analysis. An overview of the applied research methodology is presented in Fig. 1. A detailed description of the methods used can be found in the following subsections.

2.1. Energy models and definition of input data

For the performed analysis, a single-family residential building was selected as a basis for the devised energy models. According to the EU statistical data, the average floor area of a dwelling in the EU 28 is 42.56 m² per person [49]. In EU member states, a typical number of people per household is between 2 and 3, with an average of 2.3 people in 2019 [50]. Considering the EN 16798-1 standard [51], 43 m² of floor area per person, three persons per household, and a 25% addition to floor area due to technical and communication spaces resulted in 162 m² net floor area per modelled building. Therefore, the geometric characteristics of the model represent an average single-family detached residential building in the EU. The floor-to-floor height was set at 3 m so that the corresponding volume of the modelled buildings was 486 m³.

Next, all building-related inputs were thoroughly defined to represent a distinctive design and operation of European buildings. Due to practical reasons for limiting the number of total possible combinations in the population and reducing the amount of modelled buildings to a manageable number, several building-related input parameters were set constant for all the models. Most of them are related to building use and operation and are presented in Table 1.

For the parametric study, the following variable input parameters were selected: opaque envelope thermal transmittance (U_O), window thermal transmittance (U_W) and the corresponding solar heat gain coefficient (SHGC), window to floor ratio (WFR), window distribution (W_{dis}), building shape expressed through shape factor (f_0), diurnal heat storage capacity (DHC), external surface solar absorptivity (α_{sol}) and summer natural ventilation cooling rate (NV_C) (see Table 2). The U_O parameter was simultaneously altered in each external building envelope element (slab-on-grade, external wall, roof). Unlike in the walls and roof, the DHC of ground floor slab-on-grade construction was not parametrised. There, a concrete slab (i.e. DHC = 146 kJ/m² K) was used in all of the cases. The paper aims at achieving universal comparability among the building models. Therefore, WFR was adopted as a variable parameter instead of WWR because the analysed building models with the same WFR also have the same total window area. However, models with the same WWR would not necessarily have the same total window area since also building shape was chosen as a variable parameter of the analysis. Furthermore, the aim of using parameter W_{dis} was to evaluate the impact of the focus either on passive solar heating (i.e. south concentrated windows) or ignoring it (i.e. equal area of windows at all orientations) and not the effect of glazing orientation. Information regarding individual parameter ranges, variable increments and the number of the resulting simulated cases is provided in Table 2; see also Fig. 1.

It should be noted that the chosen parameter ranges (Table 2) represent technologically feasible building solutions to the most extensive possible degree. However, the resulting specific cases might sometimes not be practical due to economic and/or buildability reasons. For example, U_O of 0.10 W/m² K will result in extremely thick thermal insulation, challenging to execute and questionable from the point of view of return on investment. Moreover, the selected studied passive measures represent the most universally applicable measures. They are

INPUT DATA AND PARAMETERS

BUILDING MODEL GEOMETRY

VARIABLE INPUT PARAMETERS

0.10	opaque envelope thermal transmittance (U_O)	1.00	$[\text{W}/\text{m}^2\text{K}]$
0.60	window thermal transmittance (U_W)	2.40	$[\text{W}/\text{m}^2\text{K}]$
5	window to floor ratio (WFR)	45	$[\%]$
uniform	window distribution (W_{dis})	south	$[\text{n/a}]$
0.778	shape factor (f_0)	1.080	$[\text{m}^{-1}]$
63	diurnal heat storage capacity (DHC)	146	$[\text{kJ}/\text{m}^2\text{K}]$
0.20	external surface solar absorptivity (α_{sol})	0.80	$[-]$
0.00	summer natural ventilation cooling rate (NV_C)	8.00	$[\text{h}^{-1}]$

LOCATIONS AND CLIMATE

CLIMATE CHANGE PROJECTIONS

SIMULATIONS

RESULTS

Fig. 1. Overview of the applied research methodology.

used by building designers in contemporary energy-efficient buildings in Europe, either explicitly or implicitly. There are indeed other passive measures (e.g. evaporative cooling) that might be worthy of investigation in the context of building energy performance concerning the

projected climate change. However, we opted to limit ourselves to those design measures that are already established in the design community while at the same time showing real potential for enhancing building performance under all studied climates.

Table 1

Constant input parameters for the energy models.

Parameter	Value	Note
Heating set-point	21 °C	EN 16798-1, Table B.2 [51]
Cooling set-point	26 °C	EN 16798-1, Table B.2 [51]
Indoor temperature control	operative temperature	Based on Dovjak et al. [52]
Infiltration + natural ventilation rate	0.600 (1st April to 31st October), 0.375 (1st November to 31st March)	Based on Hou et al. [53], Bekö et al. [54]
Internal heat gain rate and schedule (appliances)	2.4 W/m ²	EN 16798-1, Annex C [51]
Internal heat gain rate and schedule (occupants)	2.8 W/m ²	EN 16798-1, Annex C [51]
Internal heat gain rate and schedule (lighting)	3.3 W/m ²	EN 16798-1, Annex C [51]
Shading schedule	active from 1st April till 31st October	Based on Tzempelikos and Athienitis [55]
Shading set-point, type, and operation	incident solar radiation on window ≥ 130 W/m ² and external temperature ≥ 16 °C, external blinds, always block beam solar	EN 15232, class A [56]
Building envelope system and external surface thermal emissivity	the externally insulated building envelope, 0.80	Based on Pissello [57]

Table 2

Variable input parameters for the energy models.

Parameter	No. of variable increments	Parameter range
U_O [W/m ² K]	10	0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.80, 1.00
U_W [W/m ² K], in brackets: corresponding SHGC [-]	10	2.40 (0.75), 2.20 (0.75), 2.00 (0.70), 1.80 (0.70), 1.60 (0.65), 1.40 (0.65), 1.20 (0.60), 1.00 (0.55), 0.80 (0.50), 0.60 (0.45)
WFR [%]	9	5 ("base" case), 10, 15, 20, 25, 30, 35, 40, 45
W_{dis} [n/a]	2	equal area of windows at all orientations, south-concentrated windows (3.75% of WFR equally distributed among other orientations)
f_0 [m ⁻¹]	3	0.778 (compact, cube-like, two storeys), 0.796 (semi-compact, cuboid, two storeys), 1.080 (non-compact, "U" shaped, single storey)
DHC of loadbearing construction ^a [kJ/m ² K], in brackets: thickness [m], thermal conductivity [W/mK], density [kg/m ³], specific heat [J/kgK]	3	63 (0.06, 0.20, 600, 2090, e.g. cross laminated timber), 98 (0.15, 0.50, 1200, 920, e.g. brick), 146 (0.24, 0.80, 2000, 960, e.g. concrete/stone)
α_{sol} [-]	4	0.2, 0.4, 0.6, 0.8
NV_C ^b [h ⁻¹]	9	0, 1, 2, 3, 4, 5, 6, 7, 8
total number of models ^c	496,800	

^a $R = \text{constant} = 0.30 \text{ m}^2\text{K/W}$.^b NV_C is applied between April and October when the following conditions are met: internal air temperature >24 °C, external air temperature is between 16 and 30 °C, and temperature difference between internal and external air is <4 K.^c an actual number of combinations would be 583,200 if a compact and non-compact building shape allowed larger WFRs than 35% or 30%, respectively.

The building shape factor (f_0) represents the ratio between the building envelope area and the building volume. It was calculated using equation (1).

$$f_0 = \frac{A_{\text{envelope}}}{V_{\text{building}}} \quad (1)$$

A_{envelope} is the building envelope area (i.e. the area in contact with the external environment), and V_{building} is the building volume.

DHC of loadbearing construction was calculated according to equation (2) [58].

$$DHC = \sqrt{\frac{P\lambda\rho c}{2\pi} \left(\frac{\cosh\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right) - \cos\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right)}{\cosh\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right) + \cos\left(2t\sqrt{\frac{\pi\rho c}{P\lambda}}\right)} \right)} \quad (2)$$

P is the period of 24 h in seconds, λ is material's thermal conductivity in W/mK, ρ is material's density in kg/m³, c is material's specific heat in J/kgK, and t is the layer thickness in m.

In terms of building geometry, three distinct shapes (see Fig. 1) with equal volumes and floor areas were modelled following the above-described statistical information about average EU dwellings. The first one is a cube-like, compact building ($f_0 = 0.778 \text{ m}^{-1}$) with a square floor plan (9 × 9 m), two floors and 6 m of total height. The second one is a cuboid-shaped building ($f_0 = 0.796 \text{ m}^{-1}$) with a rectangular floor plan

(12 × 6.75 m), two floors and 6 m of total height. The last one is a non-compact building ($f_0 = 1.080 \text{ m}^{-1}$) with a semi-enclosed atrium (i.e. "U" shaped) and a single storey with 3 m of total height. Numerical models were implemented in EnergyPlus [59], which is recognised as accurate building energy simulation software with sophisticated features [43]. Each of the models was divided into thermal zones. In particular, each floor was split into four thermal zones according to each cardinal axis. The contact of the slab-on-grade with the ground was simplified by using a constant ground temperature of 18 °C applied directly below the slab-on-grade of the building model.

The defined EnergyPlus models were then entered into the jEPlus [60] software for parametric analysis. Simulations were executed using four time steps per hour and under the presumption that occupant thermal comfort was achieved at all times by the set-point operative temperature for cooling and heating (Table 1). Effectively, this means that the simulated models are in a "free-run" operation when the indoor operative temperature is between 21 and 26 °C. As a result of the energy analysis, the annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m² of floor area was calculated. Several results were evaluated against Q_T , which is the sum of Q_{NH} and Q_{NC} . However, Q_{NH} and Q_{NC} must be understood only as a part of the overall building energy performance because energy-relevant aspects, such as the efficiency of the heating or cooling system, hot water supply and artificial lighting, are not considered. The specific equations behind the calculations of Q_{NH} and Q_{NC} in EnergyPlus can be found in Engineering Reference [61].

Table 3

Selected locations with corresponding geographical coordinates and altitude, Köppen-Geiger climate classification according to the historical (i.e. recorded) and future projected climate characteristics and ASHRAE climate zone.

Location	Country	Latitude	Longitude	Altitude	Köppen-Geiger (K-G) climate type	K-G climate (2051–2075, IPCC SRES A2 scenario) [65]	ASHRAE climate zone [66]
Östersund	Sweden	63.18	14.50	370 m	Dfc	Dfb	7
Moscow	Russia	55.75	37.63	156 m	Dfb	Dfb	6A
Berlin	Germany	52.47	13.40	49 m	Cfb	Cfb	5C
Ljubljana	Slovenia	46.22	14.48	385 m	Cfb	Cfb	5A
Milan	Italy	45.43	9.28	103 m	Cfa	Cfa	4A
Madrid	Spain	40.45	−3.55	582 m	Bsk	Bsk	3C
Athens	Greece	37.90	23.73	15 m	Csa	Csa	3A
Porto	Portugal	41.23	−8.68	73 m	Csb	Csa	3C

2.2. Selected locations and climate data

The building energy performance calculations were executed for eight locations across Europe, as presented in Table 3 and Fig. 1. Locations were selected in accordance with our previous findings from bioclimatic potential analyses, presented in Pajek et al. [62] and Košir et al. [63] and thus represent various climate types existing in continental Europe. The necessary weather files (i.e. EPWs) were sourced from the official EnergyPlus web page [64] and represent distinct climate types according to the recorded historical weather data.

The climate data in the obtained EPWs are sourced from the International Weather for Energy Calculation (IWECC) database and represent weather data measured between 1982 and 1999. In the paper, this historical climate data period was labelled as “2000”. In order to simulate building performance under projected future climate conditions, historical data for the period of 2000 were used to generate projected EPW weather files for the periods “2020” (2011–2040), “2050” (2041–2070) and “2080” (2071–2100). The generation of the projected climate characteristics was executed using the morphing technique in the CCWorldWeatherGen tool [67] introduced by Jentsch et al. [14] from the University of Southampton. As a basis for the executed morphing, the IPCC’s SRES A2 projected climate change emission scenario was used. The SRES A2 scenario describes a heterogeneous world with nations focused on self-reliance and local identity, with continuous population growth and increasing GHG emissions (i.e. a regional and economy-focused world), resulting in projected warming above 3 °C by the end of the current century (Fig. 1) [68]. The SRES A2 climate change scenario has a similar radiative forcing trajectory to a more recent IPCC’s RCP8.5 scenario with both reaching about 8 W/m² by 2100, while mean surface temperature change in SRES A2 scenario is projected about 0.3 K lower than in RCP8.5 [12]. In addition, the projected global mean surface temperature increase for the SRES A2 scenario in 2050 is approximately 1.5 °C, which is midway between the projected temperature change of the RCP8.5 and RCP6.0.

3. Results

The following subsections present the simulated building models’ energy performance in current and the projected climate scenarios. Section 3.2 provides general guidance on recommended passive measures for long-term energy efficiency. The presented results are evaluated according to the annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m² of building floor area as well as Q_T , which is the sum of Q_{NH} and Q_{NC} .

3.1. Impact of projected climate change on building energy use

Fig. 2 presents scatter plots of the Q_{NH} and Q_{NC} combinations for every calculated building energy model at eight studied locations for each of the four investigated periods. As expected, the results show that, in general, Q_{NH} and Q_{NC} are strongly affected by the projected climate change at each location. Observing Fig. 2 also reveals a general trend of

the projected decrease in Q_{NH} and increase in Q_{NC} over time. In particular, in Athens, Q_{NH} is projected to drop to 0 kWh/m² in 1.7% of the calculated cases until 2080. In 2000 there were no such cases, although some building models had Q_{NH} close to zero. In Milan and Ljubljana, a projected increase in Q_{NC} demonstrates that in 2080 at both locations, it will no longer be possible to achieve 0 kWh/m² of Q_{NC} in residential buildings solely by using the studied passive design measures. In particular, at present (i.e. the 2000 period), there are 4% of building models in Ljubljana that have Q_{NC} equal to zero, while in Milan in 2000, there are already only 0.6% of such cases.

If the average value of Q_T ($=Q_{NH} + Q_{NC}$) for the entire sample is observed in Fig. 3, it can be deduced that the projected climate change will have a positive effect on the overall energy use of buildings under cold and also temperate climates, such as Ljubljana and Berlin, and a negative effect in Athens. In Milan, Madrid and Porto, Q_T ’s average value for the entire sample will remain relatively similar throughout the century. Although Q_{NH} and Q_{NC} change over time in all the studied cases, which can be detected through the shift in the point clouds in Fig. 2, generally speaking, the cases in the 5th and the 95th percentiles (i.e. the best and the worst-performing 24,840 building models) are respectively less or more affected by the projected warming climate (Fig. 3).

The 5th percentile represents building models with the best combination of passive design measures regarding their energy efficiency and climate adaptability. In contrast, the highest Q_T cases, namely the 95th percentile, will be more affected by the warming climate (Fig. 3). Therefore, a different conclusion can be drawn for each of the percentiles. For the 95th percentile, which consists of building models with the worst combination of passive measures, global warming will, on average, result in the highest decrease of Q_T by the end of the century. The stated is valid for all the analysed locations, except Athens, where the Q_T increase is the highest in the 95th percentile models. The latter exception is the consequence of the already warm climate getting even warmer, resulting in an above-average increase in overheating in the least climate-adapted building models. These are typically less thermally insulated buildings (i.e. high U_O and U_W values) having low DHC and NVC , and at the same time high WFR and α_{sol} . This specific combination of parameters results in high vulnerability to a warming climate.

On the other hand, the average Q_T of building models in the 5th percentile is typically less affected by climate change. However, the trend of change in Q_T average values for the 5th percentile during the 21st century at some locations (i.e. Athens, Madrid, Milan, Porto) contradicts the one observed for the entire sample. For the exposed locations, building models in the 5th percentile will exhibit an increase in average Q_T during the 21st century, which means that the increase of Q_{NC} has a more significant effect on Q_T than the decrease of Q_{NH} has at these locations for the buildings of the 5th percentile.

Although climate change is projected to decrease most dramatically the Q_T of building models in the 95th percentile, this change will be far smaller than the effect of making buildings more climate-adapted and thus more energy efficient. Designing a new 5th percentile building or energy retrofitting an existing building of the 95th percentile to get an

Fig. 2. Annual projected energy performance of simulated cases at various studied locations and periods. Each dot represents an individual model with particular annual energy use for heating (Q_{NH}) and cooling (Q_{NC}) per m^2 of the floor area. For each location and period, 496,800 model cases were calculated, resulting in 15,897,600 simulated cases.

Fig. 3. Annual projected average $Q_T (=Q_{NH} + Q_{NC})$ for the entire sample (middle), the 95th percentile (left) and the 5th percentile (right) at various studied locations and periods.

average building or even a 5th percentile building will have a far greater effect on reducing Q_T than the projected climate change effects. For this reason, the 5th percentile models (colour-coded in Fig. 2) were chosen for detailed analysis because they represent the most energy-efficient and the most climate-adapted examples and provide insight into the design measures required to achieve low Q_T by simultaneously optimising both Q_{NH} and Q_{NC} . According to Q_T , it is crucial to note that the 5th percentile is characterised by promisingly low energy use for cooling and heating buildings. However, it also becomes evident that the relative importance of individual studied passive design measures and their resulting impact on Q_{NH} and Q_{NC} will change over time since the resulting Q_T is significantly different until 2080 compared to the historical period of 2000.

As identified above, a high level of buildings' energy efficiency can be achieved by applying the appropriate combination of the studied passive design measures. Therefore, the relationship between a projected climate change and characteristic values of Q_{NH} , Q_{NC} and Q_T (Fig. 4) for the 5th percentile was observed in greater detail. Fig. 4 shows that Q_{NH} is highest in cold climates, such as Östersund and Moscow, and the lowest in warm climates, such as Madrid and Athens, and oceanic climates such as Porto. On the other hand, warm climates have the highest demand for Q_{NC} . Speaking in absolute terms, according to the reached Q_T in 2000, the energy use of the 5th percentile buildings is confidently below 80, 70, 45, 45, 40, 20, 25 and 5 kWh/m² in Östersund, Moscow, Berlin, Ljubljana, Milan, Madrid, Athens and Porto,

respectively. Simultaneously, the min–max range of Q_T , Q_{NH} and Q_{NC} is narrower in warm locations (coloured bars in Fig. 4). In terms of climate change impact, in locations with warmer conditions (i.e. Athens, Madrid, Porto, Milan), Q_T is projected to substantially increase until the end of the century, almost doubling the average Q_T of the 5th percentile in the instance of Madrid and Athens. A reverse trend applies to the colder locations of Ljubljana, Berlin, Moscow and Östersund, where Q_T is projected to decrease, albeit to a smaller degree (e.g. average Q_T for Östersund will be reduced approximately by 30% by 2080 in comparison to 2000). Although this trend may apply to all the mentioned locations, a turning point in the average Q_T curve can be detected in Ljubljana, where a minimum projected total energy use would be reached sometime between 2020 and 2050 ($Q_{T,2000} = 28.2$ kWh/m², $Q_{T,2020} = 27.2$ kWh/m², $Q_{T,2050} = 27.3$ kWh/m², $Q_{T,2080} = 28.1$ kWh/m²). In general terms, this means that the Q_T of the 5th percentile at the end of the century will still be highest in cold climates and lowest in warm and oceanic climates. However, the gap in the average Q_T between the cold and warm locations will decrease substantially, while the ratio between Q_{NH} and Q_{NC} will also change significantly for all locations (Fig. 4). Both described trends signal a profound change in the building energy use patterns across Europe.

This phenomenon indicates that it is easier to achieve low Q_T in temperate and warm locations solely by using passive measures than in colder climates. However, in warm and some temperate climates, by 2080, the situation is projected to change towards higher Q_T regardless

Fig. 4. Long-term energy performance of the best performing building models (according to Q_T) presented through the 5th percentile's Q_{NH} , Q_{NC} and Q_T . The coloured bars demonstrate the energy use range, while the black lines show the average value for the building models in the 5th percentile.

of the used passive measures (see Fig. 4).

3.2. Impact of individual passive design measure on energy use

To gain insight into the impact of passive design measures at each location and for every future time slice, a quantitative analysis was performed for the 5th percentile using descriptive statistics. The results can be seen in Figs. 5–7.

3.2.1. Opaque envelope thermal transmittance (U_O)

Fig. 5 shows that the range of applicable U_O values in the 5th percentile is wider in warm climates than in temperate and cold climates. Therefore, to achieve the lowest 5% of Q_T , in extremely cold locations, such as Östersund, U_O of 0.15 W/m² K or lower should be used. In contrast, in another cold (Moscow) and temperate (Berlin, Ljubljana, Milan) climates, U_O of 0.20 W/m² K or lower is necessary. For warm climates, the same analysis shows that in order for a building to be in the 5th percentile, according to Q_T , its U_O should not exceed 0.30 W/m² K. However, even under warm (i.e. Madrid and Athens) and oceanic (i.e. Porto) climates, the average U_O of the models in the 5th percentile is lower than 0.15 W/m² K, with a noticeable increase towards the end of the 21st century (Fig. 5). The average U_O value is lowest in cold locations and highest in warm and oceanic climates. Nevertheless, the 5th percentile analysis results demonstrated that low U_O values (<0.15 W/m² K) are beneficial for the energy performance of the climate-adapted buildings regardless of the climate type. The only difference is that slightly higher U_O values can be used under warmer climates, giving designers in such climate types more freedom of choice in developing

their designs. According to Q_T , the U_O value of the best case is for all the locations and all periods at 0.10 W/m² K, namely at its lowest analysed value. The average U_O value in the 5th percentile gradually increases towards the end of the century for all the analysed locations. The stated signals a trend indicating that in the future high energy efficiency, i.e. low Q_T , will be achievable on average with slightly higher U_O values than today.

3.2.2. Window thermal transmittance (U_W)

A similar observation can be made for the thermal transmittance of windows (U_W), where unexpectedly, even relatively high U_W values of up to 2.40 W/m² K can be found in the 5th percentile building models for all locations (Fig. 5). However, in the building models of the 5th percentile, high U_W (i.e. 2.40 W/m² K) is always combined with lower WFRs (below 10% in cold or below 20% in a warm climate) and minimal U_O values (i.e. 0.10 W/m² K in a cold or 0.20 W/m² K and lower in a warm climate). Similarly, as for the U_O , the average U_W value is lowest for cold locations and highest in warm and oceanic climates. Nevertheless, the average U_W is always below 1.30 W/m² K, regardless of location and period. The change in the average U_W values of the 5th percentile concerning the projected climate change is similar to that of the U_O . It means that the average U_W values are projected to steadily increase throughout the century with an increment of 0.01 to 0.10 W/m² K (i.e. $\Delta U_{W,cold} \approx 0.04\text{--}0.10$ W/m² K, $\Delta U_{W,temperate} \approx 0.09\text{--}0.10$ W/m² K, $\Delta U_{W,warm} \approx 0.01\text{--}0.04$ W/m² K, $\Delta U_{W,oceanic} \approx 0.07$ W/m² K) when comparing the 2000 and 2080 periods. The best case's U_W value is for all the locations and all periods at 0.60 W/m² K, namely at its lowest analysed value.

Fig. 5. Characteristic values of U_O , U_W and WFR represented in the 5th percentile according to Q_T . The coloured bars demonstrate the parameter range, while the black lines show the average value for the building models in the 5th percentile.

Fig. 6. W_{dis} shares represented in the 5th percentile according to Q_T . The coloured bars show the share of cases with south-concentrated windows of WFR > 5%, equal area of windows at all orientations of WFR > 5% and equal area of windows at all orientations of WFR = 5% (i.e. "base" cases) for the building models in the 5th percentile.

3.2.3. Window to floor ratio (WFR)

For cold and temperate locations, the analysis showed that it would be possible to achieve the 5th percentile Q_T by using any of the analysed WFRs, namely 5–45%, during all periods. In contrast, in warm and oceanic climates, the WFR maximum value in the second half of the century is limited to 35 or 40%. Furthermore, in the oceanic climate (i.e. Porto), the WFR for 2000 and 2020 is also limited to minimum values (Fig. 5). Be that as it may, for building models with a WFR of 45%, in cold locations (e.g. Östersund), U_W needs to be 0.8 W/m² K or lower and

combined with U_O equal to 0.15 W/m² K or less. In temperate climates (e.g. Ljubljana), the maximum WFRs are achievable with U_W of 1.0 W/m² K or less and U_O below 0.15 W/m² K, while in a warm climate (e.g. Athens), U_W should not be higher than 0.6 W/m² K. In the latter case of locations with a warm climate, such high WFR resulted in only two cases out of the whole sample of the 5th percentile. Indeed, one should be aware that such a choice may result in a predominately cooling dominated building. However, any U_W can be used for WFRs up to 20% in temperate and warm locations (e.g. Ljubljana, Athens) and up to 15% in

Fig. 7. Characteristic values of f_0 , DHC, α_{sol} and NV_c represented in the 5th percentile of Q_T . The coloured bars demonstrate the parameter range, while the black lines show the average value for the building models in the 5th percentile.

cold locations (e.g. Östersund). The influence of WFR on the resulting Q_T of the 5th percentile is probably most affected by the projected climate change, which can be seen by observing WFR ranges and average values in Fig. 5. To demonstrate, observing the 5th percentile WFR average value trend until 2080 shows that they will substantially decrease at all the analysed locations, with the most significant decrease of 8.6 percentage points in Porto and the slightest change of 2.8 percentage points for Östersund. In Porto, the “average optimal” WFR is projected to shift from 20.3% to 11.7%, a decrease of 8.6 percentage points. Simultaneously, even in Östersund, where the decrease in WFR is the smallest, the “average optimal” WFR is projected to shift from 19.5% to 16.7%, a change of 2.9 percentage points. WFR is the only studied parameter that displays a constant projected decrease in its value for the best case at all locations and all periods (Fig. 5).

3.2.4. Distribution of windows (W_{dis})

The share of building models with south-concentrated windows and WFR above 5% regarding the total number of building models of the 5th percentile can be seen in Fig. 6. This share is higher for warm and oceanic locations than for cold and temperate locations. Choosing south-concentrated windows allows using higher than average U_O values

under temperate (e.g. Ljubljana) and cold climates (e.g. Moscow), namely $0.20 \text{ W/m}^2 \text{ K}$, as well as in warm climates (e.g. Athens), namely $0.30 \text{ W/m}^2 \text{ K}$. “Base” cases with an equally distributed 5% WFR usually perform best only when combined with U_O of $0.10 \text{ W/m}^2 \text{ K}$ due to an increased influence of the thermal characteristics of the opaque building envelope on the resulting final Q_T . Observing the W_{dis} shares shows that for a building to be included in the 5th percentile of Q_T , the share of south-concentrated cases decreases over time due to the projected climate change. In particular, at many locations, the number of cases with south-concentrated windows drops below 50% by the 2080 time period. Simultaneously, the share of “base” cases is on the rise for all the locations, indicating that south-concentrated glazing is becoming a burden due to the increased overheating.

3.2.5. Shape factor (f_0)

Data presented in Fig. 7 show that, as it could be expected, the average value of f_0 for buildings in the 5th percentile according to Q_T is lower in cold climates and higher in warm and oceanic climates. Nevertheless, at all the locations, any of the analysed building shapes can be used and still result in a low enough Q_T to be included in the 5th percentile. In cold locations, lower U_O application (e.g. $0.10 \text{ W/m}^2 \text{ K}$)

allows for higher f_0 (e.g. a semi-enclosed atrium). The same is true for warm locations (e.g. Athens), but there the value of U_O can be up to $0.20 \text{ W/m}^2 \text{ K}$ when choosing a non-compact building shape. For all locations, the average f_0 values increase until the 2080 time period. However, in terms of Q_T , the best case usually has an f_0 equal to 0.796 (i.e. a semi-compact building shape), with a slight tendency to shift towards a compact building shape (i.e. $f_0 = 0.778$) with the progression of time.

3.2.6. Diurnal heat storage capacity (DHC)

Considering the DHC (Fig. 7), it can be said that although the average DHC ($\approx 110 \pm 5 \text{ kJ/m}^2 \text{ K}$) of the 5th percentile is somewhere between a medium (e.g. brick) and a heavy (e.g. concrete or stone) weight construction, all the analysed DHCs can be used to reach the 5th percentile Q_T energy use at all the locations and during all periods. The latter is primarily the result of the ability to offset the undesirable impact of low DHC (i.e. $63 \text{ kJ/m}^2 \text{ K}$) on the resulting Q_T by using low values of U_O . However, to achieve the 5th percentile of Q_T in temperate (e.g. Ljubljana) and cold (Östersund, Moscow) climates, U_O must be $0.15 \text{ W/m}^2 \text{ K}$ or lower if choosing a lightweight timber construction (i.e. DHC = $63 \text{ kJ/m}^2 \text{ K}$). Similarly, U_O must be equal to or below $0.20 \text{ W/m}^2 \text{ K}$ in Athens when using lightweight timber construction.

3.2.7. External surface solar absorptivity (α_{sol})

In Fig. 7, the characteristic values of α_{sol} can be seen, where similar as for other parameters, any of the analysed values (i.e. 0.2, 0.4, 0.6 and 0.8) can be used to achieve the 5th percentile of Q_T . Nonetheless, in the case of warm climates (e.g. Athens), α_{sol} equal to 0.2 can be used in all the cases, while higher values are limited by applying lower U_O , namely α_{sol} of 0.8, can only be used with U_O equal to or lower than $0.20 \text{ W/m}^2 \text{ K}$. The opposite is true for temperate climate locations (e.g. Ljubljana, Milan), where α_{sol} equal to 0.2 can only be used with U_O equal to or lower than $0.15 \text{ W/m}^2 \text{ K}$, while $\alpha_{sol} = 0.8$ is acceptable in all the cases inside the 5th percentile. Observing the α_{sol} values in future climate projections shows that the average value is steadily decreasing. The projected decrease in the average α_{sol} is less noticeable in cold and more pronounced in warm but above all in oceanic climates.

3.2.8. Summer natural ventilation cooling rate (NV_C)

Lastly, observing the NV_C parameter results in the 5th percentile (Fig. 7) shows that, as expected, higher average NV_C values are found for warm and lower in temperate and cold locations. Using any NV_C value can result in the Q_T of a building model that falls inside the 5th percentile. However, a more in-depth analysis of the results showed that higher NV_C rates are generally used in cases where external opaque surfaces are characterised by higher α_{sol} (i.e. 0.6 and 0.8) in all the locations. Additionally, more models with a lower DHC were included in the 5th percentile when a non-zero NV_C was simultaneously used (i.e. $\geq 1 \text{ h}^{-1}$). For all the locations, the average NV_C value of the 5th percentile is gradually rising towards the end of the century, which is a logical consequence of a warming climate trend. In brief, any non-zero NV_C value will effectively decrease Q_T , but the extent is limited by climate characteristics and the ratio between cooling and heating energy use since NV_C only affects the Q_{NC} values.

4. Discussion

The study aimed to evaluate the effectiveness of the selected passive building design measures and their ability to influence building energy use concerning projected climate change. This evaluation was achieved through a comprehensive parametric study, with a further in-depth analysis of the best performing 5% of building models (i.e. the 5th percentile). In our opinion, this approach to finding optimum building configuration is better than the construction of Pareto fronts as it gives a higher number of potential candidates with still acceptable low energy use. Unlike optimisation, the most significant asset of the selected approach is that not just the global or local minimums are found, but

also numerous neighbouring solutions are detected, still resulting in a low-energy building. Therefore, a vast pool of candidates is acquired without affecting the precision of the results. However, such an approach has some drawbacks: significantly longer calculation times and a need for a mindful insight by the assessor.

4.1. The effect of passive design measures on building energy efficiency under climate change

The results demonstrate that building energy use can be effectively regulated by passive design measures, while several parameter combinations resulted in an impressive or at least satisfactory energy efficiency level. The latter is expressed by the energy use results for the 5th percentile according to Q_T , where at numerous locations, a relatively low energy use rate was achieved by passive measures only, for example, Q_T below 20 kWh/m^2 in warm and below 40 kWh/m^2 in temperate climates. However, the results show that even if the most favourable combination of the proposed passive design measures is used at any of the analysed locations, the impact of climate change on buildings' thermal performance will be difficult to neutralise. In other words, the calculated Q_T of a building will inevitably be affected by the warming climate, resulting in either higher or lower energy use in comparison to the historical climate (i.e. 2000 period) and a substantially different ratio between cooling and heating energy demand. That is an important outcome in the context of building resilience. Nonetheless, while the stated might not be considered a problem in cold locations, where Q_T is in general projected to decrease with an only slight increase in Q_{NC} , it represents a significant issue for buildings under temperate, oceanic and warm climates. For these locations, Q_T is, in general, projected to increase, and the increment cannot be effectively counterbalanced by modifying the parameters of the studied passive design measures. In this perspective, Attia and Gobin [69] warned that even thermal adaptation strategies, such as clothing level and human thermal comfort adaptation, cannot suppress the effect of global warming. Therefore, the results provide crucial information for designing energy-efficient buildings that strive for climate adaptation and provide a general outlook for policymakers.

Moreover, the results section brings several values of the studied passive design measures, which are recommended to be practised when designing low energy buildings in each evaluated climate type. Besides, for some parameters, potential counterbalances are defined. For example, low DHC can be compensated by using very low U_O . Similar compensation can be made when applying high WFRs or high α_{sol} of the opaque building envelope. The study shows that in order to optimise (i.e. reduce) Q_T of future buildings, slightly higher U_O , U_w , f_0 , DHC and NV_C and a slightly lower α_{sol} should be used. Be that as it may, there is no need for any substantial change in the current optimal value of these parameters to achieve the lowest of Q_T also in the future. On the other hand, in future, considerably lower WFRs, than those in contemporary energy-efficient buildings should be used. However, considering WFR, the results should be interpreted to acknowledge its impact on daylighting and view as well as the corresponding occupant preferences.

4.2. Long-term climate adaptation of the best case models

For each period, the best building model (i.e. an absolute optimum) with the lowest Q_T for that period was identified. Given the effects of projected climate change on buildings' energy use and energy efficiency, there has been a broad debate in the literature about how buildings can be optimised to achieve long-term climate adaptation. This issue was further investigated in the study of the effects of passive design measures on climate adaptation. The results are presented in Fig. 8, where the long-term development of energy performance for an absolute best case among building models can be observed for each particular period and each location.

Fig. 8 shows that cold locations (i.e. Östersund and Moscow) could

Fig. 8. Long-term development of energy performance of each best case according to Q_T .

benefit from the warming climate since Q_T is projected to drastically decrease regardless of the period to which a building is optimised. If a residential building was built in Östersund in 2020 according to the optimum defined by the climate data for the 2000 period, after 50 years, it would cumulatively use 425.6 MWh of energy with a ratio between heating and cooling energy use (Q_{NH}/Q_{NC}) of 18. If opting for the 2020/2050 period optimum, cumulative energy use would be 418.3 MWh ($Q_{NH}/Q_{NC} = 80$) and 422.1 MWh ($Q_{NH}/Q_{NC} = 214$) if going for the 2080 period optimum.

On the other hand, Q_T of the best case in warm and some temperate locations (i.e. Athens, Madrid and Milan) is projected to significantly increase, so that buildings at such locations will use considerably more energy than in the current situation. If we look at the example of a residential building built in 2020 in Athens, after 50 years, the building will consume 185.5 MWh of energy ($Q_{NH}/Q_{NC} = 0.006$) if opting for the 2000 period optimum, 177.3 MWh ($Q_{NH}/Q_{NC} = 0.057$) if deciding on the 2020/2050 period optimum and 187.7 MWh ($Q_{NH}/Q_{NC} = 0.265$) if going for the 2080 period optimum.

In some cases, such as Berlin and Ljubljana, Q_T does not appear to be significantly affected or dependent on the optimisation period. However, the Q_{NH}/Q_{NC} ratios in these locations will be affected. The same example of a residential building as above, built in Ljubljana in 2020, would use after 50 years 226.9 MWh of energy ($Q_{NH}/Q_{NC} = 5.0$) if opting for the 2000/2020 period optimum and 226.4 MWh ($Q_{NH}/Q_{NC} = 7.3$) if choosing the 2050/2080 period optimum. In general, it is clear that in all the locations, except Milan, in the context of cumulative Q_T , it is best to design a new building according to the mid-term optimum (i.e. the 2020/2050 period). Milan is the only case where the best set of parameters is achieved using the best case for the 2080 period.

It is important to note that even if the above-described energy use indicates that for some locations, the design of a building according to climate change projections does not have a significant impact on the resulting cumulative Q_T , the energy use and heating to cooling energy use ratios are shown for the absolute best cases only. It means that such

building models represent one of the best climate-resilient building designs possible. At this point, it also has to be stressed that choosing the long-term optimum building design is not as easy as just choosing a set of passive design measures that would lead to the lowest Q_T but is somewhat more complicated. Since the warming climate will result in lower Q_{NH}/Q_{NC} ratios and higher Q_{NC} use, the building energy performance optimisation must be a thorough process. Higher Q_{NC} results in progressively higher electricity consumption for cooling, which is particularly worrisome [70] due to increased peak demand. If more and more buildings become actively cooled during summer or even in spring and autumn, it will lead to a significantly different energy demand for building operation – the energy demand for which energy suppliers may not be prepared.

4.3. Study limitations

The results of the study must be interpreted within the framework of applicable limitations. The primary limitation to the generalisation of the presented results is that the floor area and the corresponding volume and shape of the analysed building models were devised according to the statistical average of the EU. We are clearly aware that such a sample represents residential buildings in the EU but has limitations in applying the derived results to specific countries or building. Therefore, the study's findings should be used with caution when used as guidelines for the performance of buildings that have much smaller or much larger floor areas or are, in any case, geometrically considerably different. Second, several input parameters for energy models were set constant, limiting our study primarily to passive building envelope elements and natural ventilation. Shading of the transparent elements was set constant since it was recognised by our previous findings (see refs. [7,71]) as one of the crucial actions to control overheating at present and in future. Of course, we are aware that shading performance's parametrisation may provide alternative insights into the problem. Besides, occupant interaction with the built environment was also set constant,

essentially limiting the impact of thermal comfort and occupant behaviour on the building's energy performance and vice versa. Third, considering the weather data, the simulated building model's location is defined by the weather station where the weather time series is recorded. The latter ignores aspects such as urban morphology induced wind speed and direction, shading by the surrounding urban context and the effects of the urban heat island [13]. Another limitation of the study concerns the weather data because it considers the IWEK database weather, which has a different timeframe than HadCM3. Therefore the EPW data are expected to slightly overestimate the effect of climate change, as stated by Jentsch et al. [14] and Moazami et al. [72]. However, the weather data are still accurate enough to estimate the projected impact of climate change on building energy use.

5. Conclusions

This paper investigates the long-term energy performance of single-family detached residential buildings by means of a comprehensive parametric study. Numerous sets of passive design measures were simulated and found effective in achieving high building energy performance. The main findings and conclusions of the conducted analysis are as follows:

- In the analysed single-family residential buildings, the projected warming climate will result in lower heating and higher cooling energy use. However, the total energy use (Q_T) is projected to increase in warm climates and decrease in cold climates, while in temperate climates, the evolution of Q_T depends on the location.
- Low total energy use (i.e. $Q_T \leq 30 \text{ kWh/m}^2$ per year) of single-family residential buildings can be assured to a large extent solely by passive building design measures, particularly in oceanic, warm and temperate climates.
- In all the considered climates, it will be difficult to completely neutralise climate change effect on building energy use for heating and cooling by employing the studied passive building design measures. This issue is especially alarming in warm climates, where total energy use is projected to increase compared to the historical period substantially.
- The most effective passive design measure for long-term climate adaptation of residential buildings is in all the analysed locations applying lower WFR, which in warm climates needs to be supplemented by lower α_{sol} . Due to global warming, the overall importance of low U_O and U_W values will decrease to a certain extent, as illustrated by a slight increase in the average U values of building models in the 5th percentile. However, selecting a combination of passive design measures depends largely on whether one aims for a heating or a cooling dominated building, which leads to different seasonal energy demands.
- The energy efficiency of residential buildings may be further improved by active building measures (e.g. heat recovery ventilation, etc.). Nonetheless, it is inevitable that in a warm oceanic climate, such as Porto's, it would be possible to design a nearly zero-energy building solely by using appropriate passive design.
- Although the results represent crucial information on the effectiveness and eligibility of passive building measures for achieving low energy use and climate change adaptation, additional research in this field is recommended in order to aid policymakers to develop appropriate strategies and guidelines in terms of future energy performance of buildings and their impact on the overall energy supply network.

CRedit authorship contribution statement

Luka Pajek: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Mitja Košir:** Conceptualization, Methodology,

Validation, Investigation, Resources, Writing - review & editing, Visualization, Supervision.

Declaration of Competing Interest

The author declare that there is no conflict of interest.

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