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Energy flexibility of building systems in future scenarios: optimization of the control strategy of a dynamic shading system and definition of a new energy flexibility metric

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ABSTRACT

The growing awareness of climate change is constantly moving the attention of designers and policymakers from typical and current scenarios to future layouts. This new approach introduces a degree of uncertainty that should be accounted in the building design process. The multitude of possible scenarios suggests considering dynamic system that can adapt themselves to unpredicted operating conditions. The aim of this study is to test a new approach and a new flexibility metric analysing the behaviour of a high-performance dynamic internal curtain in current and future scenarios. The first part of the paper focuses on the optimization of the dynamic system in the current scenario; this preliminary analysis represents the traditional design approach and is considered the baseline for all the comparisons. Hence, defining a matrix of likely scenarios, this paper explores the behaviour of three different selected control strategies – always off (i.e., no curtain), fixed control, optimized control – in the different scenarios considering possible variations of i) climate, ii) urban context, iii) internal loads, and iv) building use. The main outcomes of the research are, on the one hand, the comparisons of the control strategies and the benefits of the dynamic system and, on the other hand, the definition of a new metric that can properly describe the flexibility of the building systems with reference to the future scenarios analysed. This metric is based on six classes – which describe the statistical distribution of the energy consumptions of all the scenarios simulated in the matrix – and an index called Energy Flexibility Index (EFI) that quantifies the flexibility of the technology considered. The case study analysed highlights how implementing a dynamic shading system, considering the same building use, can increase the EFI of nearly 21% for non-optimized control strategy and up to 23% when optimized. While changing the building use in residential reduces these values respectively, to 6% and 7%.

1. Introduction

One of the clearest trends that has emerged during last years is, undoubtedly, the soaring interest and attention to the energy efficiency, especially in the building sector. Starting from the first main international agreements to reduce the greenhouse gas emissions – such as the United Nations Sustainable Development Goals [1] and the Paris Agreement Commitment [2], first, and the Glasgow Climate Pact [3], then – many Countries have started to develop and update energy codes to control the energy consumptions in the building sector. Currently, the EU is updating the existing regulatory framework (Energy Performance of Buildings Directive [4,5]) as part of the "Fit for 55" Commission Work Programme to achieve the full decarbonisation of the building stock by 2050 [6].

All these actions are driven by the rising awareness that the human-induced climate change is causing adverse events and damages to ecosystems, sometimes with irreversible consequences. The increasing frequency and magnitude of extreme weather events is reducing the chances to adapt ourselves to these new boundary conditions. The increase of 1.5 °C related to pre-industrial temperatures in the current scenario (i.e., near term scenario 2021–2040) will lead to an increase of the climate related hazards, depending also on other concurrent factors such as the socioeconomic development. Limiting the global warming to 1.5 °C should reduce the damages but can't entirely avoid them [7]. A

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higher degree of uncertainty features the long-term scenario (2040–2100) as the near-term mitigation actions can significantly affect the risk of adverse events in the future. Nevertheless, the main trend in the next future is defined at least until the mid-century as the global surface temperature will increase regardless the scenario considered [8].

Starting from this new awareness, the number of studies regarding the energy behaviour in future climates is continuously rising [9]. Nevertheless, one of the main weaknesses in the future-projected studies is the strict focus on single variables – usually related to future weather scenarios as affected by climate change – excluding many other factors that could affect the performance of the buildings in the future as well. The urban context [10,11], the internal loads [12], the building use [13], and the socio-demographic variations [14] are examples of other main variables that could vary in the future changing the environment where the designed building will operate. For example, the realization of a new building, the spread of a new efficient lighting technology, the change of use from office to residential could be the causes of additional variations in the boundary conditions that are usually neglected in the future-based studies.

While architects and designers tend to focus on flexibility as an internal functional spatial property of layouts and the versatile use of buildings, initiatives such as Open Buildings [15] transpose flexibility on neighbourhoods and urban contexts as an equally important element of the flexibility-term. The flexibility goes both ways, buildings may adapt to changing conditions in the local environment, and the opposite happens when a neighbourhood can change when single buildings are used for other purposes.

Consequently, one unresolved issue in finding the optimal balance between the energy and the environmental performance of buildings depends on the (changing) local context [16]. Other aspects of changing local environments focus on climate resilience. As part of the European delegated acts of sustainable taxonomy, economic activities must substantially reduce climate risks. For large-scale investments, analyses need to include at least 10-to-30-year climate projections concerning chronic and acute climate-related hazards. A central aspect of urban changes is the altered solar and heat flux and changing wind patterns resulting in the phenomena related to the urban heat island (UHI) effects [17]. Studies (e.g., [18,19]) have shown the significance of the impact on the heating and cooling energy demand of buildings by changing ambient temperature due to UHIs. Santamouris et al. [20] showed that mitigations of UHI can be achieved by altering the public realm and the built form. As such, the building height of existing and future buildings directly impacts the UHI and how new developments perform over time.

Nonetheless, no established requirements for accounting for future developments surrounding a given building have been defined when it comes to building energy performance. Though in practice, design guidelines, such as for example [21], do prescribe shadow impact analyses on pedestrian areas where it distinguishes between a) current context buildings, b) approved buildings under construction, and c) submitted and proposed buildings.

Flexibility of buildings addresses the crucial aspect of buildings' expected lifespan, as it potentially and fundamentally can alter the typology and use of new and existing buildings. In a recent study, Andersen and Negendahl [22] showed, by looking at the demolition data of more than 100000 buildings, that the typology of buildings significantly affected their average lifespan. New office buildings in general lasts 41 years compared to 168 years of multifamily housing. Consequently, a building that have topological flexible uses may in theory last at least as long as the lifespan of the longest lasting topology it covers. Any extension of the lifespan of buildings greatly affects both life cycle impacts (global warming potential and other) and life cycle costs [22].

Moreover, as better described in the following sections, the internal loads changed significantly in the past years thanks to a growing awareness of energy efficiency supported by significant technological improvements. This reduction trend is likely to be confirmed in the following years, but currently there are different uncertainties regarding the magnitude of the reduction due to its strict dependency on the technological advancements. Similarly, the internal layout and the use of the designed building could change in the future due to external socio-economic reasons.

All these considerations outline a huge number of possible future scenarios where the buildings could operate increasing the uncertainty about the boundary conditions and, therefore, the discrepancies between the design context and the actual operating context. The variability of the boundary conditions can be considered somehow already accounted in the current design process – even if in a different connotation – if we consider mid and short-term changes. For example, the alternation of the seasons, the hourly and sub-hourly variations in the outdoor climate and the occupancy are only a few factors that define a dynamic environment in the mid and short term. One of the latest solutions to improve the building performances accounting for this variability is the responsive envelope. Responsive technologies allow changing the envelope properties according to different possible stimuli (solar radiation, temperature, occupancy, daylighting, etc.) to reduce energy consumption and increase the indoor comfort. Recent studies are starting to evaluate the capability of these technologies to adapt themselves also in a long-term future scenario entwining these two themes in an interesting new research topic. Nevertheless, currently the future scenarios are considered only from a weather point of view rather than with a wider approach.

In light of the above, the main aim of this study is to define a new methodology and metric to describe the behaviour of a building technology – not necessarily responsive – in different possible future scenarios. The main complexity of considering different uncertainties sources in the future scenarios – e.g., weather, building use, internal loads, urban context – is the management and interpretation of the results of a wide number of possible combinations. Therefore, the main goal and outcome of this study is the definition of the methodology and a new metric that allows to sum up the future behaviour of a technology in a single index.

To define and test the proposed methodology, a case study is considered, and a dynamic shading system's behaviour is evaluated and optimized in different possible future scenarios. Firstly, the first part of the paper focuses on the technology's optimization in the current scenario and defines three control strategies – always off, standard control, optimized control – used as the basis for the following flexibility analyses. Once the design in current scenario is completed, a matrix of likely scenarios, including four possible variations – climate, urban context, internal loads, and building use –, consider how the selected control strategies behave in all the scenarios adopted. Finally, in the second part of the study, a new energy flexibility metric – the Energy Flexibility Index (EFI) – was defined and applied to the case study and to the matrix considered, to quantify the capability of the technology to improve the energy behaviour in an intensely uncertain scenario.

The following sections provide, firstly, a review of the state of the art of the main topics involved in this study then a methodology insight is provided to define the characteristics of the case study, the technology selected, and the theoretical apparatus behind the flexibility index proposed. Hence, after the methodological framework, the proposed methodology is applied to a case study located in Denmark.

2. Definition of future scenarios

Any impact on predicted building energy performance requires precise assumptions and clear boundary conditions regarding the climatic conditions, the context the building is built in, and how the building is expected to be used. None of these aspects are entirely settled when predictions happen in the future. Thus, typical performance-based energy simulations are set in standardized weather formats, based on in as-built and as-approved [21] context with standard building use and load profiles [23]. As an attempt to define and calculate the adaptability of a building in the uncertain space of imprecise assumptions, an

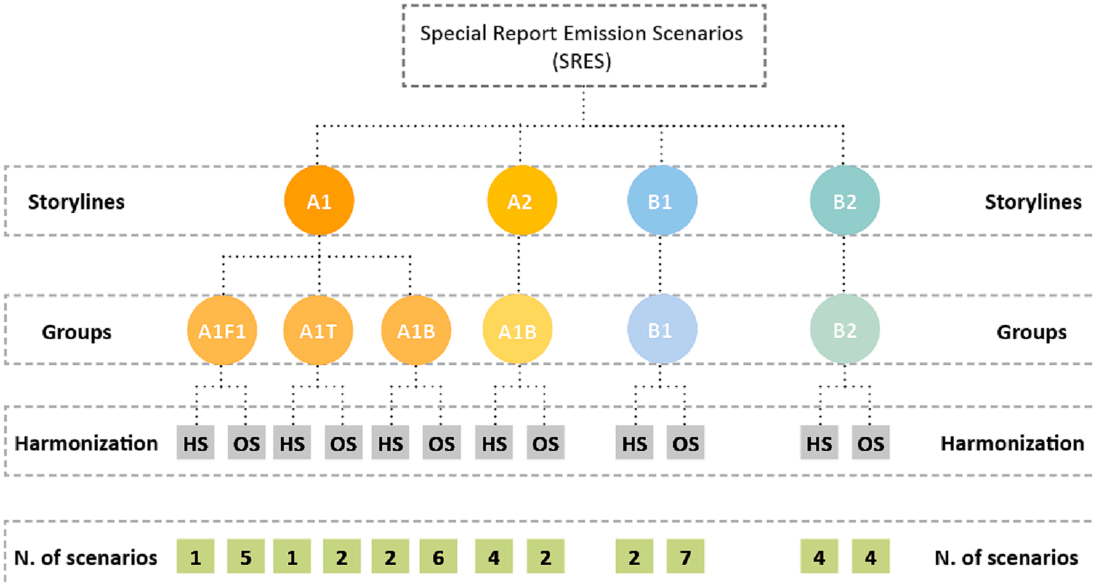

Fig. 1. Schematization of the Special Report Emission Scenarios.

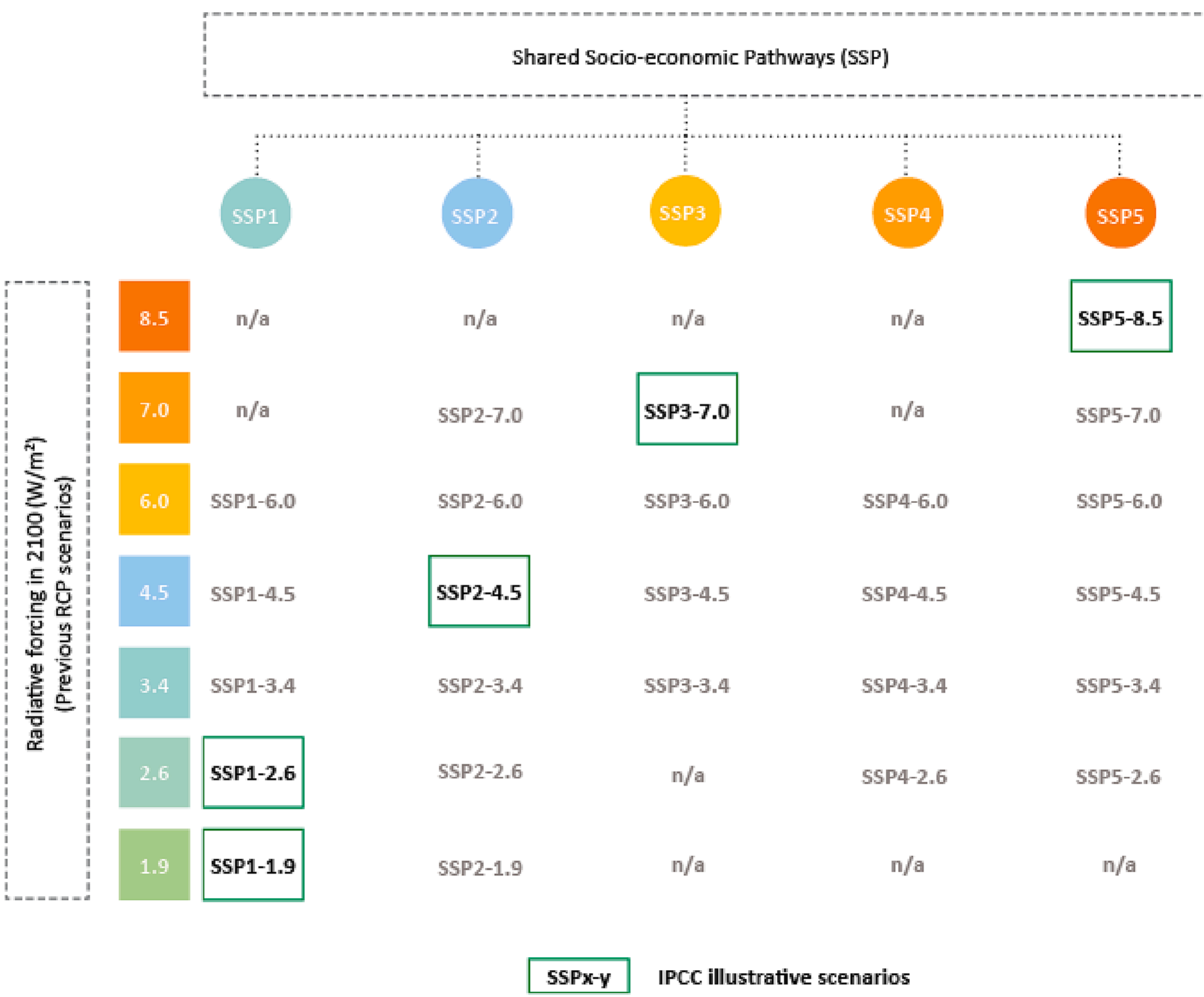

Fig. 2. Schematization of the AR6 scenarios.

establishment of probable future scenarios is defined by state-of-art and current practice. As a result, we distinguish between two types of future scenarios. The first category is based on a widely established consensus in the literature: future weather scenarios. The second category covers less understood and researched consequences, and yet are important for building energy performance impacts: other future scenarios.

2.1. Future weather scenarios

Building energy analyses are usually performed using Typical Meteorological Year (TMY) weather files, introduced in 1978 [24] and updated in 1995 (TMY2) [25] and 2008 (TMY3) [26]. These files are composed by a concatenation – one for each month and for each parameter – of the most typical and representative weather data selected from a series of weather recordings (usually at least 10 years) that compose a fictitious representative typical year.

Nowadays, the awareness about climate change has triggered a soaring interest in building performance analyses in future scenarios and, consequently, in the creation of future weather files. Future climate scenarios are based on the future projections of the warming trends related to different anthropogenic emission scenarios. The Intergovernmental Panel on Climate Change (IPCC) released in 1992 with the supplementary report [27] the first emission scenarios – IS92 – for the global circulation models, which are needed for developing climate change scenarios. Starting from this first set, a new set was developed in 1996 – then used for the Third Assessment Report (TAR) in 2001 [28] – and then refined in the Fourth assessment report (AR4) released in 2007 [29] which have been and are still largely used in the research field. In the AR4 four different qualitative storylines of the emissions driving forces – demographic, social, economic, technological, and environmental forces – are provided. Each storyline yields different scenarios that belong to the same family (A1, A2, B1, B2). The A1 family includes three groups of scenarios (A1F1 for the fossil fuel intensive scenario, A1T predominantly non-fossil fuel scenario, A1B balanced scenario) while the A2, B1, and B2 families are composed by one group each. Finally, within each group and family, scenarios are distinguished in Harmonized Scenarios (HS) and Overshoot Scenarios (OS); the first ones share harmonized assumptions on global population, gross world product, and final energy, while the second ones consider uncertainties in the driving forces [30] (Fig. 1).

The fifth assessment report (AR5) released in 2014 [31] introduced the Representative Concentration Pathways (RCPs) which are different scenarios that include different series of emissions and concentration of GHGs up to 2100. To understand the RCP it is fundamental to define the radiative forcing, which is "*the change in the net, downward minus upward, radiative flux at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as, for example, a change in the concentration of carbon dioxide (CO2) or the output of the Sun*" [32]. The RCP provides only one (as explained by the word "representative") of the possible scenarios that lead to a specific radiative forcing, which is represented by the RCP number. Hence, four different pathways – from a stringent mitigation to a high GHG emission scenario – are defined. In the RCP2.6 the radiative forcing peaks at nearly 3 W/m^2 and then declines up to 2.6 W/m^2 in 2100, in the intermediate RCP4.5 and RCP6 the radiative forcing stands respectively at 4.5 and 6 W/m^2 in 2100 while in the RCP8.5 the radiative forces reach 8.5 W/m^2 in 2100 with a growing trend in the following years. For practical feedback, the RCP2.6 allows to keep the temperature increase below 2 °C over the preindustrial temperatures in 2100 while in the RCP8.5 the CO2 concentration is 3–4 times higher than the preindustrial levels with a global average temperature change of nearly 4 °C.

The latest assessment (AR6) released in 2022 [33] considers the Shared Socio-Economic Pathways (SSPs) that include a greater range of scenarios. The SSPs are based on five narratives concerning socio-economic development starting from the sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil fuelled development (SSP5), and an intermediate scenario (SP2) [34]. These socio-economic scenarios are coupled with the RCP projections to provide an exhaustive framework (Fig. 2); the resulting scenarios are usually described as SSPx-y where x refers to the Socio-Economic Pathways while y refers to the level of radiative forcing in 2100 (e.g., SSP5-8.5, SSP2-4.5, SSP1-1.9 etc.). The AR6 report evaluates the climate response with reference to five possible future development called illustrative scenarios [7].

Table 1
Comparison between statistical and dynamical downscaling methods.

	Statistical downscaling	Dynamical downscaling
Advantages	• Low computational resources required • The same method can be applied everywhere improving the comparability of the studies • Downscaling based on easy-to-use open-source tools • Refers to specific weather stations and are based on observed weather data	• Based on physical assumptions • More accurate • All variables are internally consistent in time and space • Provides information of sites without observational data
Disadvantages	• Assumes that the large/local scale relationships will be the same in the future • ess accurate	• Computationally expensive • Limited number of RCMs • Larger resolution scale, may require further downscaling

These emission scenarios are used to force the Global Climate Models (GCMs) – which are numerical models validated against past climate observations [35] – in order to obtain future weather forecasts. The GCMs are based on coarse resolution from both spatial (>100 km^2) and temporal point of view (monthly scale). It follows that GCMs in their original form are not suitable for building energy analyses; to solve this issue, GCMs are temporally and spatially downscaled using different methods: statistical method, dynamical methods, and hybrid methods [36]. Statistical downscaling defines empirical relationships between historical large-scale data and local weather data. Then, the future local climate is generated combining these relationships and the future predictions obtained from the GCMs large-scale predictions [37]. Starting from this general concept, statistical approaches can include different specific techniques such as the extrapolating statistical, the imposed offset, and the stochastic method. In the building energy modelling field, the most widely used statistical method is the imposed offset method [38] which is based on the morphing technique [39]; this method consists of three transformation algorithms – shifting, stretching, and their combination –, applied to the baseline climate parameters to obtain future projections.

On the contrary, the dynamical downscaling is based on the Regional Climate Models (RCMs) represent local landscape and atmosphere thanks to a higher spatial resolution (from 2.5 to 50 km^2). Hence, the dynamical downscaling method processes – through local data and equations – the atmospheric fields simulated in the GCMs to obtain local weather data [37].

Table 1 sums up the main advantages and disadvantages of the dynamical and statistical downscaling methods.

Finally, the hybrid method merges the statistical and dynamical approaches to reduce the computational requirements of the dynamical downscaling.

The higher accuracy notwithstanding, the dynamical downscaling is still less applied than the statistical methods in the built environment. This trend is probably related to the ease of use of the statistical methods and to the large availability of commercial and open-source tools such as CCWorldWeatherGenerator [40], WeatherShift [41], Meteonorm [42]. However, considering the main parameters used in the building energy modelling – such as the outdoor temperature – and the final energy consumption, the results obtained with these two methods can be

Fig. 3. Rendering of the pavilion considered as case study.

considered comparable [43].

2.1.1. Other future scenarios

Despite the climate change will probably be the main variable that we will consider in our building design in the next years, many other factors could affect the building energy behaviour. The trends registered in the past years can help us to define possible future evolutions of variables that can affect the energy consumption of buildings.

2.1.2. Internal loads scenarios

Among these, one of the clearest trends being defined regards the reduction of the internal loads related to lighting and electrical equipment. One of the main differences between the energy simulation and the real operation consumption relies on the overestimation of the internal gains and hence of the HVAC capacity. Kim et al. [44] analysed the internal gains in office buildings in the past 30 years to define specific trends for lighting systems and electric equipment. The results of this study show that the power consumptions related to desktops, laptops, and monitors are on a decreasing trend started in 2000–2005. Moreover, this study identifies a significant reduction (nearly 50%) in the lighting loads thanks to the spread of LED lights. The only increasing trend was found for the small printers which has, however, a very limited impact on the overall internal loads. This change in the internal loads can be a very influential driver for energy demand [45], and the increasing sustainability awareness will probably confirm and emphasise this trend.

Table 2
Building envelope characteristics.

Building component	Thermal transmittance U [W/m^{2}K]	Solar Heat Gain Coefficient SHGC [-]	Visible Light TransmittanceVLT [-]
Wall	0.136	–	–
Roof	0.102	–	–
Slab	0.100	–	–
Window without curtain	1.00	0.78	0.82
Window with curtain*	0.77	0.34	0.04

* Values were obtained simulating the glazed envelope with LBNL Window 7.7 [54] consistent with the ISO 15099 standard.

2.1.3. Urban context scenarios

Determining the contextual change in the local environment in the future is a challenging task. Local initiatives, regulations, and changes in regional and urban planning politics significantly affect which building typologies can be expected to be built in the future. When available long-term plans are given, contextual changes to the urban environment can be more precisely anticipated. An indirect measure of changing contextual topology has been developed by modelling the urban canyon effect. Urban canyon characteristics describe the spatial difference between the ground segments versus the height of any obstructive elements carrying thermal capacity and invoking heat stress to the surroundings [46]. Similarly, the changing properties of the building envelopes may affect the Urban Heat Island changing the local microclimate. Moreover, as already mentioned, recent studies [22] highlight that buildings' lifespan can be significantly shorter than expected especially in the case of office buildings. This outcome introduces further uncertainties in the future scenarios as the urban context – and consequently the local environmental context – can be significantly influenced by surrounding buildings.

2.1.4. Building use scenarios

Another key role in the definition of new unpredicted scenarios could be played by the changes in building use. Different drivers – such as market forces, new businesses, new ways of working and/or living, etc. – can trigger a change in the building use [47] with consequences on the building energy behaviour. Moreover, the reuse of buildings is spreading as it is considered one of the most promising strategies in the circular construction approaches. Indeed, the reuse allow to minimize the energy consumptions of transport and/or reprocess the building components leaving a large portion of embodied carbon untouched [48]. In a Life Cycle Energy Assessment (LCEA) perspective, on the one hand the reuse of buildings – and the consequent increased lifespan – helps to significantly reduce the embodied energy demand. On the other hand, it increases the operational energy cost, reducing the overall benefits [49].

This tendency has increased the attention to architecturally flexible spaces as these spaces can absorb internal variations [50] starting from the simple wall adjustments up to a complete change of use. Usage alterations of existing buildings are a common phenomenon, often acknowledged as transformation or adaptation. Any such intervention is aimed at changing its capacity and function to adjust, re-use or upgrade a building to meet new conditions or requirements [51]; examples range from former religious buildings [52] to changing use of commercial buildings [53].

3. Methodology

3.1. Simulation settings, control strategies, and current scenario

3.1.1. Software and simulation settings

A small multifunctional pavilion – mainly conceived as open space office – designed by Henning Larsen in Fredericia (Denmark) – was considered as case study to define and evaluate a new metric for the energy flexibility of buildings. The pavilion is characterized by a 130 m^2 ellipse shaped plan – divided into a main hall (70 m^2) and in service areas – with a variable height that ranges from 2.2 m to 3.8 m. The Window to Wall Ratio (WWR) is nearly 30% in the main hall and the windows are partially shaded by the external 3D-printed structural columns and by the overhanging roof as shown in Fig. 3.

From a performance point of view, the building envelope characteristics are described in the table below (Table 2). To improve the energy behaviour in both summer and winter period, a high-performance dynamic curtain was considered on the glazed sun-exposed surfaces of the building. The curtain considered is located inside the pavilion and is characterized by the following parameters: Visible Light Transmittance (VLT) equal to 0.04, infrared emissivity equal to 0.21, Solar Transmission (Ts) equal to 0.04, and Solar Reflection (Rs) equal to 0.74. The above-described parameters allow to both improve the winter behaviour reducing the overall thermal transmittance (U) – despite the daylighting and internal gains are reduced – and improve summer behaviour reflecting the solar radiation as shown in the table below.

To evaluate the energy performance of the case study described, EnergyPlus v.9.6 [55] was considered as simulation engine. Considering the complex shape of the building, Rhinoceros v.7 [56] and Grasshopper [57] – based on the Honeybee v.1.4.0 [58] plugin – were used to create the reference energy model in EnergyPlus.

With reference to the building systems and internal loads, the lighting loads in the current scenario were set to 6.57 W/m^2 in accordance with the IECC 2021 [59] for open space offices, the electric equipment was set to 10.3 W/m^2 and the occupancy considered was 0.057 people/m^2 according to ASHRAE 90.1 2019 [60] which was used also to define the operational schedule. To better describe the energy behaviour of the dynamic curtain, a dimmable lighting system was connected to a daylighting sensor with a setpoint equal to 300 lux in order to account for the reduction of natural daylighting when the curtain is closed. Finally, to avoid the results dependency on specific HVAC system, the real HVAC system was substituted with an ideal loads system. The heating and cooling setpoints were set respectively to 21 °C and 24 °C and the consumptions used for the energy considerations were obtained dividing the heating and cooling demand (thermal loads of the ideal loads system) by a reference COP and EER (COP = 3, EER = 3) to allow comparisons with the electrical lighting consumptions.

3.1.2. Control strategies

Before discussing and analysing the future scenarios, the first step of the study was focused on the choice and optimization of the control strategy adopted for the dynamic curtains system in the current scenario. To that end, a baseline and eight different control strategies were evaluated to optimize the energy consumption of the pavilion. The control strategies considered in the preliminary optimization are described in the following list and equations where: t is the analysis timestep considered, a shading state equal to 0 corresponds to the open curtain state, while 1 corresponds to the closed curtain state. The control strategies that require a specific activation threshold and/or specific functioning schedule were optimized to improve the behaviour of the dynamic system. Despite the optimization of the system itself is not the main aim of the paper, the envelope behaviour was optimized to avoid inconsistencies in the flexibility output which are not attributable to the technology itself but are rather related to an improper control of the shading system. Therefore, to obtain a more reliable result, the genetic optimization was run in the Grasshopper environment, coupling the consumption outputs got from EnergyPlus with a genetic optimization tool (Galapagos). In particular, – considering that the shading system acts on both thermal and lighting consumptions with opposite effects – the following function (Eq. (1)) was minimized in the optimization process considering the activation threshold and/or the control strategy schedule as genome of the optimization.

$$f(x,y) = E(Heating(x,y)) + E(Cooling(x,y)) + E(Lighting(x,y)) \quad (1)$$

where x and y are the activation threshold and the control strategy schedule to optimize and E is the electrical consumption related respectively to Heating, Cooling, and Lighting.

- Always off (Mod. 00): it is the baseline of this first part of the study and corresponds to the model without curtains; Eq. (2) describes mathematically the algorithm considered for this control strategy. In this case, no dynamic system is considered, and the windows are unshaded during the whole year.

$$Shading\ State_{Mod.00}(t) = 0\ \forall t \in [1^{st}\ January; 31^{st}\ December] \quad (2)$$

- On if high zone temperature during summer (Mod. 01): the curtains are closed during the summer period (1st June – 1st September) only if the zone temperature (T_{in}) exceeds the set threshold. The genetically optimized setpoint is 24 °C and Eq. (3) describes mathematically the algorithm considered for this control strategy. The first condition of the Eq.3 ensures that the curtains are opened during colder seasons, while the second condition allows to reduce the incoming solar radiation when – during summer – the temperature is too high, finally the third one allows to reduce the lighting consumption when the temperature are below the cooling system activation threshold.

$$Shading\ State_{Mod.01}(t) = \begin{cases} 0 \rightarrow \forall t \notin [1^{st}\ June; 1^{st}\ September] \\ 1 \rightarrow \forall t \in [1^{st}\ June; 1^{st} September] \bigwedge T_{in}(t) \geq 24^{\circ} C \\ 0 \rightarrow \forall t \in [1^{st}\ June; 1^{st} September] \bigwedge T_{in}(t) < 24^{\circ} C \end{cases} \quad (3)$$

- On during night (Mod.02): the curtains are closed during night hours as shown in equation (4) where the first condition ensures that the curtains are closed during nighttime and the second allows to open them during daytime.

$$Shading\ State_{Mod.02}(t) = \begin{cases} 1 \rightarrow \forall t \in Nighttime \\ 0 \rightarrow \forall t \in Daytime \end{cases} \quad (4)$$

- On if high zone temperature during whole year (Mod. 03): the curtains are closed during the whole year only if the zone temperature exceeds the set threshold; the genetically optimized setpoint is 24 °C (Eq. (5)). The first condition allows to take advantage from the solar gains during cold days reducing the heating demand, while the second one reduces the cooling consumption during summer.

$$Shading\ State_{Mod.03}(t) = \begin{cases} 0 \rightarrow T_{in}(t) < 24^{\circ} C \\ 1 \rightarrow T_{in}(t) \geq 24^{\circ} C \end{cases} \quad (5)$$

- On if high solar radiation during summer (Mod. 04): the curtains are closed during the summer period (1st June – 1st September) only if the solar radiation (G) exceeds the set threshold; the genetically optimized setpoint is 100 W/m^2 (Eq. (6)). The first condition ensures that the curtains are open during the coldest period of the year, the second one allows to close the curtains during summer when the solar radiation is high, while the third one aims to reduce the lighting demand during summer when the solar radiation – and hence the cooling demand – is low.

$$ShadingState_{Mod.04}(t) = \begin{cases} 0 \rightarrow \forall t \notin [1^{st} June; 1^{st} September] \\ 1 \rightarrow \forall t \in [1^{st} June; 1^{st} September] \ \wedge G(t) \geq 100\, W/m^2 \\ 0 \rightarrow \forall t \in [1^{st} June; 1^{st} September] \ \wedge G(t) < 100\, W/m^2 \end{cases} \tag{6}$$

- On if cooling is on (Mod.05): the shading device is connected to the cooling system and the curtains are open when the cooling system is off (Eq. (7), first condition) closed when the cooling system is on (Eq. (7), second condition).

$$ShadingState_{Mod.05}(t) = \begin{cases} 0 \rightarrow Cooling(t) = 0 \\ 1 \rightarrow Cooling(t) > 0 \end{cases} \tag{7}$$

- On if high cooling (Mod. 06): the curtains are closed only when the cooling power exceeds a certain threshold – in this case 2500 W – identified through a genetic optimization to find the lowest energy consumption for this control strategy. Similarly to the previous model, Eq. (8) shows that the curtains are open when the cooling power is lower than 2500 W (first condition) and are closed when it exceeds 2500 W.

$$Shading\ State_{Mod.06}(t) = \begin{cases} 0 \rightarrow Cooling(t) < 2500W \\ 1 \rightarrow Cooling(t) \geq 2500W \end{cases} \tag{8}$$

- Mixed 1 (Mod. 07): this strategy is based on the Mod.01 (zone temperature threshold) during summer (1st June – 1st September) and on the Mod.02 (night control) during winter; the genetically optimized setpoint is 24 °C (Eq. (9). The first condition of the equation regards the behaviour during autumn, winter, and spring during daytime when the curtains are always open to maximize the solar gains while the second condition allows to close the curtains in the same period during night-time to reduce the thermal transmittance when there is no solar radiation. The third and the fourth conditions regard the summer period when the curtains are closed when the temperatures are higher than 24 °C and are open below this threshold to reduce the lighting consumption.

$$Shading\ State_{Mod.07}(t) = \begin{cases} 0 \ \rightarrow \ \forall\ t \notin [1^{st}\ June; 1^{st}\ September] \ \ \wedge t \in\ Daytime \\ 1 \ \rightarrow \ \forall\ t \notin [1^{st}\ June; 1^{st}\ September] \ \wedge t \in\ Night\ time \\ 1 \ \rightarrow \ \forall\ t \in [1^{st}\ June; 1^{st}\ September] \ \wedge T_{in}(t) \geqslant 24^{\circ}C \\ 0 \ \rightarrow \ \forall\ t \in [1^{st}\ June; 1^{st} September] \ \wedge T_{in}(t) < 24^{\circ}C \end{cases} \tag{9}$$

- Mixed 2 (Mod. 08): starting from the Mod.07 strategy, the length of the summer period was optimized to improve the performance; the genetically optimized period is 24th June – 9th September (Eq. (10). The conditions reported in the Eq.10 are the same described in the previous point except for the length of the summer period mode, which was optimized to find the right balance between heating, cooling, and lighting demand.

$$Shading\ State_{Mod08}(t) = \begin{cases} 0 \ \rightarrow \ \forall\ t \notin \left[24^{th}\ June; 9^{th}\ September\right] \wedge t \in Daytime \\ 1 \ \rightarrow \ \forall\ t \notin \left[24^{th}\ June; 9^{th}\ September\right] \wedge t \in Nighttime \\ 1 \ \rightarrow \ \forall\ t \in \left[24^{th}\ June; 9^{th}\ September\right] \wedge T_{in}(t) \geqslant 24^{\circ}C \\ 0 \ \rightarrow \ \forall\ t \in \left[24^{th}\ June; 9^{th}\ September\right] \wedge T_{in}(t) < 24^{\circ}C \end{cases} \tag{10}$$

The Mod.08 was selected for the following analyses thanks to its high energy efficiency as better described in the results section.

3.2. Definition of the future scenarios matrix

The first step in the future scenarios analysis was the projection of the TMY weather data. In this study, future weather data were generated using Meteonorm v.7 which is widely used by both researchers and practitioners [61]. Meteonorm can be used for spatial interpolation of the main weather parameters but also to generate future weather data through the statistical downscaling under the IPCC assessment report [43]. The weather files can be generated with 10 years intervals and in this study 2050 and 2080 weather forecasts were generated considering the A1B scenario. The use of the A1B scenario is related mainly to the software used; firstly, the latest scenario (AR6) is still not available in any tool as it has been released only in the late 2022. The choice of the AR4 instead of the AR5 is related to the use of Meteonorm v.7 which is based on AR4 IPCC scenarios. As the aim of this paper is to provide the methodology and test the metric rather than providing detailed future projections, the A1B was considered a reliable – even though it is not the newest – scenario. Indeed, many of the latest (last three years) studies on climate change in the building energy field, are still based on the AR4 IPCC scenarios [9]. Despite the statistical downscaling is theoretically less accurate, the use of the statistical approach assures consumption results similar to those obtained with dynamical downscaling as already explained [43].

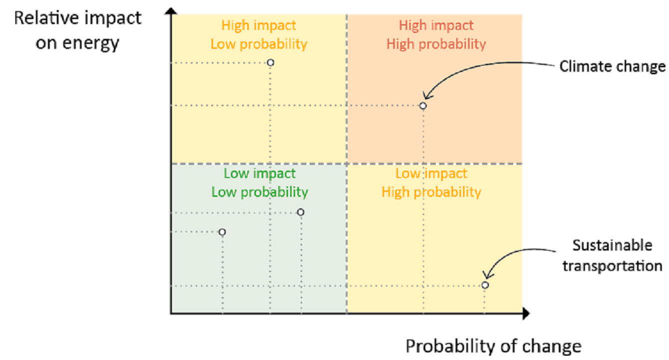

Fig. 4. Relation between impact and probability of change related to future uncertainties' sources.

Once defined the current scenario and the future weather data, a matrix of possible future scenarios was created to test the energy behaviour of the dynamic system in different contexts. This section reports, for each uncertainty source, the variations of each parameter considered. Before this insight, it is worth highlighting that uncertainties can have different probabilities of change and impacts on the building energy consumption. Fig. 4 shows how uncertainties' sources can be classified according to their impact and probability of change. Considering high/low probability and high/low impact, four different combinations can be identified in the graph below to describe an uncertainty source. For example, the climate change is characterized by a high impact on the building energy consumptions and, as already described, it is a very likely change. On the contrary, the spread of sustainable means of transportation is extremely likely but it has only low indirect impact – related to the urban microclimate – on the building energy consumptions.

In view of the above, the climate change was considered as the main variable of this study due to its high impact and high probability. As already stated, the main trend in the next future is already defined as the global surface temperature will increase regardless the scenario considered [8]; even under the latest and most optimistic emissions scenario (SSP1-1.9), temperatures are going to be above those of the most recent decade until 2100 [7]. Therefore, in all the simulations of the matrix, the climate change was considered as the main variable and, hence, always included in all the scenarios.

On the contrary, variations of the urban context, of the building use, and of the internal loads may or may not happen in the future depending on different urban and socio-economic transformations that we cannot confidently predict. Therefore, in the matrix considered, the climate always changes in the future projections (main variable) while other uncertainties sources – urban context (UC), internal loads (IL), and building use (BU) – can change depending on the different combinations

Table 3
Matrix of future scenarios.

Secondary Variables	Urban context	U1			U0			U2		
	Building use	T0		T1	T0		T1	T0		T1
	Internal loads	L0	L1	L0	L0	L1	L0	L0	L1	L0
Main Variable (climate change)	Current	–	–	–	Baseline	–	–	–	–	–
	2050	Cl1.U1.T0.L0	Cl1.U1.T0.L1	Cl1.U1.T1.L0	Cl1.U0.T0.L0	Cl1.U0.T0.L1	Cl1.U0.T1.L0	Cl1.U2.T0.L0	Cl1.U2.T0.L1	Cl1.U2.T1.L0
	2080	Cl2.U1.T0.L0	Cl2.U1.T0.L1	Cl2.U1.T1.L0	Cl2.U0.T0.L0	Cl2.U0.T0.L1	Cl2.U0.T1.L0	Cl2.U2.T0.L0	Cl2.U2.T0.L1	Cl2.U2.T1.L0

U0 = Current urban context.
U1 = Demolished urban context.
U2 = doubled height urban context.
T0 = Current building use typology.
T1 = Residential building use.
L0 = current internal loads.
L1 = Alternative halved internal loads.
Cl1 = 2050 climate scenario.
Cl2 = 2080 climate scenario.
Clx.Ux.Tx.Lx = Future alternative scenario.

considered (secondary variables).

According to the previous sections, two alternatives urban contexts were considered to define the matrix. In particular, the fully demolished context (U1) and the doubled height context (U2) were considered as the extreme alternatives to the current scenario (U0). In the current scenario (U0), the real surrounding buildings were modelled to consider the effect of the local shadings on the energy consumption. In the fully demolished context (U1), the park around the pavilion is expanded and the buildings around the pavilion are demolished. Oppositely, in the U2 context the buildings are two times higher to account for possible alternative city development. Considering the methodological nature of the paper, these two opposite possible developments of the city can be considered acceptable to test the proposed metric. Regarding the building use, a possible change of use of the building was considered moving from the current typology (T0) to a residential typology (T1). Finally, with reference to the internal loads, the current law compliant internal loads (L0) could be halved in the future – according to the increasing sustainability awareness and to the technological developments – in an alternative low consuming scenario (L1). The uncertainty sources included in the matrix are those considered the most significative – i.e., those with high impact and probability – by the authors. This choice does not aim to be fully exhaustive but simply wants to constitute a reliable starting point for a methodological definition of a new metric to analyse the energy flexibility of buildings in future scenarios.

Table 3 briefly describes the matrix of the scenarios considered in this study. Considering that the pavilion is a newly constructed building, we can consider that the context will not change in the current scenario as all the variables are verified and confirmed during the design phase and are supposed to be the same in the very near future. Hence, the current scenario is unique and represents the baseline of the comparisons conducted; therefore, it corresponds to the current design scenario and, hence, to the designed building typology, the current real urban context, the current weather data, and the current designed internal loads.

Each scenario defined in the table (Clx.Ux.Tx.Lx) was simulated under three different control strategies (C1, C2, C3) in order to compare the different behaviour of the dynamic shading system. In particular, the always off control (C1 = Mod.00), the high zone-temperature control (C2 = Mod. 01), and the optimized control that showed the best energy behaviour (C3 = Mod. 08) were selected to test the new metric and to compare the behaviour of different control strategies. Regarding the C3 control strategy, in each scenario the summer control period was re-optimized according to the new boundary conditions.

3.3. Energy flexibility index

3.3.1. Normalization of the energy consumption

After the matrix definition, a new metric was developed to summarize the behaviour of each control strategy in all the possible scenarios considered. The aim of this new index is to describe the flexibility of a control strategy – or, more generically, a technology or building element – accounting for the different uncertainties that could affect a future projection.

The first fundamental step to define the Energy Flexibility Index (EFI), is to evaluate the variation of the energy consumption throughout the different evaluated scenario. Eq. (11) defines the Energy Consumption Variation (ECV) for a specific control strategy k (i.e., C1, C2, C3 in this study) and for a specific future scenario Si (i.e., the Clx.Ux.Tx.Lx scenarios described in the previous table):

$$ECV_{ki} = \frac{EC_{k\,Si} - EC_{k\,CS}}{EC_{k\,CS}} \tag{11}$$

where $EC_{k\ CS}$ is the energy consumption of the current scenario (baseline) and $EC_{k\ Si}$ is the energy consumption for the k-th control strategy in the i-th future scenario.

Considering that each control strategy starts from a different baseline, to allow a reliable comparison between the different control strategies (or technologies) we need to normalize the ECV with respect to a reference model that describes the current state of the art of that building component. To that end, a weighting factor (w) was introduced to account for the variations in the current scenario related to the different control strategies (or technologies). Hence, a reference technology in the current scenario (ref CS) is considered; in this specific study, the reference model is the model without curtains (corresponding to C1). In other studies, for example a PCM opaque wall, it could be the model without the dynamic technology such as a static law-compliant wall. Eq. (12) defines the weighting factor w which depends on: the ratio between the energy consumption in the current scenario for the reference model ($EC_{ref\ CS}$), on the consumption in the current scenario for a specific control strategy ($EC_{k\ CS}$), and on the sign of the ECV. This ratio allows to improve the value of the ECV if the current scenario for the k-th control strategy is more efficient than a reference one and vice versa. The exponent depends basically on the numerator of the ECV_{ki} and can take only values + 1 or −1 depending on the sign of the ECV to obtain w factors higher than 1 (negative ECV) or between 0 and 1

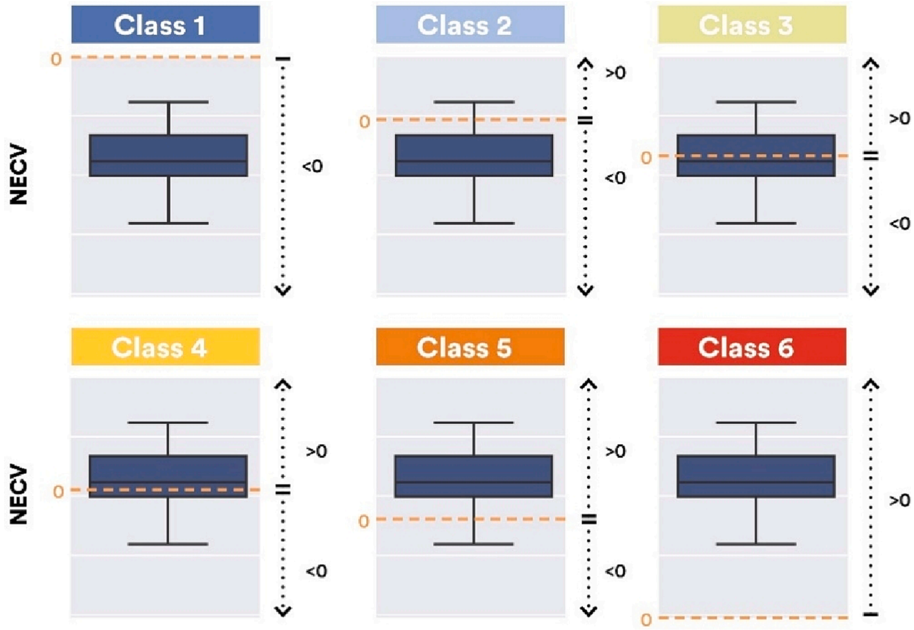

Fig. 5. Definition of the flexibility classes depending on the distribution of the NECV values around the zero.

(positive ECV), to assign the proper weight to positive or negative ECVs.

$$w = \left(\frac{EC_{ref\ CS}}{EC_{k\ CS}}\right)^{-\frac{EC_{k\ Si}-EC_{k\ CS}}{|EC_{k\ Si}-EC_{k\ CS}|}} \tag{12}$$

The need of normalizing the energy variation is related to the different behaviour in the current scenario of each control strategy. For example, in this study the C1 strategy (no curtains) corresponds to the most energy consuming model in the baseline current scenario; despite this, due to the winter "benefits" of the climate change in a very cold climate, all the future scenarios show a strong reduction of the energy consumptions. Instead, the C3 strategy is the most energy efficient strategy in the current scenario and, also in this case, shows reductions in all the future scenarios. Nevertheless, the absolute reduction in the C1 strategy is higher than the C3 strategy and, consequently, ECV is higher in C1 rather than in C3. This result could lead to misunderstandings because this difference is not dependant on the C1 control itself (which is static) but it is simply related to a very higher consumption in the baseline current scenario. To avoid these kinds of misunderstandings, the weighting factor w allows to account for the different energy consumption of the different current scenario. Hence, control strategies that consume less than a reference model in the current scenario, get benefits from the weighting factor ($w > 1$) while, on the contrary, models with higher energy consumptions are disadvantaged by this factor ($0 < w < 1$). Assuming that $EC_{ref\ CS}$ is higher than $EC_{k\ CS}$ (most likely condition), when the ECV is negative, the analysed scenario (Si) is more efficient than the current scenario ($EC_{k\ Si} < EC_{k\ CS}$), hence the exponent is $+1$ and the w is greater than 1. On the contrary, if the ECV is positive ($EC_{k\ Si} > EC_{k\ CS}$), the exponent is -1 and the w varies between 0 and 1. The most likely condition is that $EC_{ref\ CS}$ is higher than $EC_{k\ CS}$ as the evaluated technology should guarantee better performances at least in the current scenarios; nevertheless, in case $EC_{ref\ CS}$ is lower than $EC_{k\ CS}$ numerator ($EC_{ref\ CS}$) and denominator ($EC_{k\ CS}$) should be reversed. In this study, according to the results of the simulations, all the equations are referred to the most likely condition ($EC_{ref\ CS} > EC_{k\ CS}$).

Therefore, simply multiplying the ECV_{ki} by the weighting factor w, we can obtain the Normalized Energy Consumption Variation ($NECV_{ki}$) for a specific control strategy k (C1, C2, C3) and for a specific future scenario i (Clx.Ux.Tx.Lx) as shown in Eq. (13):

$$NECV_{ki} = ECV_{ki}{*}w = \frac{EC_{kSi} - EC_{kCS}}{EC_{kCS}}{*}\left(\frac{EC_{refCS}}{EC_{kCS}}\right)^{-\frac{EC_{kSi}-EC_{kCS}}{|EC_{kSi}-EC_{kCS}|}} \tag{13}$$

The $NECV_{ki}$ can be calculated for each scenario defined in the matrix (18 in this case study) and for each control strategy k (3 in this study).

3.3.2. The new metric: EFI and flexibility classes

To sum up all the scenarios analysed in a single parameter, the Energy Flexibility Index of a specific control strategy k (EFI_k) is defined as the opposite of the mean of the $NECV_{ki}$ evaluated in all the scenarios analysed as described in Eq. (14).

$$EFI_k = \begin{cases} EFI_k = -\frac{1}{n}{*}\sum NECV_{ki} = -\frac{1}{n}{*}\sum ECV_{ki}{*}w \rightarrow \left(CV = \frac{\sigma}{\mu}\right) \langle 0.5 \\ Asymmetric flexibility, exclude one or more variables \rightarrow \left(CV = \frac{\sigma}{\mu}\right) > 0.5 \end{cases} \tag{14}$$

Before applying this metric to the case study, two main aspects should be highlighted in this definition to avoid misunderstandings. Firstly, as the EFI is the mean of the scenarios studied, it is useful and reliable only if it is representative of the original data. Therefore, it can be calculated including all the variables considered only if the set of $NECV_{ki}$ values obtained for each control strategy are characterized by a Coefficient of Variation (CV) lower than 0.5. Otherwise, if the CV is higher, we can talk of "asymmetric flexibility". In case of asymmetric flexibility, one or more variables could behave in a completely different way if compared with the others. In these cases, the variable that significantly changes the energy behaviour should be considered in a separate EFI analysis obtaining two different indexes. Usually, the change of building use is the only variable that can completely upset the energy behaviour due to a simultaneous change of many parameters, causing the asymmetry of the scenarios. Finally, the use of the minus sign simply allows to associate higher index values to more flexible solutions (i.e., lower energy consumptions) in the future scenarios.

On the one hand, the use of a single index eases the management of the data and can directly describe the behaviour of the technology evaluated; on the other hand, certain information could be lost in this process simplifying too much the complexity of the topic. Therefore, it could be suggestable to couple the EFI index with a flexibility class

Table 4
Evaluation of the control strategies in current climate scenario. Values reported in brackets are the percentage variation with respect to the baseline (Mod. 00). The control strategies highlighted in bold (C1, C2, C3) are those selected to test the EFI definition.

Model	Control Strategies	Setpoint	Heating [kWh]	Cooling [kWh]	Lighting [kWh]	Total [kWh]
00 (C1)	Always off (Baseline)	–	1950.2	423.9	699.2	3073.3
01 (C2)	On if high zone temperature (period: 1st June – 1st September)	24 °C	1951.5 (+0.07%)	320.9 (−24.3%)	728.4 (+4.18%)	3000.8 (−2.4%)
02	On during night	–	1748.7 (−10.3%)	424.6 (+0.17%)	699.2 (0%)	2872.5 (−6.5%)
03	On if high zone temperature (period: whole year)	24 °C	1960.1 (+0.5%)	299.8 (−29.3%)	757.82 (+8.4%)	3017.7 (−1.8)
04	On if high solar radiation (period: 1st June – 1st September)	100 W/m^2	1954.7 (+0.2%)	346.1 (−18.4%)	703.6 (+0.63%)	3004.4 (−2.2%)
05	On if cooling is on	–	1951.9 (+0.1%)	228 (−46%)	1149.9 (+64.5%)	3329.8 (+8.35%)
06	On if high cooling	2500 W	1965.5 (+0.8%)	279.8 (−34%)	804.7 (+15.1%)	3060 (−0.8%)
07	Mixed 1: Summer: On if high zone temp. (period: 1st June – 1st September) Winter: On during night	24 °C	1756.9 (−9.9%)	321 (−24.3%)	728.4 (+4.2%)	2806.3 (−8.7%)
08 (C3)	Mixed 2: Summer: On if high zone temp. (period: 24th June – 9th September) Winter: On during night	24 °C	1754.5 (−10%)	314.1 (−25.9%)	723.3 (+3.45%)	2791.9 (−9.2%)

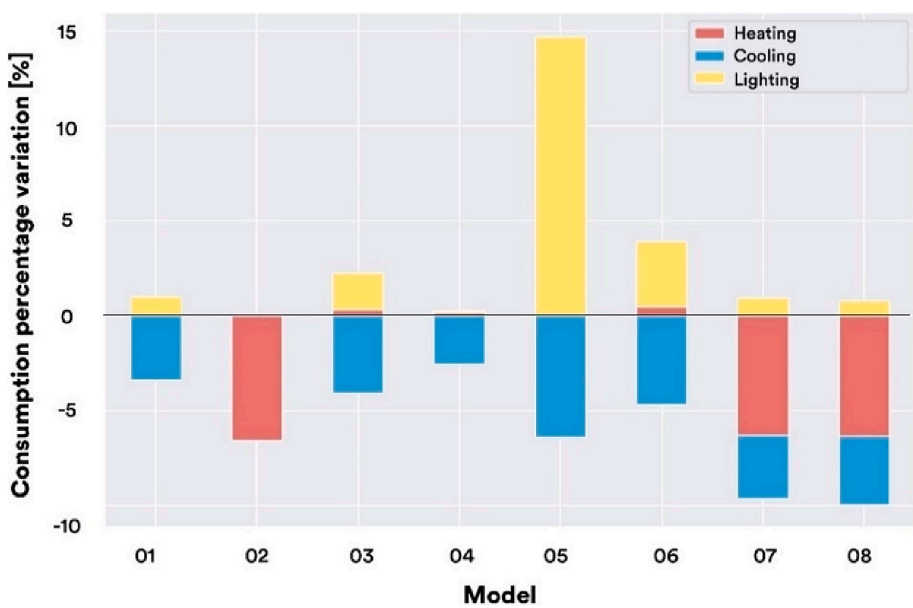

Fig. 6. Energy consumption variation referred to the Mod.00 baseline.

depending on the distribution of the $NECV_k$ in each scenario. Fig. 5 shows the 6 classes proposed depending on the position of the mean and quartiles with respect to the 0. This allows to distinguish between technologies that can always improve the energy behaviour in future scenarios (class 1) and technologies that will always worsen the energy consumptions (class 6). The other four intermediate classes describe how many scenarios could improve the energy consumption and how many could worsen it.

Finally, to add the variability of the NECV with respect to the scenarios analysed, the CV could be the third and last indicator for an exhaustive description of the future projections. Values of the CV close to zero describe energy consumptions similar in all the scenarios analysed while, on the contrary, values far from zero – both positive and negative – describe scenarios that can significantly change the energy consumption. A better understanding of the proposed metric could be gained in the next section where the results of the case study adopted are directly analysed with the EFI metric.

4. Results and discussion

4.1. Energy analyses in current scenario

Considering the analyses run for the current scenario, Table 4 and Fig. 6 sum up the results for the control strategies considered.

The first clear conclusion that can be drawn from this plot is that the Mod.02 is the only control strategy that can improve the winter behaviour of the envelope because it reduces the thermal transmittance during night without increasing the lighting consumption. In all other strategies, the use of the curtain in presence of daylight leads, on the one hand, to a reduction of the cooling consumption but, on the other hand, also on an increase of the lighting consumption. This is the reason why the Mod.02 was considered as the basis of the two mixed control strategies (Mod.07 and Mod.08). To also improve the summer behaviour, the Mod.02 control strategy was coupled with the Mod.01 which is the strategy that assures the best balance between cooling and lighting demand. Simply coupling the Mod.01 and Mod.02 leads to a reduction of the total consumptions of nearly 8.7% while optimizing the start and

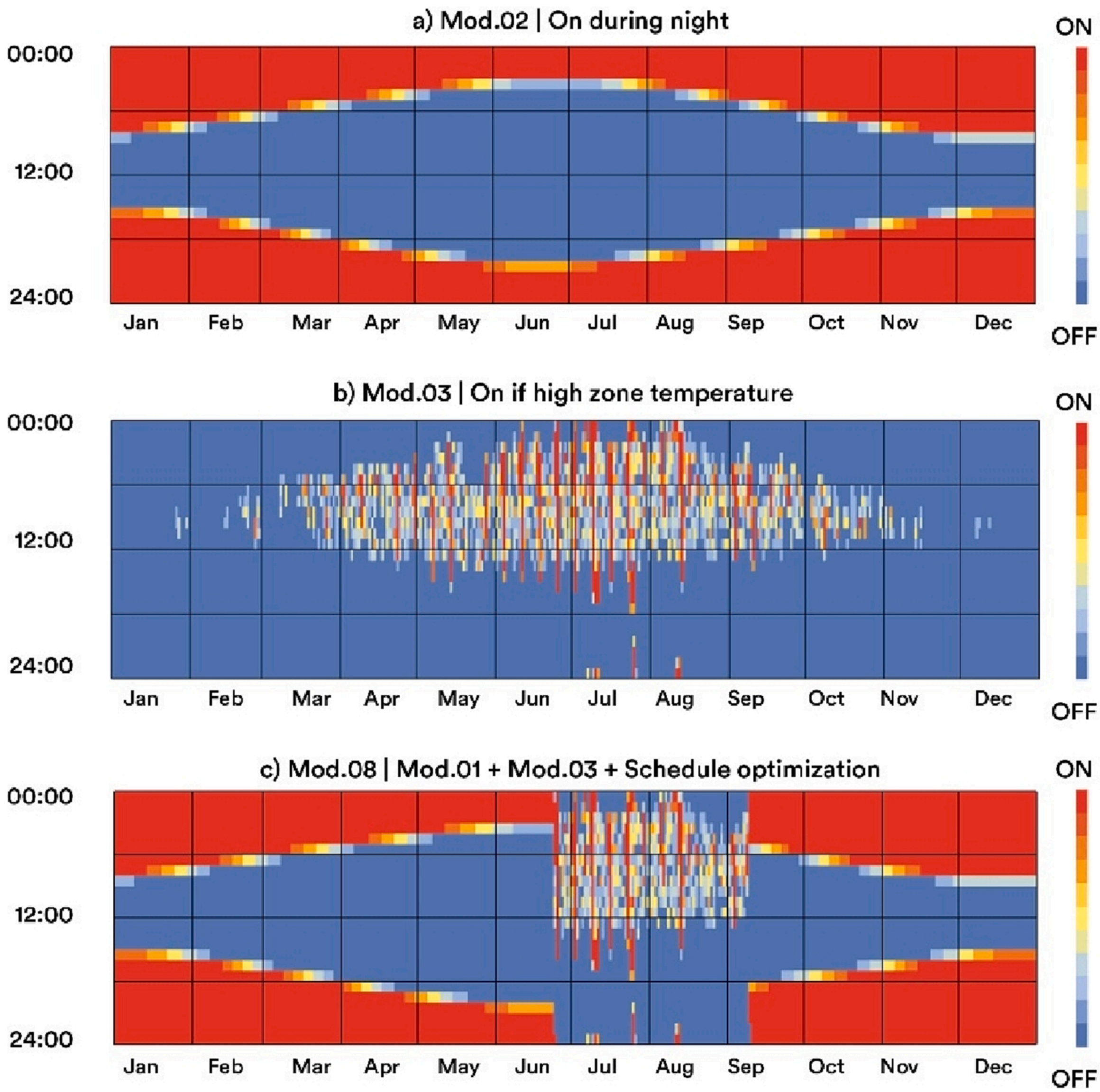

Fig. 7. Curtain state during the whole year for the Mod.02, Mod.03, and Mod.08.

end date for the summer period leads to an extra 0.5% of energy reduction resulting in a total reduction equal to 9.2% for the Mod.08. Fig. 7 shows the curtain state during the whole year in the Mod. 02, Mod.03, and Mod.08 to better explain the control strategies adopted for the next phases of the studies.

In this figure, the on and off state corresponds respectively to the curtain closed (blue) and open (red) while intermediate colours correspond to the curtain open/closed for a fraction of the hour plotted.

After this first analysis, the models Mod.00, Mod.01, and Mod.08 were considered as control strategies to analyse the future scenarios and test the flexibility metric defined for this study. The Mod.00 represents the reference model without any curtain and any dynamism, the Mod.01 represents a standard control strategy usually considered by practitioners, while the Mod.08 represents the optimized solution developed after the preliminary analyses.

4.2. Energy analyses in future scenarios

Considering the future scenarios, all the settings previously defined were simulated and the main results are summed up in Fig. 8. Each column of the figure represents the results of a specific control strategy k (C1, C2, C3), while each row represents a specific building use (T0, T1) and internal loads (L0, L1) scenario. Finally, the different urban contexts (U0, U1, U2) are represented with different line types described in the legend and the different weather scenarios are reported on the x-axis of each graph. Therefore, each point of each graph corresponds to a specific scenario and each column includes all the 19 scenarios defined in the methodology section for a specific control strategy. Moreover, to ease the comparisons among different graphs, in the last two rows a dashed baseline was added to show the energy consumption in case we change only the main variable, namely the climate (i.e., scenarios baseline, Cl1. U0.T0.L0., Cl2.U0.T0.L0.).

This representation allows to easily compare the different control strategies in all the scenarios. For example, it can be straightforwardly deducted that, overall, the energy consumption is always improved moving from C1 to C2 and from C2 to C3 – as highlighted by the dotted line that connects the subplots – regardless the scenario considered.

It is worth highlighting that in each column (i.e., for the same control strategy) all the lines start from the same point because the current scenario is unique and, hence, always the same regardless the assumptions made for the future variations. Since we are talking about a newly constructed building, the current scenario is fixed and does not include any possible variation of the considered variables.

Looking further into the graphs, different trends can be identified for

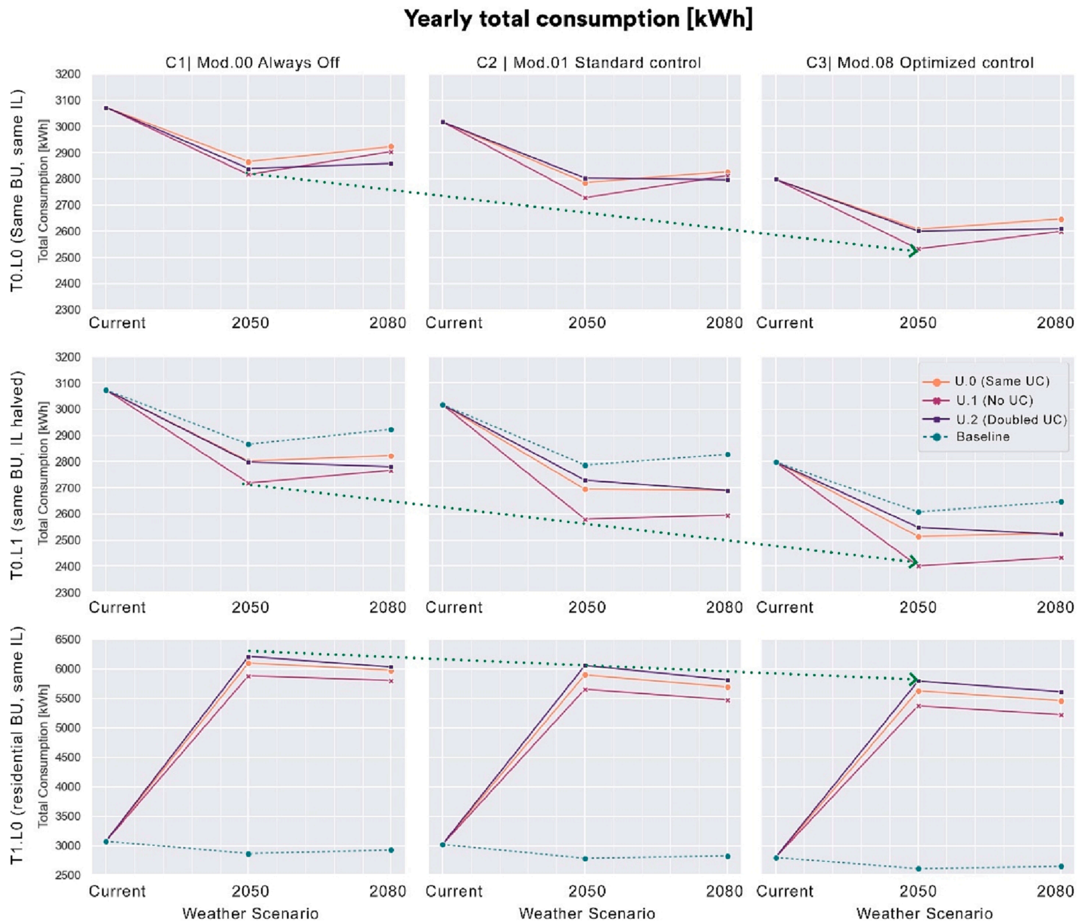

Fig. 8. Yearly total energy consumption (heating + cooling + lighting) for the selected future scenarios.

the last and the first two rows. In the first two rows – i.e., changing the internal loads (row), the urban context (lines), and the control strategies (column) – the total energy consumption of the model decreases in both 2050 and 2080; even though the 2080 weather data register consumption values slightly higher than 2050. This is because of the effect of the climate change in a cold climate; in 2050 the increasing temperature leads to a reduction of the heating consumptions without significantly increasing the cooling demand. On the contrary, in 2080 the further increase of the outdoor temperature leads to a slight further decrease of heating consumption overtaken by a significant increase in cooling consumption.

On the contrary in the last row – i.e., changing the building use (row), the urban context (lines), and the control strategies (column) – consumption increases in 2050 and decreases slightly in 2080. It is fundamental to explain that the first increase is not related to the climate change itself – which in this specific climate can "help" to reduce the consumption – but it is related to a different use of the building. When we are comparing the current scenario with the 2050 scenario in the last row, we are comparing an office building in the current scenario (the baseline designed building use) with a residential building in 2050. As already hinted, changing the building use can upset the energy behaviour of the building as this change regards simultaneously a series of elements (schedule, occupancy, internal loads, etc.) that varies significantly. Hence, in the last row, the abrupt consumption's increase between current and 2050 scenario should not be addressed to the climate change; on the contrary, the differences between 2050 and 2080 can be considered reliable because are referred to the same building use.

Another important result obtained in this phase, regards the optimized control strategy C3. Moving towards future scenarios, the optimization tends to increase the period of the year characterized by the summer control strategy. In particular, Fig. 9 shows the changes in the control strategy (considering only the climate change); in these graphs the effect of the global warming is clear and is translated in an increase of the summer control period that grows from 77 days in the current scenario, to 82 days in 2050, up to 129 days in 2080. Clearly, this update in the summer control period helps to improve the flexibility of the building that can handle the weather changes without increasing the energy consumption.

4.3. Application of the energy flexibility index

Once studied all the future scenarios, the results obtained were used to test EFI as the main indicator of the energy flexibility of the case study.

Firstly, the CV of the data obtained in the future scenarios' matrix were analysed to understand if all the variables can be considered together in a single EFI value. As already mentioned, the change of building use introduces a completely different energy behaviour. It follows that the CV including the change of use is too high ([1.9, 2.0, 2.1] for [C1, C2, C3]) to consider all the variables in the same index; on the contrary, considering an index for the change of building use and another one for the other secondary variables the CV values are respectively [0.05, 0.07, 0.07] and [-0.23, −0.28, −0.29].

Fig. 10.a and 10.b help to classify the different control strategies analysed according to those defined in Fig. 7. If we do not consider the change of use as one of the secondary variables of the study (Fig. 10.a) all the control strategies considered can be classified in class 1 as they always show a reduction of the energy consumption, regardless the scenario considered. On the contrary, if we consider the residential use (Fig. 10.b), all the scenarios show an increase of the energy consumption

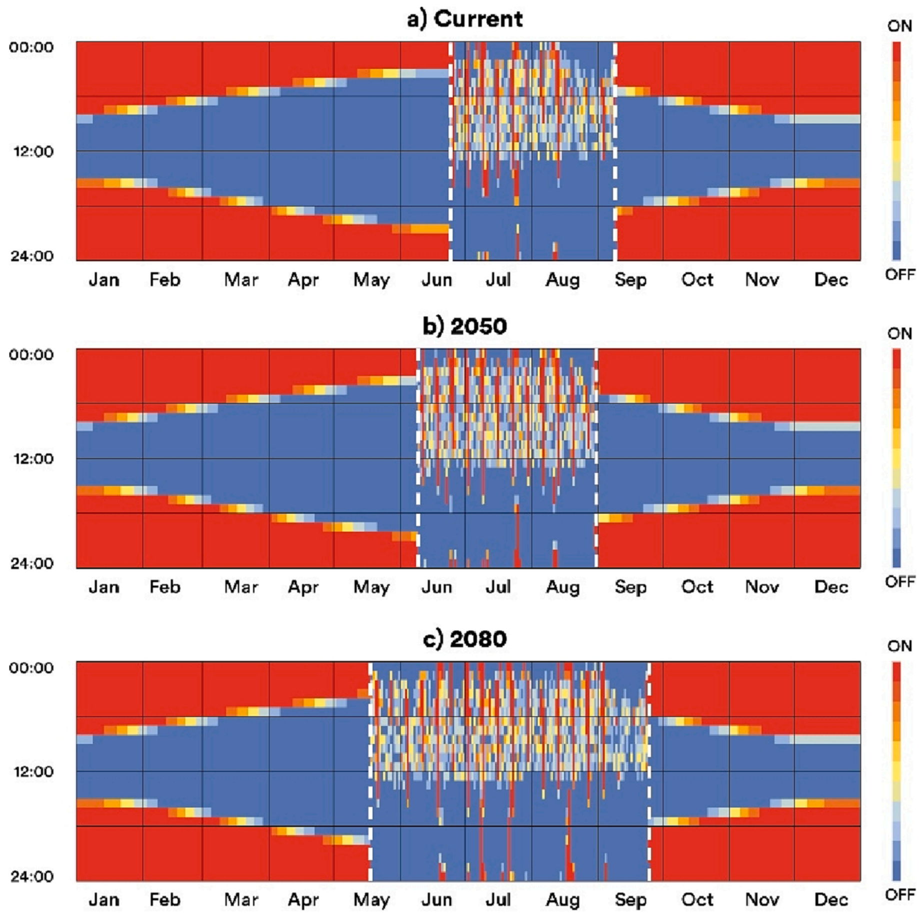

Fig. 9. Curtain state during the whole year in the a) current, b) 2050, and c) 2080 scenarios.

– with respect to the baseline – and are, therefore, classified as class 6.

Considering the EFI values, introducing a dynamic curtain (changing from C1 to C2) improves the energy flexibility of the building; this improvement is quantified in an increase of the EFI in both the original use (from 0.081 to 0.098) and residential use (from −0.953 to −0.894). Finally, enhancing the control strategy from standard (C2) to optimized (C3), EFI values are furtherly improved in both the cases (from 0.098 to 0.099 for the same building use and from −0.894 to −0.884 for the residential use) as shown in Fig. 10.c and 10.d.

The reliability of the metric proposed is well described in Fig. 10.c and 10.d where it is clear that a higher dynamism of the building envelope improves consequently its energy flexibility in the future scenarios. This result is achievable thanks to the normalization of the ECV adopted in the methodology. Indeed, considering the simple ECV – rather than the NECV – would have led to EFI values not comparable between C1, C2, and C3 because each ECV would be referred to a different baseline.

5. Conclusion

The methodology and the results showed in this study aim to define a new way of approaching the energy analyses in future scenarios. The high uncertainties degree that regards the future projections should not be limited to the only climate change as is customary. Despite the climate change is undoubtedly the main and the most liable change that buildings will face during their lifespan, it is also likely that other external factors could change the boundary conditions of the energy phenomena. From an energy point of view, changes in urban context, internal loads, and building use are examples of other factors that are usually neglected in the future-based studies but that can significantly affect the energy behaviour.

In this study, rather than defining a specific future scenario, a matrix of possible scenarios is defined to understand how different control strategies of a dynamic system behave in an uncertain scenario. The high impact and probability of the climate change is accounted in this study considering the climate change as main variable. It follows that every future scenario analysed considers always future weather projections instead of current weather data while other secondary variables – that can be considered or not – define the rest of the matrix. As already explained, this matrix does not pretend to be fully exhaustive and should be adapted considering each specific application; basically, in this phase, the fundamental role of this matrix is to provide support to test this new methodology and index. It follows that the definition of the matrix is flexible and depends on the future perspective of the building analysed; new variables and new variability ranges should be defined according to the specific case. Despite there are some limitations in the definition of the matrix – such as the simplification of the local shadings and urban density – they are however accounted in the variation of the urban context as a representative example to account for this issue. These aspects can be potentially included more in detail in the analyses – clearly affected by uncertainties related to socio-economic aspects – using this methodology. Once the methodology and the index structure are set, more detailed analyses of the variation of the urban density and local shadings can be included in future applications of this methodology.

Moreover, future studies could implement other methods, such as the Analytic Hierarchical Process (AHP), for defining different weights to increase the reliability and complexity of the matrix. In this way, the probability of a change and its impact can be quantified and used as weighting factors in the matrix to improve or reduce the weight of each

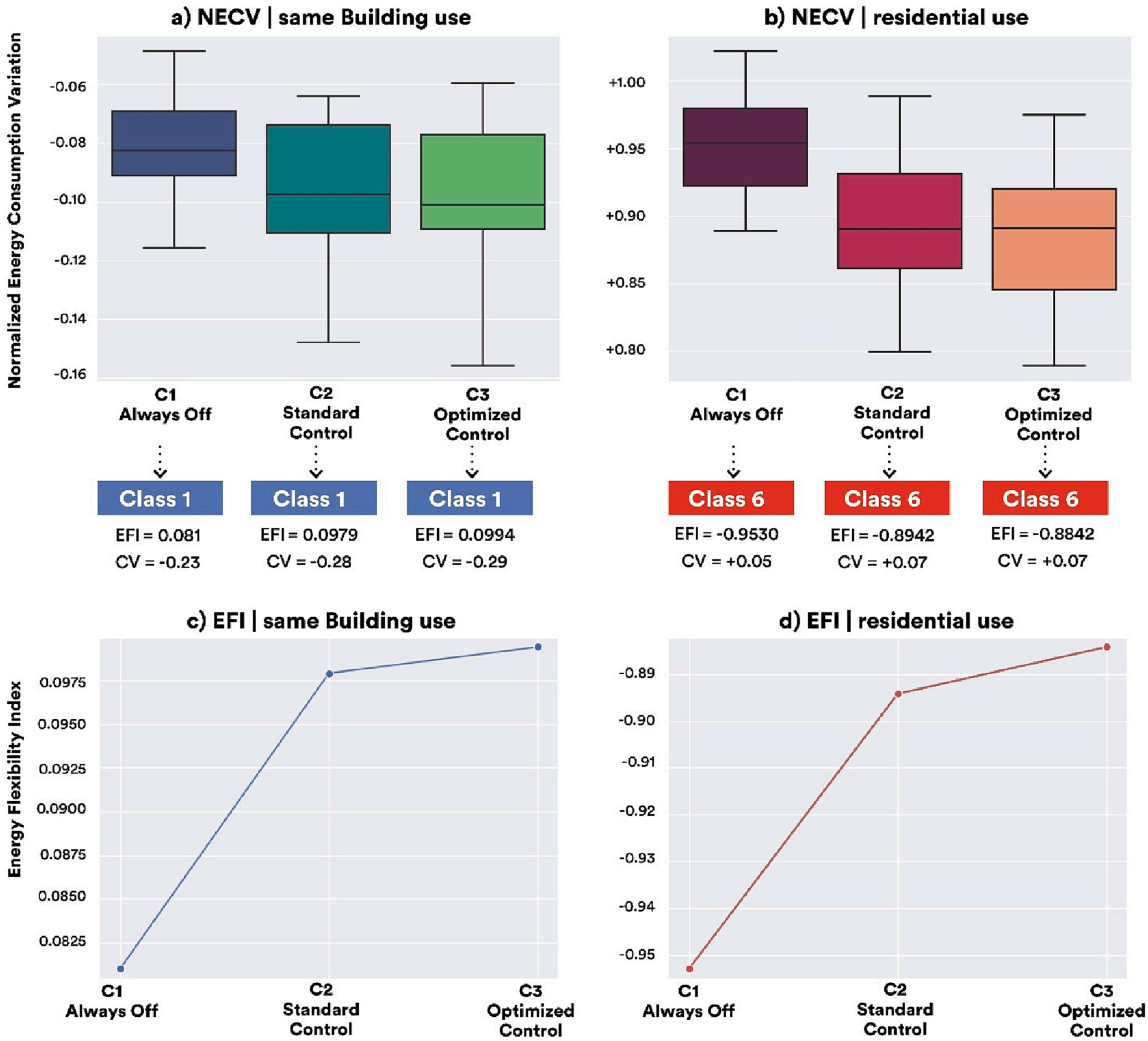

Fig. 10. a) distribution of the NECV for the same building, b) distribution of the NECV for the residential use, c) EFI values for the same building use, e) EFI values for residential use.

scenario according to its probability. Another important future development for this study could regard the uncertainty study for each scenario included in the analyses, Nevertheless, currently, very limited data are available to make these evaluations for changing contexts, technologies, and uses and hence further preliminary studies should be conducted to quantify the extent of probability of the parameters involved. Regarding the application fields of the index, there is a clear potential to expand the use of the EFI to other technologies such as other building systems, other dynamic envelope systems, thermal and electrical storage systems, etc.

Starting from this framework, the analyses conducted aims to understand the behaviour of a simple dynamic system – the internal automated curtain – in all the future scenarios considered. The first interesting outcomes regards the control strategies adopted; indeed, the optimized control strategy (C3) allows to reduce the energy consumption more than the other strategies analysed (C1, C2) in all the considered scenarios. This result confirms that a properly controlled responsive envelope can adapt itself not only in short/mid-term scenarios (days and seasons) but also in long-term scenarios (decades), improving the energy behaviour during the whole building lifespan. As this trend is registered in all the scenarios considered, the flexibility of the optimized control strategy can be evaluated higher than the others as demonstrated in the last part of the study. However, the analyses conducted are referred to weather files generated considering the A1B scenario (AR4), since the most recent assessment report (AR6) was still not available. Despite the AR4 can still be considered reliable – as already explained in the dedicated section –, future studies could consider the newest scenarios to improve the reliability of the results.

The main goal of the last part of the paper is to develop a new metric that can summarize all the analyses conducted in a single index (EFI). The proposed definition of the EFI gathers the energy results of all the scenarios defined in the matrix allowing to compare different control strategies thanks to the normalization of the energy variation. It is worth highlighting that this methodology can be used to compare different technologies and not only control strategies of the same dynamic system. For example, future studies could compare the flexibility of other innovative technologies such as for example photochromic and thermochromic window. In this case, the control strategies adopted in this paper (k in the equations) could be substituted by the photochromic and thermochromic technologies. Instead, the scenarios (i in the equations) could be considered the same or changed, depending on preliminary analyses that assess the impact and probability of the considered changes. Hence, an EFI can be obtained for each technology and the comparison of these indexes can help to identify the most flexible solution. The main advantage of the EFI is undoubtedly its easiness but, coupling the index with the class and the CV, we can obtain a triplet that offers a good description of a theoretically unlimited number of possible future scenarios.

To sum up, future projection of energy consumption is a complex topic due to the wide number of variables and uncertainties that defines these analyses. Nevertheless, the results obtained in this study confirm that there is a workflow to account for different aspects of the future projections carrying out analyses that can define a single index that describes well the energy flexibility of buildings. Clearly, the same approach could be used in other studies to describe the flexibility of other parameters such as, for example, the indoor thermal comfort. In this case, the energy consumption terms in the ECV should be substituted by a parameter that describe the indoor thermal comfort (e. g., the PMV). Therefore, the ECV can be substituted by a Thermal Comfort Variation (TCV); subsequently, the index could be developed similarly to the one proposed in this study as the mean of the Normalized Thermal Comfort Variation (NTCV). Hence, this study strives to be a reference framework for any research that aims to analyse future scenarios with a holistic – and not only climate-focused – approach, to define the flexibility of buildings from different points of view.

CRediT authorship contribution statement

F. Carlucci: Conceptualization, Methodology, Software, Data curation, Investigation, Writing – original draft, Visualization, Formal analysis. **K. Negendahl:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision. **F. Fiorito:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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