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An integrated building energy simulation early—Design tool for future heating and cooling demand assessment

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ABSTRACT

Climate change and its effects are becoming clear on a global scale either from the perspective of global warming and the increase in the rate of occurrence of weather events of extreme magnitude. This has impacts also for sure on the standard building performance analysis approach, since the buildings designed today are supposed to withstand for the following decades climate impacts that may be different than those they were designed for.

The paper proposes a simple, easy to use and freely available building simulation utility which performs morphing of existing weather data files and, by connecting to the Energy Plus simulation routine, allows to perform future climate building simulation analyses. Users are required to select one of the ASHRAE buildings models or provide one of their own choosing and to input the original weather data file. The tool will generate a future weather data file with the preferred assumptions (e.g. RCP scenarios, time frame) and elaborate results in terms of heating and cooling required for air conditioning.

The paper proposes also an implementation of the tool to a case study aimed at showing the potential of the application proposed. A typical office building model from the ASHRAE library was simulated in two different locations under different climate change assumptions up to the year 2090. The analysis of the results in the two locations of Palermo (Italy) and Copenhagen (Denmark) highlight relevant increases in the current century of up to +20% of cooling requirements and similar reductions for heating in both case studies, if compared to current levels.

The research targets a specific limit in the investigation of climate resilience of buildings and follows the principles described by SDSN in the definition of SDGs and the interest at the EU level towards climate neutral and innovative cities.

In this context, the paper may contribute to the limited availability of easy to use and free tools available for practitioners to investigate the design of climate resilience buildings.

1. Introduction

The effects of climate change are widespread into different areas and domains, including also potential future repercussions on nearly all sustainable development goals, as substantial variations on current climate patterns might impact the standards of living for people throughout the world.

Poverty, hunger, health and wellbeing, clean water and sanitization, affordable and clean energy, cities and communities – just to mention some of the most relevant Sustainable Development goals – can and will be impacted by an increase of extreme weather events, which rate of appearance has been increasing dramatically in the past few years (Gunay et al., 2013).

In the past years, very high temperature values and prolonged heat waves have set all time high records in many countries throughout the world, with 48 °C registered in Portugal and Spain, 41 °C in Tokyo in late July and also in South Korea in the past years, temperature surpassed high thresholds more than a hundred year old.

However, the consequences of climate change do not only apply to specific extreme events, as their impacts can be widespread also on average trends on most climate weather variables (Moazami et al., 2019b).

The intergovernmental Panel on Climate Change (IPCC) (Lucon et al., 2014) states unequivocally that if a joint global effort

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Nomenclature

AR5	IPCC's Fifth Assessment Report
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
GCM	General Circulation Model
HVAC	Heating, Ventilation and Air Conditioning
IPCC	Intergovernmental panel on climate change
p	Predicted value of the atmospheric pressure
p_0	Present value of the atmospheric pressure
r	Predicted value of global horizontal radiation
r_0	Present value of global horizontal radiation
RCM	Regional Climate Models
RCP	Representative Concentration Pathways
SHGC	Solar Heat Gain Coefficient
t	Predicted value of dry-bulb temperature
t_0	Present value of dry-bulb temperature
$t_{0\max,m}$	Monthly mean of the current daily maximum temperature
$t_{0\min,m}$	Monthly mean of the current minimum daily temperature
WWR	Window-to-wall ratio
x_0	Current hourly climate variable
α_{rm}	Scaling factor in monthly global horizontal radiation for the month m
α_{tm}	Scaling factor for the dry-bulb temperature
Δp_m	Monthly increment in atmospheric pressure
Δr_m	Absolute increment for monthly average solar shortwave flux received at the surface
Δt_m	Predicted monthly daily mean temperature
$\Delta t_{\max,m}$	Predicted monthly daily maximum temperature
$\Delta t_{\min,m}$	Predicted monthly daily minimum temperature

towards decarbonization of all sectors of the economy is not actively pursued, a significant increase of the average air temperature at planetary scale by the end of the current century even by more than 4.5 degrees should be expected.

In this perspective it is not possible to overlook the building sector, as it is one of the most highly energy consuming (Cellura et al., 2018a; Sartori and Hestnes, 2007).

The building sector direct emissions on a global scale are in fact on a rising trend, over 3 Gt CO_2 in 2018, with a slight rebound than the previous years. If also the indirect emissions are included in the calculations, buildings were responsible for 28% of global emissions due to energy use in 2018 (Ortiz et al., 2014; Guarino et al., 2015).

Moreover, global warming will continue to evolve unpredictably in the next decades, depending on the current state on climate action and politics involvement: this clearly means that buildings constructed today will be facing a very different climate in some decades, with the risk that a good design adapted to the current climate will perform poorly in twenty to thirty years from. Although there is a wide variability within current available climate change estimations, scenarios and tools – that mainly lies in how efficiently our current system will be able to advocate decarbonization efforts in the next decades – the use of provisional tools to investigate future climate data files is paramount to achieve more efficient building design.

Lastly, it is worth mentioning that practitioners usually do not have enough instruments and tools available to approach with the required degree of detail building design while including the effect of global warming, let alone approach detailed dynamic building simulations while taking in considerations global warming scenarios which require usually the use and manipulation of large amounts of datasets and specific weather databases. Since IPCC scenarios for the next century depict trends and increases in average temperature alone by up to 5–6 °C, failing to take these factors in considerations when performing a building design will have significant impacts on the performances of the building sector itself in next decade: this means that it is much needed to develop innovative design tools help in developing solutions for resilient to climate change, thus starting to design buildings today for the future.

State of the art

The application of global warming considerations within building simulation weather data is based on different methodologies and approaches that will be briefly recapped in the following.

1.1. Climate change scenarios modelling approach

Concerning the climate change modelling approaches, in the past decades IPCC has developed several scenarios and climate change projections, in different assessment reports starting in 1990 up to the assessment report five in 2007 and six in 2022, where specific scenarios called "Representative Concentration Pathways" were based on the change in net radiative flux at the tropopause, due to a modification in the climate change, i.e. the concentration of carbon dioxide. The scenarios, defined as Representative Concentration Pathways (RCP) 2.6, 4.5, 6.0, 8.5 are based on the increasing provisional radiating forcing, with the RCP 8.5 being a business as usual scenario with increasing values of radiating forcing up to 2100 and onwards and RCP 2.6 being a conservative, declining carbon emission scenario (Roberge and Sushama, 2018; Edenhofer et al., 2014).

It is nevertheless worth mentioning that these scenarios do not specifically give indications or estimations about global warming (Ghoniem, 2011) per se, but rather investigate the variations of the causes i.e. carbon dioxide concentration in the atmosphere.

The first modelling approach towards the quantification of global warming effect is achieved usually through the use of General Circulation Models (GCM) (2018): they are numerical models of the main physical processes in the atmosphere, oceans and land surface and are usually considered the state of the art on modelling and simulation of the global climate system. These models are based on three-dimensional grids with resolution of around 250 km, based on the calculation of energy, mass, airflow balances and therefore of all the main weather and climate parameters. While this kind of models represent a very effective solution for investigating large scale modifications of the climate and of the impact of global warming, it does not properly fit the requirements of building simulation, whereas a much smaller grid is required if a precise site is to be investigated. This is usually approached through the use of Regional Climate Models (RCM) (Jiang et al., 2013; Berardi and Jafarpur, 2020), based on similar assumptions than GCMs but rather based on limited areas and with a higher density of points within the domain of interest (Asimakopoulos et al., 2012).

Outputs from either approaches need to be downscaled at the local level, to allow for the correct level of detail to be adopted within building energy simulation: as such, they usually make use of either statistical or typical ad hoc methodologies such as the well known "morphing" method (Cellura et al., 2018b), which is basically aimed at creating modifications of existing weather data files.

Through either approach, the consequences of climate change within the analysis of building performances simulation are usually confined within the research domain or very specific niche practical applications. They are not really investigated within the larger public of practitioners, which either due to the difficulty and time needed to implement such models and approaches and the unfamiliarity with the topic, tend not to involve these issues within their work practice. However, since buildings are usually expected to stand for at the very least fifty to seventy years (Dixit et al., 2013) after construction, their life cycle is certain to be impacted by climate change, which is expected to potentially make the building operate very differently than in the original design. Several studies are available with regards to the implications of climate change on the built environment. Some most recent and relevant are briefly recapped in the following.

1.2. Climate change effects and building performances

In Hosseini et al. (2021), an approach to remove the bias from GCM data is proposed through a specific workflow including a hybrid model aimed at downscaling the GCM data in order to obtain weather files for the future with hourly timestep to be used within dynamic building energy simulation.

The aim of the study is to use monitored weather data to identify similar patterns from historical data and use it to generate weather data files for future decades, without a proper artificial generation of data. Only in the case where the GCM data develop into temperatures values outside the monitored range, the approach employs a trained regression model to generate hourly weather data. The approach allows the modelling of extreme events.

In Bamdad et al. (2021) an ant colony optimization is proposed to compare the design of energy optimized solutions in buildings in current and future climate conditions. The methodology is used having as case study an office building in Brisbane and Canberra (Australia). The results demonstrate that the difference in performance between the optimization of current and future climate is moderate but can reach 6% in Canberra when cooling is concerned.

It is concluded that for the case in Brisbane it is appropriate to design for future proofing while considering the current climate conditions while in Canberra it would be advised to perform an adaptive design by taking in consideration future climate evolution.

In Nguyen et al. (2021) an adaptation and mitigation pathway is discussed by investigating multi-objective optimizations in building design for the climate of Hanoi (Vietnam). The methodology followed includes variants to a baseline building model and optimization of models performances under different climate change scenarios and time frames.

The results reveal that a non-optimized building for future climates will require roughly 7 to 12.3% increase in energy use for heating and cooling together with a longer overheating period in the future.

Optimized designs instead clearly show significant reduction in energy uses and risk of overheating if compared to the baseline design.

In Farah et al. (2019), climate change weather data are developed through a methodology to integrate climate change characteristics into historical weather data. Air dry bulb temperature is separated into three time series components and manipulated through minimum monthly averages, the number of days with maximum temperature above a specific level with respect to specific heat waves parameters. Building simulation is also performed for an office building in Adelaide (Australia).

In the climate-changed weather conditions, thermal energy requirement for heating might be reduced by more than 20% while cooling might increase by more than 30% with a total increase in thermal demands by 5%.

In Moazami et al. (2019a) Moazami et al. investigate the design of future-proofing of buildings through the use of robust design optimization techniques. The idea is to support practitioners to influence their design through easy techniques which may be able to impact the management of global warming and future extreme conditions. The analysis has taken in consideration extreme warm, extreme cold and typical weather conditions and used different objective functions.

The performances of the optimized design allow for an 81.5% reduced sensitivity to climate uncertainty, 14.4% reduced mean energy use for heating and cooling if compared to a solution compliant with American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) 90.1-2016.

Although it is clear from recent literature that the need for appropriate climate-change oriented design of buildings is paramount to focus energy efficiency targets in the next decades in the building sector, however, there is a specific need for applications of the aforementioned solid techniques and methodologies to favour the inclusion of climate change considerations within the design process of buildings. In particular, simplified tools and synthesis approaches could be particularly effective at favouring the diffusion of such needed design consideration among stakeholders and practitioners.

Some specific applications available in the state of the art on the topic of tools and applications for climate change applied to buildings performance will be briefly highlighted in the following.

In Jentsch et al. (2008), one of the first approaches to the topic is proposed. The approach followed the integration of future UK climate scenarios into TMY2 (Jiang et al., 2019) weather data files in order to be loaded directly into building simulation tools (Jentsch et al., 2008). The tool was developed to integrate the 'morphing methodology' and was used as baseline to transform CIBSE standard weather data files to take into consideration global warming weather data (Gunay et al., 2013). The tool presented is aimed at the generation of TMY2/EPW files from the morphed data files and includes calculations for solar radiation, air temperature, daylighting and humidity. A case study is also investigated, in particular to the potential impact of global warming on future summer overheating hours in a naturally ventilated building. The approach is based on the tool CCWeatherGen: Climate change Weather File Generator for the UK and includes only up to IPCC assessment report 3 data and has been a reference for the past years in the field.

In Shen et al. (2020) authors propose a framework for early design stage of climate adaptive designs for multi-family buildings under future climate scenarios. The aim is to generate future weather data through the morphing method, integrate standard building simulation with adaptive comfort models and arrange with simplified building simulation alternative designs in a framework suitable for the charrette early design stage. The paper shows that the methodology followed is clearly able to identify solutions sets being effective in the different climates of Italy and Sweden, even though, although a step in the right direction, some issues are for sure traced within the topic of the simplicity and easy replicability of the methodology within practitioners and stakeholders.

In Troup and Fannon (2016) a comparison of two specific tools available to assess the effect of global warming in buildings is proposed. The study uses Boston, Miami and San Francisco as diverse cities representing different climate challenges and to investigate regional effects on long term energy use in future scenarios. Energy simulation results obtained from "morphed" weather data files, current climate forecasts and adjusted emissions scenarios are compared and discussed to evaluate the impact of global warming on building energy consumption. The "CCWeatherGen: Climate change Weather File Generator for the UK | Sustainable Energy Research Group" is used together with the Weathershift tool. Very significant results are found among the results of the two tools. Authors conclude that impacts on a wrong assumption on the tool used can have extreme consequences on the results and thus there is a strong need to understand the elements behind future climate evaluations and weather file morphing. Of the two tools investigated, Weathershift is a web page commercial service which implements generation of weather data files for sale purposes, implementing assessment report 5 calculations based on existing weather data files.

In Van Schijndel (2017), a tool is described based on the determination of climate change effects on the performances of buildings and uses standard. No advancements per se in terms of modelling efforts of climate change are performed since climate data are input from another research but the tool allows for a simple first insight into the performance of Heating, Ventilation and Air Conditioning (HVAC) systems in future climates.

In Jentsch et al. (2008) a set of weather data files are developed through the use of the morphing methodology, using as baseline the CIBSE Test reference years. The paper develops sensitivity analyses on a range of cases. Simulations with TRNSYS coupled with TRNFLOW were performed for a specific case study at the University of Southampton. The building is unshaded and placed on a high point of the campus. Simulation are run by comparing current weather data files with morphed ones and deviations are explained and analysed.

The paper, although developed several years ago, shows one of the very first examples of tools used for the generation of future climate change data for use within building simulation application.

Zhai and Helman (2019) analysed the potential influence of 23 climate models for total of 56 model scenarios approved from the IPCC on building energy. The case study is the campus of the University of Michigan that consists of 75 buildings. In detail, the authors identified four representative climate and created 12 future weather files starting from them. Using a probabilistic based stochastic deterministic coupled method, the authors estimated the energy consumption of 5 representative buildings and simulated them on EnergyPlus to estimate the implications of climate change on energy consumption. The 12 climate projected weather files were utilized for each of the 5 representative buildings.

Wang et al. (2017) investigated the impacts of climate change on annual energy requirement of an office building located in five different cities in United States. The authors used two GCM climate change models (HadCM3 and CESM1) and considered the representative concentration pathways (RCP)2.6, RCP4.5, and RCP8.5, which represents low greenhouse gas emission, intermediate emission and high emission based on IPCC AR5. Energy simulation tool EnergyPlus was used to simulate future climate conditions and mitigation measures for five U.S. cities.

Tamer et al. (2022) presented a methodological framework for energy demand and photovoltaic generation predictions considering the climate change impacts through multivariate regression models. The case study was a hypothetical office building in Turkey. In detail, the authors utilized an existing linear morphing methodology to generate future weather files for all 81 cities in Turkey. For each year and city, corresponding weather metrics were calculated, and heating/cooling demand and PV energy generation values were computed through building energy simulations. Obtained data were used to develop two multivariate regression models to predict: (i) future weather metrics and (ii) future energy demand and generation.

Pajek et al. (2022) investigated the relevance of some passive design measures for heating and cooling energy use of single-family detached buildings at five European locations under current and three future periods. To this end, future projected weather files were generated using the climate morphing technique implemented in the CCWorldWeatherGen. The energy models of a typical single-family residential building with numerous combinations of passive design measures were defined and simulated using EnergyPlus, considering the current and projected climate. Finally, a multiple linear regression analysis was performed to rank the studied passive design measures according to their relevance regarding the building's energy need for heating and cooling under the current and projected future climate.

1.3. Objectives of the study

Within the existing literature there is a wide interest on the topic of the determination of the climate change influence on the energy performances of buildings. However, there is a very limited availability of scientifically solid tools to be used easily and free of charge to potentially influence the outcomes of the early design process through evaluation of climate change. The need for this kind of simulation tools is substantial within the building simulation community as it is paramount to being able to perform sensitivity analyses on the potential future evolution of climate to assess the reliability of any design choices. It is a knowledge gap for both research applications as well as for practitioners.

Thus, the study aims at the development of a specific building simulation tool aimed at contributing to the covering to the research gap previously highlighted.

The paper is based upon the creation of a tool for use within the building energy simulation practitioners to investigate the effect of climate change in the early design stage. The tool is developed in MATLAB environment, with a simple graphical user interface to make it easy and simple to use also to non-programmers and can be used with no command-line knowledge.

The tool uses a top-down approach that is based on the use of current weather data and monthly provisional values for climate change. Stochastic and bottom-up approaches might allow further investigation within the extreme climate change events; however the approach used is considered fitting for utilization within the early-design scope using downscaled IPCC data.

Users are required to input a weather data file, either select an existing Energy Plus building model between those available in the library or provide their own and will have the possibility to run directly in the tool Energy Plus simulations with "morphed" future weather data file and include as well wide parametric analyses on the parameters of choice.

The tool implements the possibility of either using a specific user-generated energy plus building model or the 90.1 ASHRAE standard buildings (ANSI, 2019), in case a quick assessment of similar buildings is required and offers the possibility to implement Assessment report 5 calculations in a very simple and fast approach. A case study is developed for illustrating the potential of the tool: very different weather data files (Palermo and Copenhagen) were chosen and one typical ASHRAE building model is chosen to have a meaningful example.

Table 1
Main building features.

	Net conditioned floor area [m^2]	Number of floors	WWR [%]	Number of thermal zones
High-rise apartment	7059.9	10	30	80
Mid-rise apartment	2824	4	20	33
Hospital	22 436.2	5	16	162
Large hotel	11 345.3	6	30.2	195
Small hotel	3725.1	4	10.9	54
Large office	46 320.4	12	37.5	74
Medium office	4982.2	3	33	18
Small office	511.16	1	22.2	6
Outpatient HealthCare	3804	3	19.9	118
Fast food restaurant	232.3	1	14	2
Sit-down restaurant	511.2	1	17.1	2
Standalone retail	2294	1	7.1	5
Strip mall retail	2090.3	1	10.5	10
Primary school	6871	1	35	25
Secondary school	19 592	2	33	46
Warehouse	4835.1	1	0.7	3

2. Methodology

2.1. Overview

The proposed tool tries to address the need of hourly future weather data that are the key point for the energy demand prediction under climate change by taking advantage of building energy simulation.

First of all, it can be used to generate future local hourly weather data for three future time slices up to 2090 using RCP emission scenarios developed in the last assessment report on climate change (IPCC's Fifth Assessment Report (AR5)) presented by the IPCC AR5. The CESM1(CAM5) General Circulation Modeldata were used as input to the morphing method (Belcher et al., 2005) to generate future hourly weather files. In detail, the CESM1(CAM5) is one of the GCMs produced by the World Climate Research Programme's in the context of Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012) and used in IPCC AR5 (Allen et al., 2014). It was identified as the GCM to construct future climate weather because it was chosen as the most suitable in Cellura et al. (2018b), where a validation of 24 GCM data for building simulation purposes was carried out.

In addition, the tool allows to investigate the effects of climate change for a specific site, in terms of heating and cooling energy demands as a 'stand-alone' tool. It allows to use the future local hourly weather data, generated by the tool, to directly launch a non-steady state building energy simulation in EnergyPlus environment and analyse the effects of climate change on 16 commercial reference buildings models compliant with the ASHRAE Standard 90.1 (ASHRAE, 2016, 2019).

The tool has been developed in MATLAB environment (The MathWorks, 2017). Moreover, in order to facilitate the user interaction with the tool, a graphical interface was developed in MATLAB (Smith, 2006).

The commercial reference buildings proposed by the ASHRAE Standard 90.1 (ASHRAE, 2019) were chosen to be used in this study to assess the impact of global warming on the energy performance of buildings.

In detail, the building models used in this study are compliant with ASHRAE 90.1-2016 standard (ASHRAE, 2016). These building models, developed by Pacific Northwest National Laboratory (PNNL) under contract with the U.S. Department of Energy (DOE), includes 16 buildings of different types and dimensions (Fig. 1). Detailed descriptions of the reference model development and modelling strategies can be found in PNNL's reports (Goel et al., 2017; Bartlett et al., 2016).

As it implements a very common standard and benchmark available worldwide in the ASHRAE 90.1 building reference models, the tool can be very practical and efficient in giving quick and reasonable data for practitioners willing to investigate the performances of similar constructions.

Table 2
Features of the buildings' envelope.

	U$_{value}$ [W/(m^2 K)]			Window SHGC
	External wall	Roof	Window	
High-rise apartment	0.36	0.18	2.37	0.40
Mid-rise apartment	0.36	0.18	2.37	0.40
Hospital	0.59	0.18	2.37	0.40
Large hotel	0.59	0.18	2.37	0.40
Small hotel	0.36	0.18	2.37	0.40
Large office	0.59	0.30	2.37	0.40
Medium office	0.36	0.18	2.37	0.40
Small office	0.36	0.15	2.37	0.40
Outpatient HealthCare	0.36	0.18	2.37	0.40
Fast food restaurant	0.36	0.15	2.37	0.40
Sit-down restaurant	0.36	0.15	2.37	0.40
Standalone retail	0.36	0.15	2.37	0.40
Strip mall retail	0.36	0.18	2.37	0.40
Primary school	0.36	0.18	2.37	0.40
Secondary school	0.36	0.18	2.37	0.40
Warehouse	0.34	0.21	2.37	0.40

The main thermal and constructive features of the buildings are given in Table 1. The buildings cover several types, from small office buildings to large energy intensive buildings such as hospitals. The net conditioned floor area varies from 232.3 m^2 (fast food restaurant) to 46,320.4 (large office), while the window to wall ratio (WWR) varies form 0.7% (warehouse) to 37.5% (large office), with a mean value equal to 20.5%.

The thermal properties of the building envelopes components for the selected building models are reported in Table 2. Roof U-value varies between 0.15 and 0.30 W/(m^2 K), while wall U-value varies from 0.34 to 0.59 W/(m^2 K).

Internal heat gains from occupants, equipment and lighting contribute a significant proportion of the heat gains in a building: reducing the heating energy demand and increasing the cooling energy demand. In the study, thermal internal loads are caused by lighting, occupants and both electric and gas equipment. Table 3 shows the internal loads assumed for each type of building model. In detail, the lighting is between 9 W/m^2 (Warehouse) and 20 W/m^2 (Sit-down Restaurant), occupants is between 2 m^2/Person (Warehouse) and 50 m^2/Person (Hospital), while electric equipment range from 2 W/m^2 (Warehouse) to 195 W/m^2 (Fast Food Restaurant). Finally, gas equipment were held against only for restaurants (Fast Food Restaurant: 396 W/m^2 and Sit-down Restaurant: 177 W/m^2).

Although natural ventilation is a cooling technique effective in achieving low energy requirements in current (41–42) and future buildings (43–44), the building models considered do not take

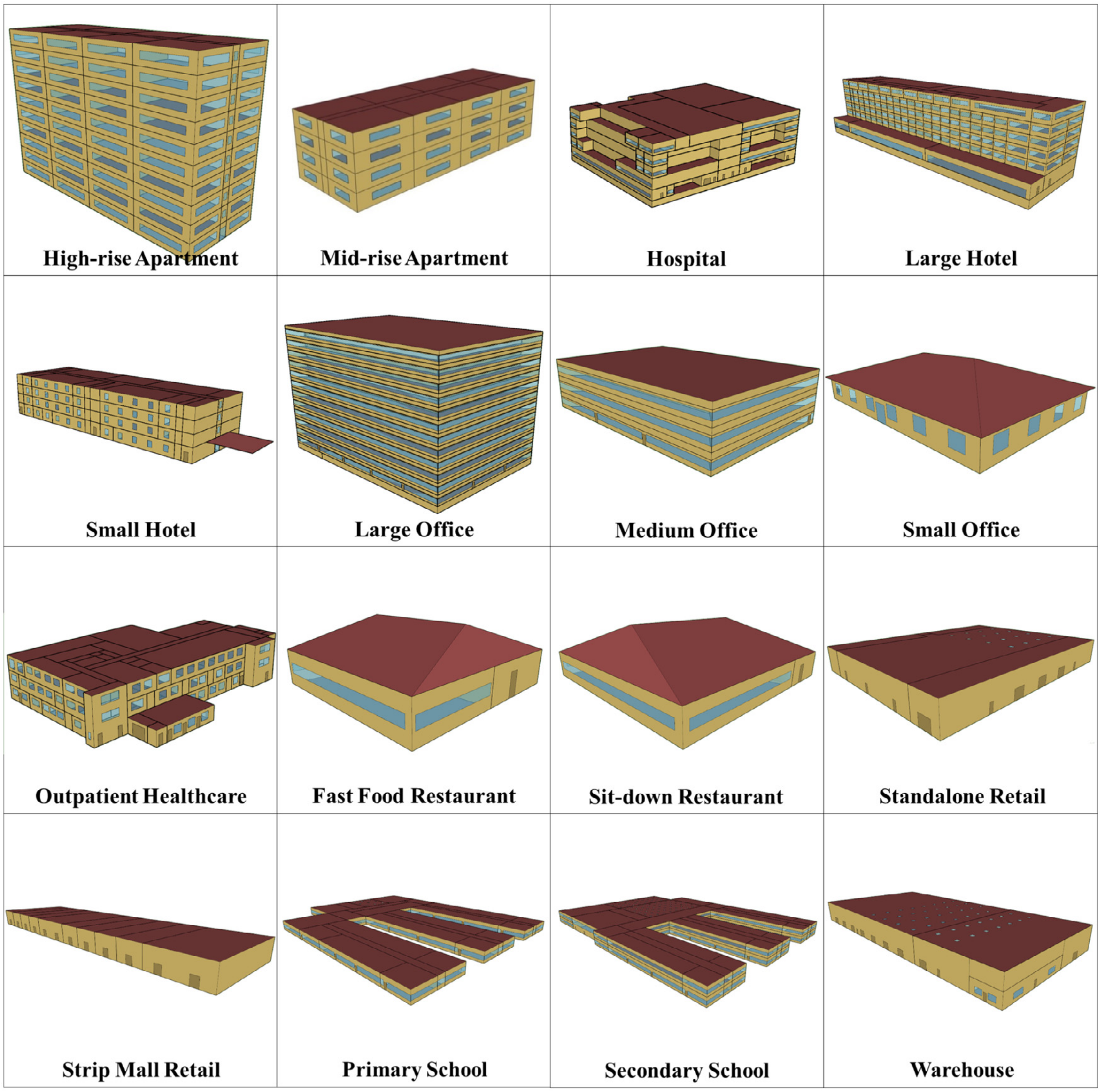


Fig. 1. Commercial reference buildings proposed by the ASHRAE Standard 90.1 (Belcher et al., 2005).

Table 3
Internal heat gains (area weighted average values).

	Lighting [W/m^2]	Electric equipment [W/m^2]	Gas equipment [W/m^2]	Occupants (m^2/person)
High-rise apartment	14	9	–	32
Mid-rise apartment	14	11	–	33
Hospital	12	24	–	50
Large hotel	11	41	–	31
Small hotel	11	30	–	16
Large office	11	18	–	18
Medium office	11	8	–	19
Small office	11	7	–	17
Outpatient HealthCare	12	32	–	6
Fast food restaurant	18	195	396	10
Sit-down restaurant	20	157	177	6
Standalone retail	17	5	–	6
Strip mall retail	18	4	–	12
Primary school	13	52	–	4
Secondary school	12	32	–	3
Warehouse	9	2	–	2

into account any natural ventilation strategy. This is due to the fact that the tool's goal is to understand building heating and cooling variation trends under the effects of climate change without considering improvement strategies or solutions. However, since it is also possible to supply the tool with the user's own model, the tool can be used to investigate the effects of natural ventilation strategies and other improvement interventions on the future performance of buildings.

Finally, to cover the heating and cooling demand an ideal loads air systems using 20 °C and 26 °C as heating and cooling

Table 4
Methodology used for each modified climate variable.

Climate variable	Unit	Morphing operation
Dry bulb temperature	°C	Combination of a shift and a stretch operation
Relative humidity	%	Shift operation
Dew point temperature	°C	Calculated based on morphed dry bulb temperature and morphed relative humidity using psychometrics formulae
Atmospheric pressure	Pa	Shift operation
Global horizontal radiation	Wh/m^2	Stretch operation
Direct normal radiation	Wh/m^2	Calculated based on global horizontal radiation using solar geometry equations
Diffuse horizontal radiation	Wh/m^2	Stretch operation
Horizontal infrared radiation form the sky	Wh/m^2	Calculated from morphed values for cloud cover, dry bulb temperature and vapour pressure
Wind speed	m/s	Stretch operation
Total sky cover	tenths of sky	Stretch operation

set-points was used. This choice is based on the uncertainty in quantifying potential energy efficiency improvements in HVAC systems up to the next century and to be able to perform a solid comparison between all results in all scenarios.

3. The morphing method

As already mentioned the paper implements the classic formulation of the 'morphing' approach (Tamer et al., 2022). The method is developed through the manipulation of existing weather data through physical parameters and by considering their variability on a monthly level while deriving them directly from IPCC RCP predictions.

Through the application of monthly variation to the instantaneous values from standard weather data file an hourly dataset is generated from monthly data. All variables considered (x_o) of the existing weather data is manipulated by a "shift", a "stretch" or a combination of both.

The "shifting" operation is usually used if an absolute monthly variation to the mean is traceable in the future climate data. Shifting raises or reduces all values of the time series by a specific value, on a monthly base.

As an example, the future hourly atmospheric pressure (p) is traceable from the current hourly value of atmospheric pressure (p_0) and from the monthly increment in atmospheric pressure (Δp_m), as in Eq. (1):

$$p = p_0 + \Delta p_m \tag{1}$$

where the subscript "0" refers to current weather data files, "m" refers to monthly data, while the absence of subscripts refers to future data.

The operation of "stretching" is instead used to proportionally perform variations in climate parameters through the use of scaling factors, as in the case of fractional monthly change.

For example, the global horizontal radiation (r), can be scaled through an increase for monthly average solar shortwave flux received at the surface (Δr_m). A scaling factor for the month m (α_{rm}) is derived from the absolute variation (Δr_m) and the monthly mean ($\bar{r}_{0m}$) from the baseline climate as in the Eq. (2):

$$\alpha_{rm} = 1 + \frac{\Delta r_m}{\bar{r}_{0\,m}} \tag{2}$$

This scaling factor is then multiplied to all m months in the data series through Eq. (3):

$$r = \alpha_{rm}\, r_0 \tag{3}$$

where r_0 is the hourly current global horizontal radiation, r is the global horizontal radiation.

Lastly, it is not uncommon to perform simultaneously both the techniques, especially for climatic variables such as dry-bulb temperature, to model modifications in both the daily mean and the peak daily values. For the dry-bulb temperature the following parameters are calculated: the monthly daily mean temperature variation (Δt_m), the monthly daily maximum temperature variation ($\Delta t_{max,m}$) and the monthly daily minimum temperature variation ($\Delta t_{min,m}$).

Using $\Delta t_{max,m}$ and $\Delta t_{min,m}$, the scaling factor for the dry-bulb temperature (αt_m) is calculated through the following equation, by using monthly mean values from both the current and future data as in Eq. (4):

$$\alpha_{trm} = \frac{\Delta t_{max,m} - \Delta t_{min,m}}{\bar{t}_{0max,m} - \bar{t}_{0min,m}} \tag{4}$$

where $t_{0max,m}$ and $t_{0min,m}$ are the monthly mean of the current daily maximum temperature and the monthly mean of the current minimum daily temperature, respectively (Cellura et al., 2018c).

Thus, when the previous parameters have been calculated it is possible to determine the future hourly variable dry bulb temperature through the following Eq. (5):

$$t = t_0 + \Delta t_m + \alpha_{rm}(t_0 - \Delta t_{0,m}) \tag{5}$$

where t_0 is the present hourly dry-bulb temperature and $\Delta t_{0,m}$ is the monthly mean temperature variation in the current climate for the month m.

4. Description of the main features of the tool

The description of the tool working routine is reported in Fig. 2. As a first step, the tool imports, from a hourly weather file for the current situation, all the climate variables that will be used as a basis for the morphing method. Furthermore, it imports from the input weather file all the geographic information, such as latitude, longitude and time zone, which are used in subsequent calculations

After receiving as input the emission scenario data and the future projections, the tool extracts from its internal database the data on future projections of the climate variables. The tool's database contains data in NetCDF extension (Network Common Data Form, .nc) and it consists of data from the CESM1(CAM5) GCM. In detail, the database contains the monthly future projections of the following climate variables: global solar irradiation on horizontal, total cloud cover fraction, daily mean temperature, daily maximum temperature, daily minimum temperature, relative humidity, mean sea level pressure and wind speed. In the next step, through a bilinear interpolation, the latitude and longitude are used to find and extract the future climatic forecasts necessary for the morphing method from the database. Therefore, using the hourly weather file for the current situation and the data on monthly future projections extracted from the database, the tool will generate a future hourly weather file, using the morphing method previously described. In detail, Table 4 shows the methodology applied to each climate variables contained in the weather file.

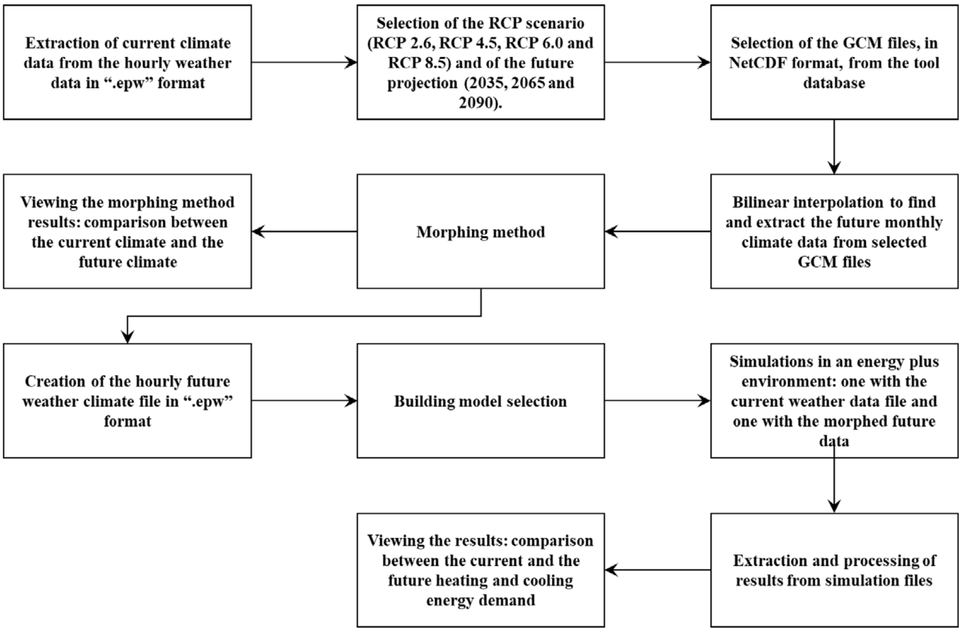


Fig. 2. The tool methodological framework.

Once the climate file has been created, it can be directly used to investigate the effects of climate change on the building performance using some reference building models contained within the tool and described previously. In detail, the tool performs two simulations at once – one with the current weather data file and one with the morphed future one – and shows a visual comparison of the results among the two alternatives. The tool is not equipped with its own building simulation engine, but it implements solid calculations through the connection to Energy Plus.

Graphically the tool can be divided into 6 sections, as shown in Fig. 3:

- **Section 1: "Current Climate weather files selection".** Using the keys "Browse" and "Load", the user have to choose the hourly weather data, in "*.epw*" format, to be used as input to the morphing method. Once the hourly weather data for the current climate situation are input to the tool, the following information will be shown:
    - Location;
    - Latitude;
    - Longitude;
    - Altitude;
    - Time Zone.
- **Section 2: "Morphing method parameters".** This stage requires some input to determine the future hourly weather file, in "epw" format, to be generated. In particular, one of the four emissions scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) is chosen as well as one of the three future projections allowed (2035, 2065 and 2090). The "Calculate" button will proceed to create the future hourly weather file, while it is also possible to easily save the generated weather data file onto any folder on the hard drive.
- **Section 3: "Morphing method results viewer".** In this section the main results on the future climate projections are showed. In particular, the comparison between the current climate and the future climate is presented. A drop-down menu allows to choose the variable to analyse (dry bulb temperature, relative humidity and global horizontal solar radiation). In addition this can be further customized by choosing a specific plot start and end date.
- **Section 4: "Energy Plus simulation parameters".** In this section the future local hourly weather data created in Section 2 can be used to investigate results calculated for the commercial reference buildings proposed by the ASHRAE Standard 90.1. In detail, 16 building models compliant with those proposed by ASHRAE Standard 90.1 are available in the library in Energy Plus environment. A drop-down menu allows to choose the model to be investigate among those shown in Fig. 1. Moreover, it is possible to supply the tool with the user's own model created in Energy Plus environment. In detail, in order to use his own model instead of the commercial reference buildings proposed by the ASHRAE Standard 90.1, the user have to select the "Your Model" option from the drop-down menu and then choose an own Energy Plus building model built in ".idf " format. At the current state of the tool implementation, the user can choose any building model built in the Energy Plus environment which, however, meets both of the following conditions:
    - The model must be equipped with a zone ideal air system that meets heating and cooling loads through the use of the Energy Plus object "HVAC Template: Zone: Ideal Loads Air System"
    - The Energy Plus object "Output Variable" must contain only the following variables: "Zone Ideal Loads: Zone Sensible Heating Energy" and "Zone Ideal Loads: Zone Sensible Cooling Energy", using "TimeStep" as reporting frequency option.

  Once the building model is chosen, the following information will be shown in the tool:
    - a figure showing the geometry of the model;
    - Conditioned floor area [m^2];
    - Building WWR [%];
    - Roof U value [W/m^2 K];
    - External wall U value [W/m^2 K];
    - Window U value [W/m^2 K];
    - Window solar heat gain coefficient (SHGC).

Data

D:\Palermo\ITA_Palermo164050_MEC.epw

Location: PALERMO Lat: 38.18 Lon: 13.1 Altitude: 34 Tz: 1

Climate Change Assumptions

RCP Scenarios
● RCP 2.6
○ RCP 4.5
○ RCP 6.0
○ RCP 8.5

Future time projections
● 2035
○ 2065
○ 2090

Plot Start: Month 1 Day 1
Plot End: Month 12 Day 31
Dry-Bulb T...

Building Energy Simulation

ASHRAE 90.1 Building Model: ApartmentHighRise

Conditioned floor area [m2]: 7059.9
WWR [%]: 30
Roof U-value [W/m2 K]: 0.18
Ext. wall U-value [W/m2 K]: 0.36
Window U-value [W/m2 K]: 2.37
Window SHGC: 0.4

EnergyPlus Completed Successfully.

Plot Start: Month 1 Day 1
Plot End: Month 12 Day 31
Cooling Ene...

	Current heating energy demand [kWh/m2]	Future heating energy demand [kWh/m2]	Heating variation [%]	Current cooling energ
Jan	0.01	0.02	69.60	
Feb	0.01	0.00	-69.14	
Mar	0.00	0.00	93775.54	
Apr	0.00	0.00	NaN	
May	0.00	0.00	-63.34	
Jun	0.00	0.00	NaN	
Jul	0.00	0.00	NaN	
Aug	0.00	0.00	NaN	
Sep	0.00	0.00	NaN	

Fig. 3. Climate change tool.

- **Section 5: "Building simulation results viewer".** This section reports the simulation results, in terms of heating energy demand and cooling energy demand (kWh/m^2). In particular, a graph box shows the comparison between the current and the future situation. A drop-down menu allows to choose whether to compare the heating demand or the cooling demand. Moreover, as for the morphing results section, it is also possible to widely customize the comparison.

  A table box shows the following monthly data:

  - current heating energy demand [kWh/m^2];
  - future heating energy demand [kWh/m^2];
  - heating variation [%];
  - current cooling energy demand [kWh/m^2];
  - future cooling energy demand [kWh/m^2];
  - cooling variation [%].

The tool was used in an application to the cities of Palermo (Italy) and Copenhagen (Denmark), for the purposes of investigating the impacts of climate change to the energy uses for heating and cooling within some selected buildings among those available in the database, thus, exploring the potential of the approach.

5. Results

The results of the paper will now be briefly discussed. The tool was used within the two sites of Palermo and Copenhagen, by testing several different climate weather data, for all time slices available within the database. The results are all acquired and generated through the tool but some of them are re-arranged and post-processed into graphs and aggregated tables.

All climatic variables of interested influenced in the morphing methodology, are arranged and modelled by the tool. As an example, and for brevity an example of output for air dry bulb temperature is following below in the following Tables 5 and 6, respectively reporting average air monthly temperature variation for the two sites of Palermo and Copenhagen.

While the difference in absolute values for air temperatures among the two sites is obvious since they refer to very different climate zones, it is worth mentioning that in both cases differences vary very significantly among the current scenario and all the climate change ones in the various time slices investigated, the maximum difference in the monthly average being close to 5 °C.

Test simulations for the tool are run for the "small office" ASHRAE building model for the two locations of Palermo and Copenhagen on all the available future time slices. Figs. 4 and 5 show two screenshots from the tool including energy simulation results for the two locations.

The tool shows on the bottom left a trend of one month of temperature variation, either on the original climate and the new future weather data file while on the right it compares ideal loads for heating and cooling in both weather data files.

Fig. 6 instead shows the aggregated results for the overall energy uses for heating and cooling within the current century. Heating for Copenhagen represents the predominant part of energy uses with more than 27 kWh/m^2 which is reduced along the decades by more than 25% in 2090 in RCP 8.5. In all cases and in all scenarios heating is reduced by roughly 20%.

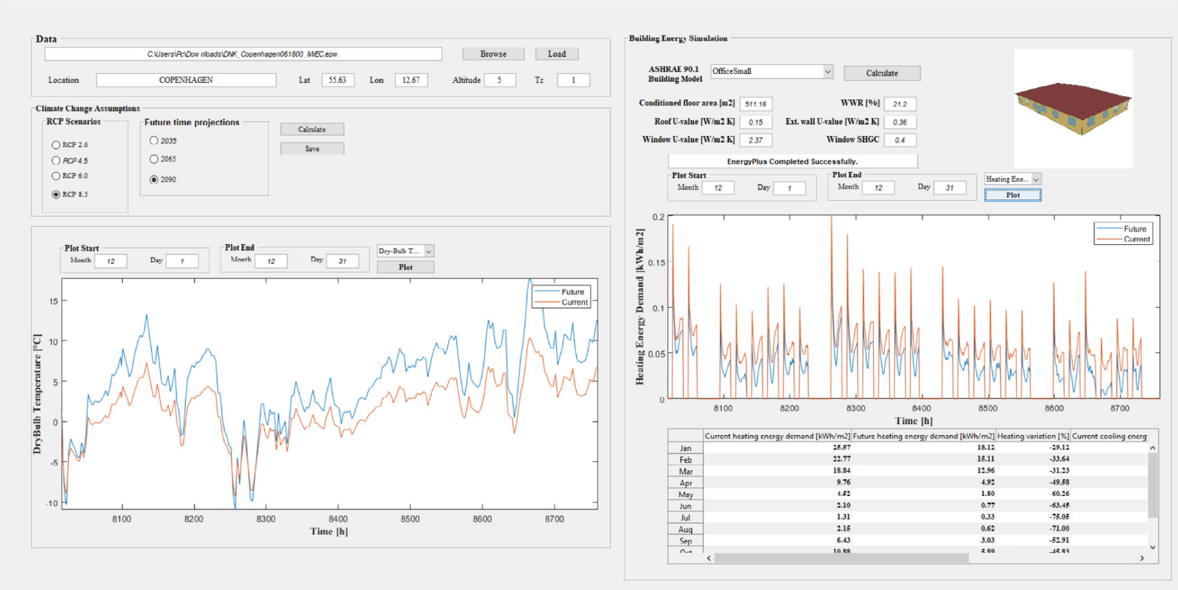
Consistent findings are traced also within the cooling energy demand which tends to increase substantially from the current situation up to 2090, where it would reach a value four times higher.

The tool also gives hourly outputs for all variables of interest: an example week comparison for February is shown in Fig. 7 for Copenhagen.

Similar trends are available for Palermo (Fig. 8) with regards to climate change impact on the results, whereas clearly the balance between heating and cooling is significantly reversed: cooling increases from nearly 15 kWh/m^2 to more than 20 kWh/m^2, while the already very limited heating (lower than 6 kWh/m^2 in the next decades is always reduced by more than 30%. A sample of dynamic outputs from the tool calculations is also given in Fig. 9.

6. Discussion

The tool proposed in the paper was described and was proven to be able to investigate the performances of existing and new buildings throughout future decades easily and with simplicity. Its integration with one among the most used and trusted building simulation tools allows for solid results; the implementation of IPCC assessment report data allows for more up-to-date results if compared to other similar approaches in literature. Also the integration with existing ASHRAE models allows for a more



C:\Users\Pc\Dow nloads\DNK_Copenhagen061800_IWEC.epw

Location COPENHAGEN Lat 55.63 Lon 12.67 Altitude 5 Tz 1

○ RCP 2.6
○ RCP 4.5
○ RCP 6.0
● RCP 8.5

○ 2035
○ 2065
● 2090

Plot Start Month 12 Day 1 Plot End Month 12 Day 31 Dry-Bulb T...

ASHRAE 90.1 Building Model OfficeSmall

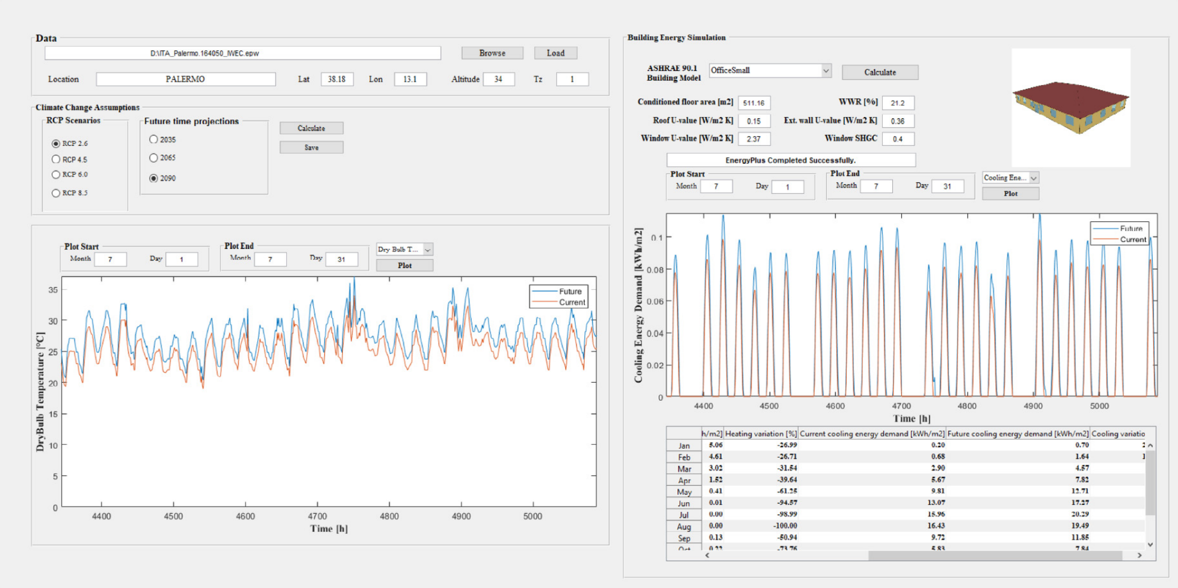
Conditioned floor area [m2] 511.16
WWR [%] 21.2
Roof U-value [W/m2 K] 0.15
Ext. wall U-value [W/m2 K] 0.36
Window U-value [W/m2 K] 2.37
Window SHGC 0.4

EnergyPlus Completed Successfully.

Plot Start Month 12 Day 1 Plot End Month 12 Day 31 Heating Ene...

	Current heating energy demand [kWh/m2]	Future heating energy demand [kWh/m2]	Heating variation [%]	Current cooling energ
Jan	25.57	18.12	-29.12	
Feb	22.77	15.11	-33.64	
Mar	18.84	12.96	-31.23	
Apr	9.76	4.92	-49.58	
May	4.52	1.80	-60.26	
Jun	2.10	0.77	-63.45	
Jul	1.31	0.33	-75.05	
Aug	2.15	0.62	-71.00	
Sep	6.43	3.03	-52.91	
Oct	10.88	5.89	-45.83	

Fig. 4. Climate change tool – Copenhagen, heating season (Scenario RCP 8.5 – year 2090).



D:\ITA_Palermo.164050_IWEC.epw

Location PALERMO Lat 38.18 Lon 13.1 Altitude 34 Tz 1

● RCP 2.6
○ RCP 4.5
○ RCP 6.0
○ RCP 8.5

○ 2035
○ 2065
● 2090

Plot Start Month 7 Day 1 Plot End Month 7 Day 31 Dry Bulb T...

ASHRAE 90.1 Building Model OfficeSmall

Conditioned floor area [m2] 511.16
WWR [%] 21.2
Roof U-value [W/m2 K] 0.15
Ext. wall U-value [W/m2 K] 0.36
Window U-value [W/m2 K] 2.37
Window SHGC 0.4

EnergyPlus Completed Successfully.

Plot Start Month 7 Day 1 Plot End Month 7 Day 31 Cooling Ene...

	h/m2]	Heating variation [%]	Current cooling energy demand [kWh/m2]	Future cooling energy demand [kWh/m2]	Cooling variatio
Jan	5.06	-26.99	0.20	0.70	
Feb	4.61	-26.71	0.68	1.64	
Mar	3.02	-31.54	2.90	4.57	
Apr	1.52	-39.64	5.67	7.82	
May	0.41	-61.25	9.81	12.71	
Jun	0.01	-94.57	13.07	17.27	
Jul	0.00	-98.99	15.96	20.29	
Aug	0.00	-100.00	16.43	19.49	
Sep	0.13	-50.94	9.72	11.85	
Oct	0.22	-73.76	5.83	7.84	

Fig. 5. Climate change tool – Palermo, cooling season (Scenario RCP 2.6 – year 2090).

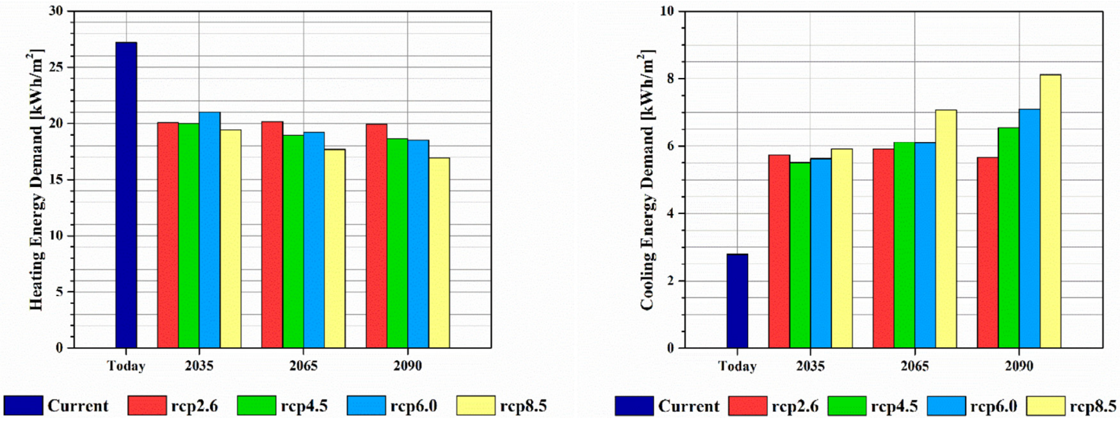


Fig. 6. Heating and cooling energy demand (Copenhagen).

Table 5
Average monthly air temperature [°C] for Palermo.

	Current	RCP2.6 2035	RCP2.6 2065	RCP2.6 2090	RCP4.5 2035	RCP4.5 2065	RCP4.5 2090	RCP6.0 2035	RCP6.0 2065	RCP6.0 2090	RCP8.5 2035	RCP8.5 2065	RCP8.5 2090
Jan	12.68	13.98	14.02	14.25	13.94	14.61	14.87	13.71	14.78	15.22	13.94	15.52	16.08
Feb	11.85	13.52	13.50	13.59	13.50	13.94	14.65	13.11	14.59	14.62	13.55	15.05	15.78
Mar	13.84	15.46	15.76	15.51	15.52	16.04	16.39	15.24	16.52	16.81	15.74	17.10	17.88
Apr	15.66	17.18	17.52	17.55	17.31	17.86	18.12	16.95	18.02	18.49	17.47	18.76	19.43
May	19.15	20.55	20.76	21.18	20.81	21.31	21.72	20.37	21.45	22.17	21.11	22.75	23.70
Jun	22.80	24.54	24.96	25.00	24.65	25.35	25.65	24.38	25.47	26.58	25.20	26.84	27.83
Jul	25.47	27.32	27.84	27.60	27.69	28.36	28.24	26.93	27.98	29.22	27.73	29.53	30.71
Aug	27.04	28.77	29.05	28.81	29.05	29.64	29.92	28.39	29.55	30.54	29.24	31.17	32.18
Sep	24.08	25.81	26.16	25.80	25.89	26.66	27.22	25.50	26.66	27.79	26.13	28.37	29.28
Oct	21.60	23.33	23.46	23.44	23.05	23.79	24.61	23.10	24.13	24.73	23.48	25.61	26.18
Nov	17.22	18.88	18.78	18.61	18.43	19.22	19.39	18.25	19.10	20.21	18.98	20.71	20.99
Dec	13.89	15.27	16.15	15.84	15.67	16.34	16.41	15.16	16.07	17.20	15.56	17.51	17.74
Year	18.82	20.43	20.71	20.64	20.50	21.14	21.48	20.13	21.23	22.01	20.72	22.46	23.19

Table 6
Average monthly air temperature [°C] for Copenhagen.

	Current	RCP2.6 2035	RCP2.6 2065	RCP2.6 2090	RCP4.5 2035	RCP4.5 2065	RCP4.5 2090	RCP6.0 2035	RCP6.0 2065	RCP6.0 2090	RCP8.5 2035	RCP8.5 2065	RCP8.5 2090
Jan	1.48	2.98	2.85	2.80	2.73	3.66	4.07	2.02	3.09	3.65	2.82	4.33	4.95
Feb	0.18	1.79	0.99	1.99	1.40	1.82	1.90	0.88	2.90	2.08	2.10	3.49	3.37
Mar	2.95	4.41	4.16	4.84	4.55	5.31	5.30	4.55	5.11	5.65	4.57	6.15	6.02
Apr	6.24	7.32	8.00	8.46	7.77	8.37	8.83	7.32	8.45	8.95	8.10	9.06	9.56
May	11.45	12.04	12.54	12.41	12.40	13.01	13.55	11.62	12.85	14.12	13.03	14.03	14.76
Jun	14.67	16.75	16.99	16.43	15.99	17.83	18.11	15.26	17.06	18.86	16.45	18.60	19.62
Jul	16.58	18.41	18.82	18.48	18.14	19.71	19.40	17.53	18.93	20.53	18.73	20.42	21.87
Aug	16.95	18.38	18.65	18.91	18.53	19.92	19.61	17.62	19.52	21.16	19.06	21.33	22.64
Sep	12.30	14.22	14.19	14.01	14.26	14.90	15.22	13.65	14.82	15.59	14.61	16.40	17.16
Oct	9.69	11.31	10.83	11.34	11.18	11.39	12.05	11.15	11.80	12.19	11.13	12.95	13.48
Nov	5.12	6.62	6.84	6.55	6.81	7.19	7.25	6.43	7.04	8.01	7.38	8.05	8.40
Dec	1.60	2.95	2.59	3.09	2.63	4.16	3.20	2.57	3.57	4.01	2.70	4.04	4.98
Year	8.32	9.81	9.84	9.99	9.75	10.66	10.76	9.27	10.47	11.29	10.10	11.62	12.29

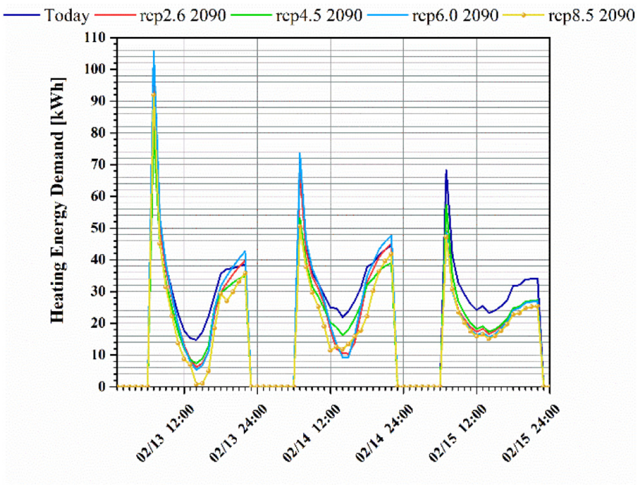


Fig. 7. Dynamic results output example: Heating (Copenhagen).

structured approach, allowing for benchmarking of the results achieved with the model used within the tool.

The tool implemented a state of the art methodology based on the morphing of existing weather data files: the approach allows for simple integration with the existing state of the art energy modelling and simulation tools and has therefore potential for covering a specific gap within practitioners and researchers.

The tool has an intrinsic level of reliability: it is based on Energy plus for the thermal building simulation engine, it uses directly Ashrae 90.1 building models, works with Energy plus weather data files and implements the well-established morphing method for calculating provisional values for future climate data files based on IPCC future climate data.

The results for the case study highlight a lower heating energy use the higher the time span considered. It also decreases with the RCP scenarios considered being the lowest with RCP8.5.

Symmetrical results are found for cooling which is always higher in both case studies the higher the time-span considered and grows considerably with the RCP scenarios investigated.

The results have highlighted a clear tendency of the next century towards the increase of energy use for air conditioning that is available in both the two locations examined: this for sure will impact the way both new constructions and existing ones may be resilient towards climate change and will require the use of suitable tools for practitioners and designers to explore its implications on the built environment.

Also the significant shift towards cooling would have consequences: either with the need for installation of a significant amount of additional conditioning power in countries that at the moment have not significant cooling requirements (i.e. in the case of Copenhagen) or for a large increase in peak power requirements for traditionally hot countries (i.e. in the case of Palermo). Also issues with buildings too airtight may arise with significant concerns for air quality coupled with a general increase in cooling requirements.

7. Conclusions

As new constructions built today are expected to fully withstand the effects of climate change in the next decades, as such building design is currently in need to plan accordingly the design of buildings by including in the design process specific efforts to the modelling and simulation of the effects of climate change to the building sector.

The current state of building energy simulation practice is currently characterized by a lack of specific simplified tools and approaches that may help, research, practitioners and stakeholders

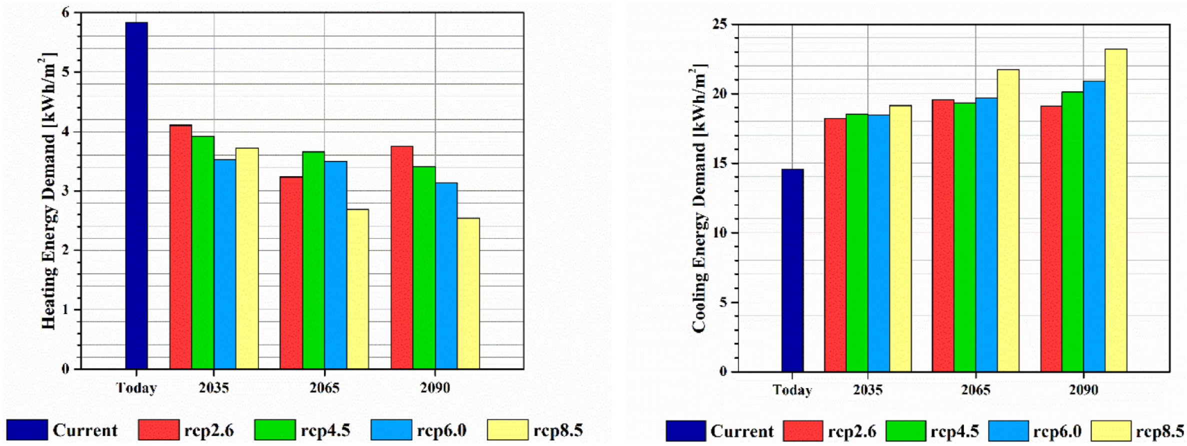


Fig. 8. Heating and cooling energy demand (Palermo).

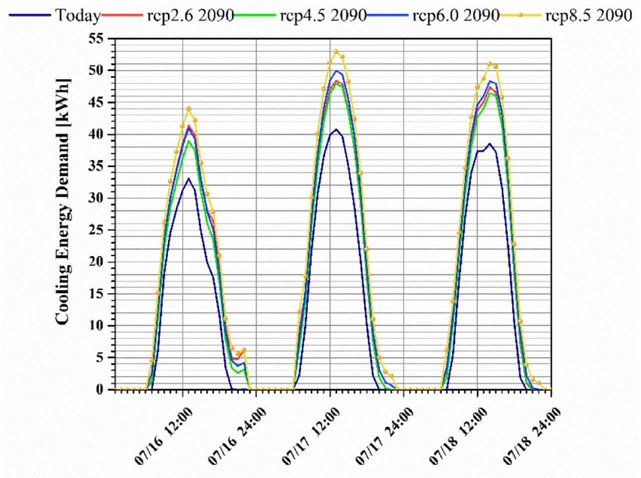


Fig. 9. Dynamic results output example: Cooling (Palermo).

in having a quick grasp on how the evolution of global warming due to climate change will induce changes in the building energy performances of the current century.

As such, this limit generates a specific potential lack of resilience in the building sector that will have severe repercussions in the estimates of energy use in the whole sector — especially so if the most needed decarbonization of the economy and the development of green and decarbonized districts (Fichera et al., 2020b,a, 2017)will not be fully pursued in the current century.

In this framework, the tool proposed is a significant contribution to the state of the art as it allows for the investigation of climate change resilience of buildings through the combined use of:

- a very easy, simple and immediate GUI, essential to guarantee its widest distribution and potential impact among practitioners;
- scientific depth of the methodological approach, as all tools used and connected are fully validated – as in the case of Energy Plus – or established in the field of climate change weather data assessment — in the case of the morphing methodology;
- the possibility of easily exporting the data generated and post-process them, while guaranteeing the possibility for easy in-tool visualization and comparison;
- the possibility of using already developed realistic and standardized building models – as in ASHRAE 90.1 guidelines – to perform quick estimations on the potential impact of climate change;
- the availability of testing ad hoc energy plus models defined by the users, potentially for more advanced and research applications.

The main limitation of the approach lies in the uncertainty of the climate evolution in the next decades, which is mirrored in the contents of the paper in the implementation of the different RCP scenarios. A wide range of parametric analyses should be investigated when approaching future climate models in building performance assessment studies.

The tool shares its scope with the current efforts developed by the United Nations — Sustainable Development Solutions Network with the joint work on the sustainable development goals, in particular with the joint efforts towards affordable and clean energy, climate action, sustainable cities and communities.

The tool may also have applications within the scaling up of the single building dimension towards the district perspective and the one of positive energy districts, as the larger perspective may allow for more insight on the performances of the whole neighbourhood, thus allowing to go beyond the single units' limits and issues. Further potential applications lie in the research of building resilience towards climate change as well as in the practitioner field to perform climate proofed building designs.

The research proposed goes also in the direction of most research at the EU level, whereas the interest towards climate neutral and innovative cities as well as for climate resilient innovation is considered a top priority in conjunction with the need to build and renovate in an efficient way, within the new European Green Deal.

The tool implements solid calculations through the connection to the Energy plus simulation routine embedded in it and can allow a wide degree of flexibility through the use of several customization options both in simulation features as well as in the visualization of the results.

Moreover, the use of a building models' library including existing benchmarks from ASHRAE can help in the applicability of the tool into different situations, including compliance calculations or pre-design analyses; while it may also find suitable use for fast and accurate parametric and scenario analysis within the climate change sector as well as being a basis for comparison for similar analyses.

The results and the case study analysis show the ability of the approach to investigate at a glance either dynamic (through fully customizable tabs) building simulation data and aggregated results (through the detailed monthly tables) reported per all variables of interest. The tools is an efficient instrument to let practitioners approach the modelling of global warming effects within the building sector, while going beyond the traditional barriers of time consuming efforts, complex applications and limited knowledge and know-how available on the topic.

The tool is free of charge and, although not yet published on a webpage online, authors are available to share it with anyone willing to test it.

CRediT authorship contribution statement

Francesco Guarino: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Giovanni Tumminia:** Resources, Software, Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Sonia Longo:** Resources, Methodology, Conceptualization, Data curation, Formal analysis. **Maurizio Cellura:** Supervision, Conceptualization, Methodology, Investigation, Resources. **Maria Anna Cusenza:** Visualization, Resources, Software.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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