Basics and recommendations on influence of future climate change on prediction of operational energy consumption

A Contribution to IEA EBC Annex 72

February 2023

Free image from Slawomir Kowalewski on Pixabay

Basics and recommendations on influence of future climate change on prediction of operational energy consumption

A Contribution to IEA EBC Annex 72

February 2023

Authors

Francesco Guarino, UNIPA, Italy, (francesco.guarino@unipa.it)

Maurizio Cellura, UNIPA, Italy

Sonia Longo, UNIPA, Italy

Maria Anna Cusenza, UNIPA, Italy

Marina Mistretta, UNIRC, Italy

Giovanni Tumminia, CRN, Italy

Reviewed by:

Aoife Houlihan Wiberg, UU, United Kingdom
Thomas Lützkendorf, KIT, Germany
Maria Balouktsi, KIT, Germany

Imprint:

Published by 2023 Verlag der Technischen Universität Graz, www.tugraz-verlag.at

Editors: Rolf Frischknecht, Thomas Lützkendorf, Alexander Passer, Harpa Birgisdottir, Chang-U Chae, Shivakumar Palaniappan, Maria Balouktsi, Freja Nygaard Rasmussen, Martin Röck, Tajda Obrecht, Endrit Hoxha, Marcella Ruschi Mendes Saade

DOI: 10.3217/978-3-85125-953-7-06

Cover picture: Free image from Sławomir Kowalewski on Pixabay

The official reports from IEA EBC Annex72 are available at following website:
https://annex72.iea-ebc.org/publications

Funding
The work within Annex 72 has been supported by the IEA research cooperation on behalf of the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology via the Austrian Research Promotion Agency (FFG, grant #864142), by the Brazilian National Council for Scientific and Technological Development (CNPq, (grants #306048/2018-3 and #313409/2021-8), by the federal and provincial government of Quebec and Canada coordinated by Mitacs Acceleration (project number IT16943), by the Swiss Federal Office of Energy (grant numbers SI/501549-01 and SI/501632-01), by the Czech Ministry of Education, Youth and Sports (project INTEREXCELLENCE No. LTT19022), by the Danish Energy Agency under the Energy Technology Development and Demonstration Programme (grant 64012-0133 and 64020-2119), by the European Commission (Grant agreement ID: 864374, project ATELIER), by the Agence de l'Environnement et de la Maîtrise de l'Energie (ADEME) in France (grant number 1704C0022), by the Federal Ministry of Education and Research (BMBF) and the Federal Ministry for Economic Affairs and Climate Action (BMWK, the former Federal Ministry for Economic Affairs and Energy (BMWi)) in Germany, coordinated by the project management agency PTJ (project numbers 03SBE116C and 03ET1550A), by the University of Palermo - Department of Engineering, Italy, by the Research Centre for Zero Emission Neighbourhoods in Smart Cities (FME ZEN) funded by the Norwegian Research Council (project no. 257660), by the Junta de Andalucía (contract numbers 2019/TEP-130 and 2021/TEP-130) and the Universidad de Sevilla (contract numbers PP2019-12698 and PP2018-10115) in Spain, by the Swedish Energy Agency (grant number 46881-1), and by national grants and projects from Australia, Belgium, China, Finland, Hungary, India, The Netherlands, New Zealand, Portugal, Slovenia, South Korea, United Kingdom, and the United States of America.

Preface

This publication is an informal background report. It was developed as part of the international research activities within the context of the project IEA EBC Annex 72. Its contents complement the report "Context-specific assessment methods for life cycle-related environmental impacts caused by buildings" by Lützkendorf, Balouktsi and Frischknecht et al. (2023). The sole responsibility for the content lies with the author(s).

Together with this report, the following background reports have been published on the subject of "Assessing Life Cycle Related Environmental Impacts Caused by Buildings" (by Subtask 1 of IEA EBC Annex 72) and can be found in the official Annex 27 website (https://annex72.iea-ebc.org/):

- Survey on the use of national LCA-based assessment methods for buildings in selected countries (Balouktsi et al. 2023);
- Level of knowledge & application of LCA in design practice: results and recommendations based on surveys (Lützkendorf, Balouktsi, Röck, et al. 2023);
- Basics and recommendations on modelling of processes for transport, construction and deconstruction in building LCA (Soust-Verdaguer et al., 2023);
- Basics and recommendations on influence of service life of building components on replacement rates and LCA-based assessment results (Lasvaux et al., 2023);
- Basics and recommendations electricity mix models and their application in buildings LCA (Peuportier et al., 2023);
- Basics and recommendations on influence of future electricity supplies on LCA-based building assessments (Zhang 2023);
- Basics and recommendations on assessment of biomass-based products in building LCAs: the case of biogenic carbon (Saade et al., 2023);
- Basics and recommendations on discounting in LCA and consideration of external cost of GHG emissions (Szalay et al., 2023);
- Basics and recommendations in aggregation and communication of LCA-based building assessment results (Gomes et al., 2023);
- Documentation and analysis of existing LCA-based benchmarks for buildings in selected countries (Rasmussen et al., 2023);
- Rules for assessment and declaration of buildings with net-zero GHG-emissions: an international survey (Satola et al. 2023).

Summary

A basis for determining and assessing the operational greenhouse gas emissions of buildings (module B6 of a building related LCA) and other impacts on resource depletion and environment already during design is the realistic prognosis of the operational energy demand. Important input variables are the outside temperatures during the heating and cooling periods as well as the thermal comfort requirements of the users. As a result of the already occurring global warming, changes in the local climate will occur at the site of specific buildings. This raises the question of what basis can and should be used to determine the operational energy demand in the future. The presentation and discussion of corresponding possibilities is the subject of this background report.

The report includes the description of the most used techniques for the introduction of global warming expected climate variations within the context of building energy simulation through the downscaling of existing global circulation models' outputs and the manipulation of existing weather data files. It discusses future provisional assessments of the air temperature variations throughout the current century as well as the analysis of existing literature that estimates potential energy use variation in heating and cooling throughout different climate zones in the world.

The main results highlight an increase in energy use for cooling in all the locations highlight the trend in rising temperatures throughout the globe that may reach up to 4.5 degrees Celsius at the end of the century, if compared to the current situation.

This will have significant implications on the energy use to operate buildings, with severe (up to 40%) increase in cooling energy use by the end of the century and peak power requirements and parallel reductions in heating requirements.

Other consequences may impact traditionally heating dominated countries which may see the rise of cooling requirements, also generating the need for HVAC equipment, actually generating a significant increase not only in energy use during the operation stage, but as well in terms of embodied energy.

As the average buildings' life cycle is in the range of the climate change time scale, the global warming trend will require innovative and more climate resilient design, with smart solutions, wider use of passive building design, improved urban solutions and planning (i.e. to counteract in-creasing heat island effects) for new buildings as well as for the energy retrofitting of the existing building stock.

It is thus recommended to future-proof buildings designed today with climate change resilient technical solutions as well as through the appropriate use of building energy simulation.

Table of content

Abbreviations

Abbreviations	Meaning
AR4	Assessment Report Four
AR5	Assessment Report Five
BAU	Business As Usual
CDD	Cooling Degree Days
DRY	Design Reference Year
EWY	Example Weather Year
GCM	Global Circulation Models
GHG	Greenhouse Gas
HDD	Heating Degree Days
IPCC	Intergovernmental Panel on Climate Change
PPD	Predicted Percentage of Dissatisfied
RCM	Regional Climate Models
RCP	Representative Concentration Pathways
SRES	Special Report on Emission Scenarios
TAR	Third Assessment Report
TRY	Test Reference Year

Definitions

Global Circulation Models (GCM): they are numerical models of the main physical process in the atmosphere, oceans and land surface and represent the state of the art of the modelling and simulation of the global climate system in response to the increase of the concentration of greenhouse gases in the atmosphere. GCMs are usually based on three dimensional grids with resolution higher than 250 km, thus calculating and simulating the physics of the airflow of air and water masses: energy balances, wind flow and speed, water currents and temperature, precipitations etc.

Regional Circulation Models (RCM): RCM models are based on limited areas and use a much denser concentration of grid points for the numerical modelling and simulation, thus being able to catch specific local microclimate trends and variations, which can often be very impactful in the performances of buildings. They can usually be combined with GCMs as they use boundaries conditions deriving from GCMs.

Representative Concentration Pathways (RCP): defined respectively as RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The specific nomenclature used in the definition of the scenarios refers to the radiative forcing implemented in the modeling, defined as the change in net – downward minus upward - radiative flux (measured in Watts per square meter) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as (and most prominently so) the concentration of carbon dioxide. These scenarios are generally developed in time and extend also beyond the end of the XXII century.

1. Introduction

The effects of climate change are widespread in different areas and domains, including potential future repercussions across nearly all the sustainable development goals, as well as, substantial variations on current climate patterns will impact the standards of living for people throughout the world. Poverty, hunger, health and well-being, clean water and sanitization, affordable and clean energy, cities and communities, responsible consumption and production – are some of the most relevant Sustainable Development goals – which can, and will, be impacted by an increase of extreme weather events which has risen dramatically in the last years. Furthermore, due to a change in the average trends of most climate variables, such as, for example, the increase in average air temperatures, climate change is also creating impacts on the world beyond extreme events.

In the work of the Intergovernmental Panel on Climate Change (IPCC) (Edenhofer, Pichs-Madruga, & Sokona, 2014) it is clearly mentioned that if no decisive action is undertaken on a global scale to decarbonize economies, then business as usual scenarios identify an significant of the average air temperature increase by the end of our century even by more than 4.5 degrees. Although this approach towards a widespread decarbonisation must cover all sectors of the economy, the decarbonisation of the construction and real estate sector, which is historically one of the main sectors contributing the worldwide CO_{2eq} emissions, must be considered as one of the main targets.

Since 1970, buildings have been significantly increasing their share of total carbon emissions, which are mostly related to indirect CO_2 emissions from the use of electricity in buildings in comparison to direct emissions, which have remained constant during recent decades. Indirect emissions have instead largely increased since the ‘70s, with at least a quadrupling of emissions from both residential and commercial buildings (Edenhofer et al., 2014) .

According to the International Energy Agency, the building and real estate sector (International energy agency, 2019a) accounts for 36% of final energy use and 39% of energy and process related carbon dioxide emissions in 2018, with an 11% of this total being caused by manufacturing of building materials or, in other words, being energy “embodied” in the building envelope and energy systems (Cabeza, Castell, & Pérez, 2014).

The emissions from the building and real estate sector have had in the past decade an increasing trend, in particular in 2018 they have kept increasing for the second year in a row, reaching an all-time high. (International energy agency, 2019b) This was caused by extreme weather which caused an increase in the demand for heating and cooling, which accounts for roughly the 20% of the total energy use increase for 2018. It is also worth mentioning that the building and real estate sector (sometimes also called area of action “buildings”) has very high potential for decarbonization, because of the widespread use of low-efficiency technologies and systems, both in terms of heating and cooling, as well as, in the quality of envelopes and the limited worldwide availability of effective policies and investments towards sustainable and high-performance buildings.

Moreover, the Pathways to Deep decarbonization project, developed by the Sustainable development solutions network (Sachs, Tubiana, & (IDDRI), 2014) stressed the necessity to limit the average temperature increase to 2°C at 2050 as per in the Paris agreement of COP21, clearly identifying the reduction threshold for carbon emissions to 56%, if compared to the 2010 levels on a global scale.

As such, short-sighted polices in the field of energy and buildings and, therefore, the embrace of un-sustainable economic pathways towards the next century could lead to potentially severe increases of energy

uses in the built environment, which could enable the vicious cycle of further increasing climate change phenomena through an increase in the emissions of carbon in the atmosphere.
This uncertainty makes the task to perform a robust and climate resilient design of sustainable buildings a challenge. The context of building performance assessment requires insight on energy demand calculations to be performed by assessing all geometrical and thermal features of the envelope and by performing specific energy calculation by taking in consideration the impact of the local weather and climate.

Practitioners usually work with weather data files only valid for the current time and buildings have a long lifespan: this means that designing buildings only for “today”, might mean that the weather conditions in the future might be largely different than what the building is designed to withstand. This could translate into increased energy uses, longer periods of thermal discomfort with higher predicted percentage of dissatisfied[1] (PPD) and fundamentally a building design which cannot adapt to climate change related future scenarios.

The building design should evolve and adapt with the climate it is supposed to withstand: it is therefore paramount to develop models to predict the evolution of global warming and its associated local consequences in the coming decades by developing designs / models and simulation tools to help building designers and energy specialists to design for the future climate change scenarios.

---

[1] provides an estimate of how many occupants in a space would feel dissatisfied by the thermal conditions

2. Overview and Fundamentals

Climate change can translate into several phenomena and issues. This chapter will discuss the impact that climate change has, in terms of global warming, and on the energy use of buildings. Fundamentals of building energy simulation will be summarized, the main issues and modeling approaches towards the modeling of global warming into building simulation practice reviewed, with limits and strengths for each. Lastly the results of a selected overview of research on the energy uses for buildings during the current century will be shown and discussed.

2.1 Climate Change Modelling

Over the last two decades, IPCC has released a set of different emissions scenarios based on different assumptions. Different scenarios were developed thus in 1990 (called SA90), 1995 (IS92) and 2000 (special report on emission scenarios – SRES). These scenarios were used within the Third assessment Report (TAR) and the Assessment Report Four (AR4) and were considered as some of the most relevant references on the subject in the past decade.

In 2007, as reported in Figure 1, IPCC developed four specific emission scenarios used in the Assessment Report Five (AR5) called "Representative Concentration Pathways" (RCP), defined respectively as RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. The specific nomenclature used in the definition of the scenarios refers to the radiative forcing implemented in the modeling, defined as the change in net – downward minus upward, radiative flux (measured in Watts per square meter) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as (and most prominently so) the concentration of carbon dioxide. These scenarios are generally developed in time and extend also beyond the end of the XXII century.

Thus, the four RCP scenarios can be briefly described as:
- RCP 2.6: the radiative forcing has a peak at 3 W/m^2 then declining. This scenario assumes large decarbonization actions and a substantial reduction in carbon-intensive practices in the next decades;
- RCP 4.5 and RCP 6.0 are two intermediate pathways which assume a stabilized rate of radiative forcing between 4.5 and 6.0 W/m^2 after 2100 with constant concentrations thereafter;
- RCP 8.5 represents roughly a 'business as usual' with radiative forcing higher than 8.5 W/m^2 at 2100 with a consecutive increase also after the beginning of the next century.

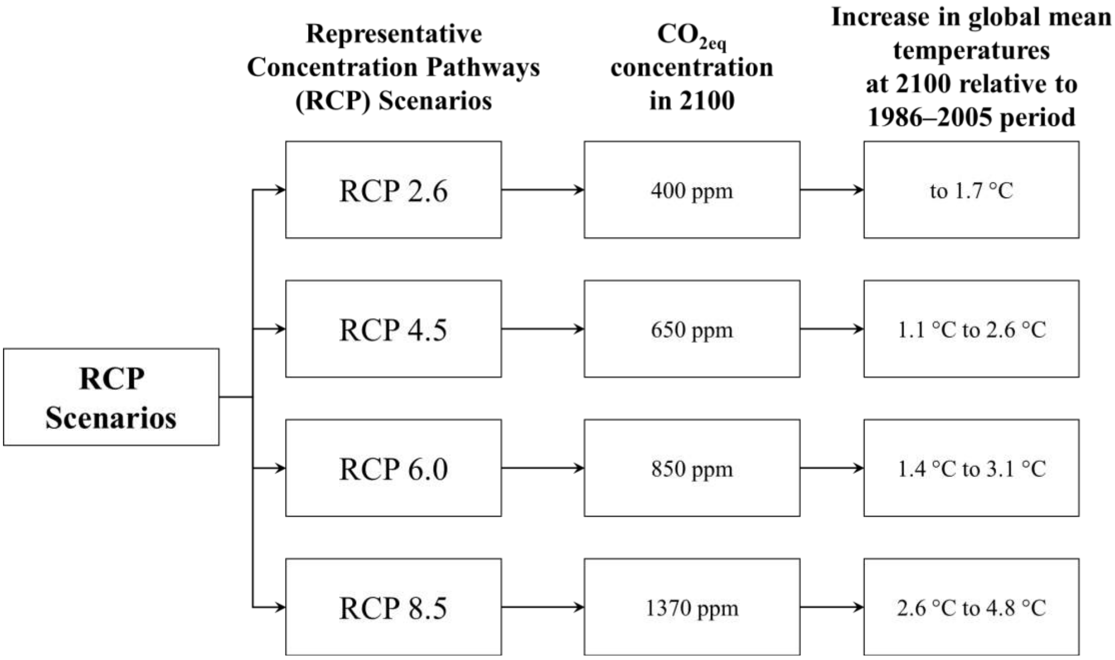

Figure 1: Representative Concentration Pathways IPCC scenarios (Edenhofer et al., 2014).

While they give an overview and aggregated information on what to expect as the perspective of global warming is concerned, these scenarios and models do not per se include climate change predictions, but rather investigate the variation of the main variables affecting climate change.

The development of variation trends for temperature and the other main climatic variables are usually achieved instead through the use of Global Circulation Models (GCM): they are numerical models of the main physical process in the atmosphere, oceans and land surface and represent the state of the art of the modeling and simulation of the global climate system in response to the increase of the concentration of greenhouse gases in the atmosphere. GCMs are usually based on three dimensional grids with resolution higher than 250 km, thus calculating and simulating the physics of the airflow of air and water masses: energy balances, wind flow and speed, water currents and temperature, precipitations etc.

However, as the focus is to develop tools and weather data files to be provided as input to the energy models for the building sector, global circulation models have in fact a resolution considered too large which makes it rather complex to identify a specific location/city. GCM outputs are usually “downscaled”, or, in other words, transposed to spatial and temporal scales lower than those provided by the original GCMs (e.g. through bilinear interpolation) (Zhu, Pan, Huang, & Xu, 2016).

Another alternative approach is called Regional Climate Models (RCM). The use of such models stems directly from the previous considerations: the local microclimate can have significant impact on the building performances, therefore using such coarse grid data can lead to some significant differences in the main climatic variables being overlooked resulting in wrong assumptions being made in the building design. RCM models are based on limited areas and use a much denser concentration of grid points for the numerical modeling and simulation, thus being able to catch specific local microclimate trends and variations, which can often have a great impact on the performances of buildings. RCM models can usually be combined with GCMs as they use boundaries conditions deriving from GCMs.

2.2 Building Energy Simulation Fundamentals

Building energy modeling and simulation is a discipline within building science, which aim at simulating all energy uses within a building with the required spatial and temporal scale (usually hourly or sub-hourly) for the investigated time span (generally one year). The models are physics – based and include detailed building geometry descriptions, construction materials, lighting features, heating, cooling and ventilation system requirements (and interconnections between them). These models also take in consideration users' related features, including occupancy features, plug loads and thermostat settings.

Most building energy simulation tools implement the Heat Balance Method, which formulates energy and moisture balances for the zone air and solve the resulting ordinary differential equations. The most common formulation of the Heat Balance of the zone air is reported in Eq.1 (Bessoudo, Tzempelikos, Athienitis, & Zmeureanu, 2010):

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i \, A_i \, (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} m_i \, (T_{zi} - T_z) + m_{inf} Cp \, (T_{\propto} - T_z) + Q_s \qquad (1)$$

Where:

$\sum_{i=1}^{N_{sl}} Q_i$ is the sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i \, A_i \, (T_{si} - T_z)$ is the convective heat transfer from the zone surfaces;

$\sum_{i=1}^{N_{zones}} m_i \, (T_{zi} - T_z)$ is the inter-zone air mixing;

$m_{inf} Cp \, (T_{\propto} - T_z)$ is the heat transfer due to infiltration of outside air;

Q_s is the air heating/cooling systems energy output;

$C_z \frac{dT_z}{dt}$ is the energy stored in the zone air.

$C_z = \rho \, C_p \, C_t$

ρ is the zone air density;

C_p is the zone air specific heat;

C_t is the sensible heat capacity multiplier. If set to 1.0, this only accounts for air capacitance, but it can be increased to higher values to account for the additional capacitance in the air loop (e.g. duct work, diffusers).

This set of equations, as well as, similar formulations for surface temperature and inter-zonal heat transfer are solved simultaneously at every simulation time step, in order to identify a dynamic set of results for the variables of interest: i.e. temperature, energy use and generation.

These models are always coupled with weather models, correlating available weather data with the building modeling tool[2]. Standard meteorological years (e.g. Example Weather Year (EWY), Test Reference Year (TRY), Design Reference Year (DRY)) are sets of meteorological data reporting values for every hour in a year (thus 8760 values) for a specific location. These data sets are usually selected from a longer time period (usually longer than ten years) and for each month in the year, the most in line with the historical database is kept in the typical weather data. Solar radiation data is usually calculated from satellite data and through the use of correlation and sky models, adapted to model solar radiation on the ground and on surfaces with variable tilt and orientation, the other variables are taken from reanalysis approaches, such as ERA Interim (Berrisford P, Dee DP, Poli P, Brugge R, Fielding K, 2011). Weather data include also all other climatic variables impactful to the building energy performance e.g. humidity, wind speed and direction, water precipitations, atmospheric pressure variations, all with one hour depth.

---

[2] Dynamic building simulation software (e.g. IDA ICE and EnergyPlus) uses weather files consisting of parameter describing the weather, with a temporal resolution of at least one hour. The main variables included in the weather files are: dry bulb temperature, relative humidity, dew point temperature, atmospheric pressure, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, horizontal infrared radiation form the sky, wind speed and direction and total sky cover

Building energy simulation is of particular interest in the field of the design of buildings, as a tool to model all design choices (e.g. building form, building components and materials, etc.) with the ultimate goal of guaranteeing increased comfort conditions to the occupants while saving energy and money in the process.

Another domain is the use for building labelling and certification, whereas the simulation of building performances is used to generate a certificate highlighting the most relevant indicators of performance of the building in terms of both envelope and energy systems.

Building simulation is also mostly used in the development of the design choices within the retrofit of existing buildings to improve the performance in a process that is similar to the design of new buildings.

Finally, several applications of building simulation are available for research purposes, either for the purpose of performance assessment of new building components/systems or control logics including innovative mathematical and statistical modeling, or building neighborhood and districts analyses.

3. Modelling Climate Change

3.1 General

It was previously mentioned that data generated from GCMs cannot be used directly in future building energy uses predictions. Thus, usually two different approaches are available: statistical and building simulation approaches.

Statistical studies are usually based on the development of correlations between historical time series of both climatic parameters and building energy uses. These relationships can be used as means to predict future weather conditions, however, excluding the relationship between the building envelope and the outdoor environment.

A typical example in this field is the “degree-days” approach. The methodology is usually based upon a single-measure steady-state approach aimed at quantifying building energy uses. It is also a common approach adopted by the building industries to relate the trends of building energy consumption with local climate conditions. As an example, heating degree days are usually calculated as in eq.2:

$$Degree\ Days = \sum_{1}^{n}(Ti - Te) \qquad (2)$$

Where T_i and T_e are respectively internal (indoor heating setpoint temperature) and external temperature. The advantage of this method is that it is simple and fast: through the analysis of historical temperature data for a specific site, it is possible to easily have a first indication on how relevant will energy use for heating and cooling could be. Furthermore, by creating correlations between the climate data, or by developing steady state tools correlating physical properties of the envelope of a building with degree days, simplified approaches are available in literature able to estimate a decently reliable assessment of energy consumption for heating and cooling.

While these approaches can have some limits when dealing with high – performance and complex-shaped buildings, they can provide a quick and simple first assessment of the energy uses of a building. They could be used for further climate change impacts assessments to the built environment, provided they are combined with reasonable estimations of degree days variations in the next decades.

Among the downscaling techniques available are statistical techniques (e.g., interpolation of the main climate related variables), stochastic (whereas models can derive variables stochastically from a few independent weather variables), or through the use of the “Morphing” method, which applies the monthly data from GCM or RCM to hourly pre-existing weather data files, through operations of “shift”, “stretch” and a combination of “shift” and “stretch”.

The results achieved from the previous step were used for development of weather data files to be used for simulation of future energy performances in a non-steady state simulation environment.

However, since solar radiation, humidity, and building characteristics such as thermal mass are not considered in degree-day analysis, studies have often found that this method can lead to large deviations when compared to energy simulations (Cellura, Guarino, Longo, & Tumminia, 2018; Guarino, Tumminia, Longo, Cellura, & Cusenza, 2022).

The alternative approach towards the prediction of future energy uses for specific future time frame or future climate change scenario lies in the use of complementing building energy simulation, already briefly discussed in the previous paragraphs, with the use of specific tools and methodologies aimed at performing climate change predictions.

Usually two approaches are available: the combination of climate projections with weather "generator" approaches, that basically generate a new, future weather data file. Weather generation approaches are based on algorithms that generate time-series of weather variables ensuring compatibility with a set of statistical parameters of the original historical weather parameters distribution. Some specific examples are reported in (Mylona, 2012), the tools COPSE (Levermore et al., 2012) and PROMETHEUS (Eames, Kershaw, & Coley, 2010). The latter is used as a basis for the publication of the UK Climate Projections to create future probabilistic reference years for use within thermal building models. The main advantages of the weather generator are seen to lie in its potentially higher spatial resolution[3], its ability to inform risk analysis and that such files, unlike ones based on observed data, carry no copyright.

Another is the 'morphing' approach (Belcher, Hacker, & Powell, 2005) which means to alter existing weather data through specific parameters which are variable on a monthly base and derive directly from RCP (Representative Concentration Pathways) predictions.

This approach is based on a mathematical procedure that generates future monthly data to generate hourly weather data to be used for building energy simulation. Every climate variable (x_o) of the existing weather data is modified by either a "shift", a "stretch" or a combination of both techniques.
Shifting operation basically raises or reduces all values of the time series by a specific value for each month of interest.

For example, the future hourly atmospheric pressure (p) could be calculated directly from the present hourly value of the atmospheric pressure (p_0) and from the monthly increment in atmospheric pressure (Δp_m), as in the following equation:

$$p = p_0 + \Delta p_m \tag{3}$$

whereas the subscript "0" relates to currently used weather data files, "m" is referred to monthly data, while the absence of subscripts implies that the term refers to future data.

The operation of "stretching" refers instead to the possibility of proportionally perform variations in climate parameters by using scaling factors. It is mostly useful if the climate change forecasts are available as a fractional monthly change. For example for the global horizontal radiation (r), an increase for monthly average solar shortwave flux received at the surface (Δr_m) is obtained. A scaling factor for the month m (α_{rm}) is calculated from the absolute variation (Δr_m) and the monthly mean ($\overline{r}_{0m}$) from the baseline climate as in the following equation 4:

$$\alpha_{rm} = 1 + \frac{\Delta r_m}{\overline{r}_{0m}} \tag{4}$$

This scaling factor is then multiplied to all months m in the time series using the following equation:

$$r = \alpha_{rm}\, r_0 \tag{5}$$

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

A further operation to be potentially performed is the simultaneous occurrence of both the previously described techniques. An operation of simultaneous shift and stretch is used for climatic variables such as dry-bulb temperature to reflect changes in both the daily mean and the peak daily values. For the dry-bulb temperature taken as example the following parameters are assessed: 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 ($\Delta t_{min,m}$).

---

[3] Spatial resolution is intended as a measure of the smallest object that can be analysed by a climate model (e.g. in degrees of latitude and longitude or in km).

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

$$\alpha_{tm} = \frac{\Delta t_{max,m} - \Delta t_{min,m}}{\bar{t}_{0max,m} - \bar{t}_{0min,m}} \qquad (6)$$

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

Thus, when the previous parameters have been calculated it is possible to determine the future hourly variable dry bulb temperature through the following equation:

$$t = t_0 + \Delta t_m + \alpha_{rm} (t_0 - \Delta t_{0,m}) \qquad (7)$$

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.

Table 1 shows the methodology applied to the climate variables contained in the weather file.

Table 1: Methodology used for each modified climate variable.

EPW climate variable	Unit	Method
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/m2]	Stretch operation
Direct normal radiation	[Wh/m2]	Calculated based on global horizontal radiation using solar geometry equations
Diffuse horizontal radiation	[Wh/m2]	Stretch operation
Horizontal infrared radiation form the sky	[Wh/m2]	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

3.2 Final Considerations

The different approaches tend to be recognized as effective in different domains: it is generally accepted that the morphing method is particularly effective provided the original weather data are detailed enough and able to adequately describe the variability of the local climate. However, since most commonly climate data used in building practice uses average and conservative values, statistical and stochastic approaches tend to be, more effective in the description of extreme climate change events, thus often causing higher peak power estimations for heating and cooling, although more computationally intensive (Moazami, Nik, Carlucci, & Geving, 2019).

Finally, it is useful to mention some official organizations in some countries which are currently providing future weather files, such as UK (CIBSE, 2022) or Germany (DWD, 2022).

4. Developments and Future Trends

In this section some results from research on the topic of effects of global warming to energy use will be investigated with a focus on research in the European area as an example[4]. Variation trends on temperature and the main climatic parameters will be shown, as well as, corresponding variations in energy uses for heating and cooling.

The research from (Cellura et al., 2018) is taken as example and focuses on the European context using some of the techniques mentioned in the previous section. In this case, the approach to the modeling and simulation of the effect of global warming is developed using dynamic building energy simulation. The building modeled is a simple detached building, based on one thermal zone enclosure, with non-residential use. The study develops a wide range of parametric analyses based on a set of different cities across Europe, choosing specific envelope features for the building, according to the existing local legislation in place and performs a downscaling of GCM data (CESM1(Cam5)) using the morphing method to address the impact of global warming to the cooling and heating energy needs of the building sector, across the different RCP scenarios investigated by IPCC.

The application of the morphing method to the currently available weather data files by using the climate forecasts for 2035, 2065, 2090 of the IPCC, delivers the results reported in Figures 2 and 3. In particular, Figure 2 reports variation in air dry bulb temperature for 2035 in business as usual (BAU) scenarios in both the RCP 2.6 and 8.5 IPCC scenarios. All cases report significant increases of the average air temperature. In the best case scenario (RCP 2.6) the average temperature is supposed to increase between 1.6 °C (Barcelona, Pisa, Palermo) and 1.9 °C (Thessaloniki). On the other hand, the BAU scenario shows temperature increases variable between 1.92° C in Palermo and 2.56 °C in Thessaloniki.

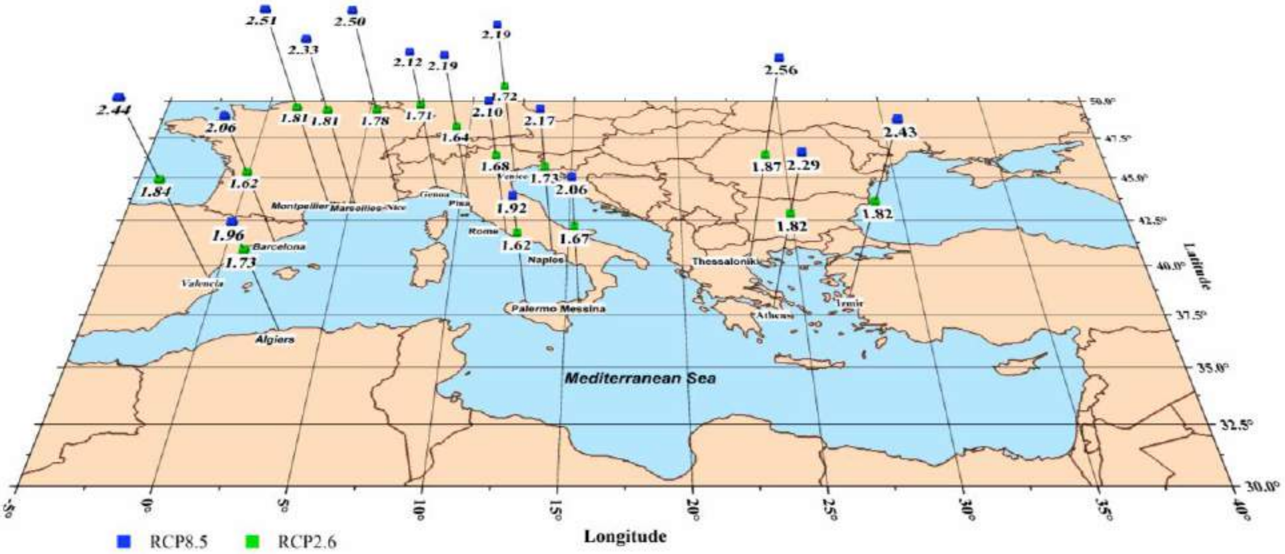

Figure 2: Variation of air temperature forecasts according to RCP 2.6 and 8.5 for 2035.

Similar trends can be found also in the case for 2090 (Figure 3), whereas the increases of average temperature become more substantial: on average the increases in the RCP 2.6 scenario is equal to 2.1 °C while it is 5.3° for the RCP 8.5. In the first case the lowest values are reported for Palermo, equal to 1.8°C, while the highest for France (2.4°C, Montpellier and Nice). Scenario 8.5 shows that the trends for Valencia

---

[4] Climate Change will also have significant impacts on embodied energy use and impacts (i.e. installation of cooling devices in cold dominated countries) that are however beyond the scope of this report.

show the highest increase in average annual temperature (6.1°C) while the lowest increase is reported for Palermo (4.4 °C).

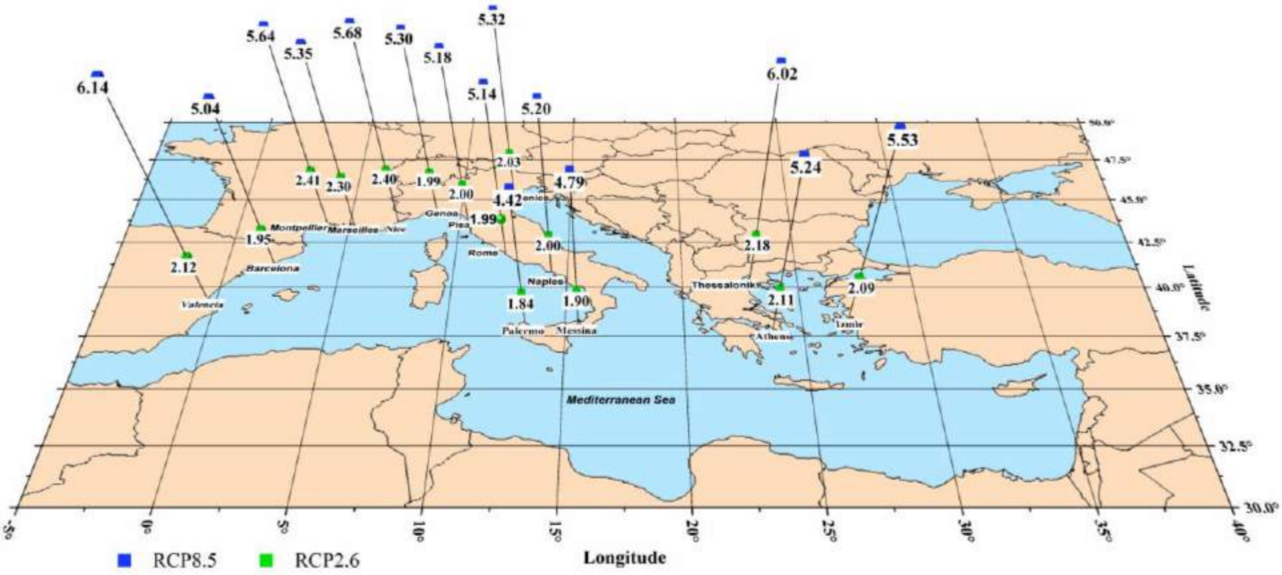

Figure 3: Variation of air temperature forecasts according to RCP 2.6 and 8.5 for 2035.

Also monthly variation data is reported in Figure 4 for all cities investigated. The RCP 2.6 data air temperature for 2090 report increases variable between 0.79°C in January (Thessaloniki) to 3.05°C in August (Nice). These data increase significantly for the case of RCP 4.5 up to 4.73 °C in July (Valencia) and 1.77 °C in November (Venice) and RCP 6.0, whereas these values reach an increase of 1.85 for January (Izmir) and 6.07 in June (Nice). The highest values fall into the RCP 8.5 category as the increase in air temperature ranges between 3.04 °C in January and 8.98 °C in Thessaloniki.

All these variations on air temperature have of course implications on the expected heating and cooling energy uses in buildings. According to the specific scenarios developed in (Cellura et al., 2018), the expected following heating and cooling demand can be traced throughout Table 2.

Table 2 shows the variability within all the investigated cities of the heating/cooling energy required to meet the heating setpoints of 20°C in winter and 26°C in summer, expressed in kWh of final nergy of cooling/heating per m^2 of walkable area. The future heating/cooling energy required requirements were calculated considering an ideal building model built in TRNSYS environment (Klein, 1988). In detail, for all the sites analysed a low-rise building model is used as ideal case study with a total heated area of 81 m^2. An isolated one-storey high building was chosen to adopt the worst conditions for cooling since climate change will most likely increase this typology of energy use in the future. Since the typical lifetime of buildings is in the range of 50–100 years and in order to ensure representativeness the buildings modelled, the building envelope features are chosen in compliance with the minimum requirements for a new non-residential building in force each country analysed (IEA, 2017). In particular, the U value for vertical surfaces varies from 0.28 W/(m^2 K) in Venice to 1 W/(m^2 K) in Thessaloniki. All walls have an internal mass layer (brick, 30 cm for external walls) and external insulation, the thickness of which varies as function of the city analysed and the regulations in force. The average global window U-value varies from 1.4 W/(m^2 K) (Venice) to 3W/(m^2 K) (Palermo).

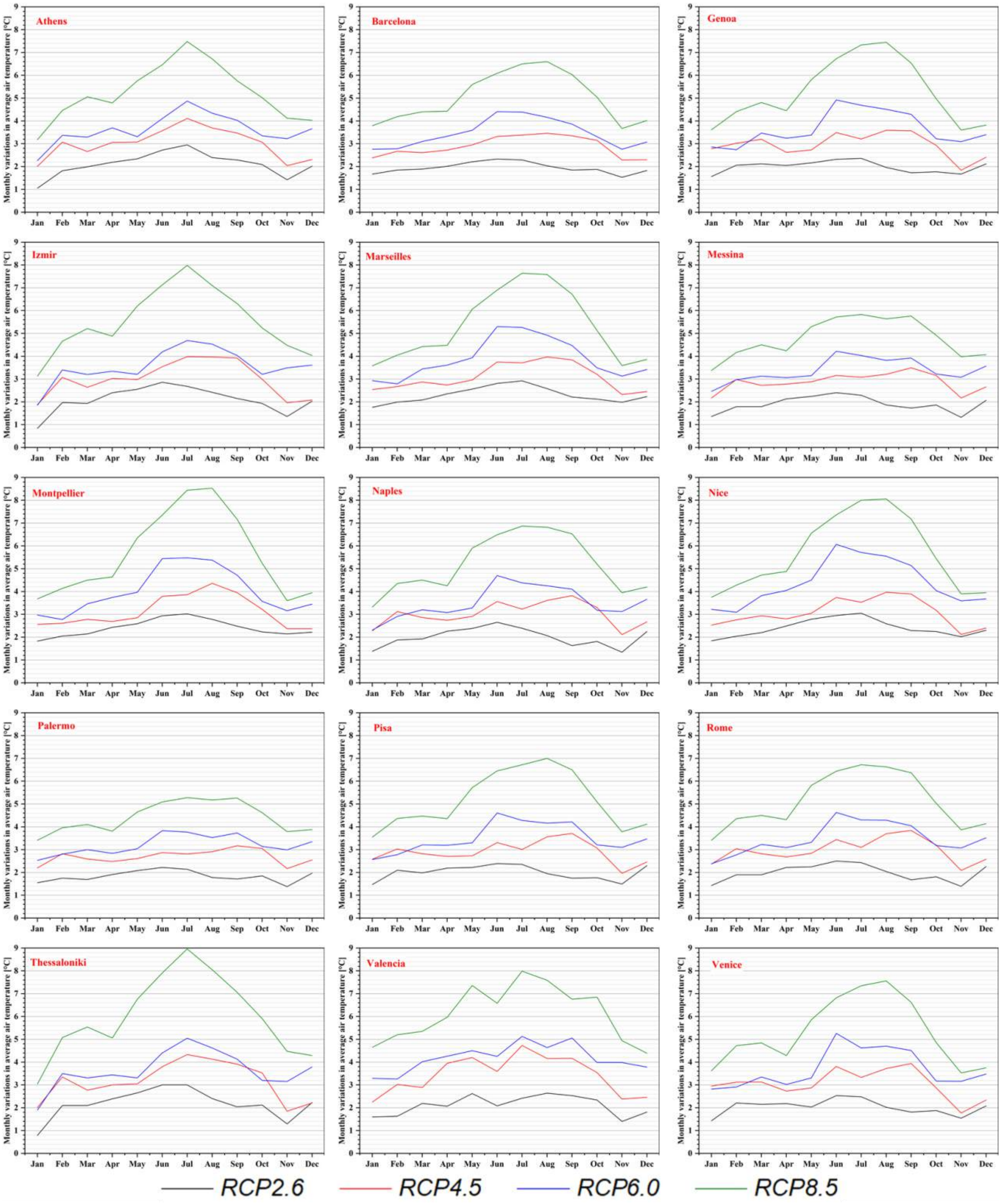

Figure 4: Monthly variations in average air temperature, scenarios RCP 2.6 to 8.5.

Table 2: Future heating and cooling energy demands.

	Today		2035							
	Heating	**Cooling**	**Heating [kWh/m^2]**				**Cooling [kWh/m^2]**			
	[kWh/m^2]	**[kWh/m^2]**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
Marseille	43.33	24.98	33.52	32.88	34.65	31.81	42.73	46.67	42.05	48.02
Montpellier	43.80	18.78	35.67	34.56	36.52	32.55	36.75	41.73	36.78	42.95
Nice	30.97	16.33	21.26	20.71	20.3	19.15	31.66	35.01	32.46	37.24
Athens	33.18	35.65	24.44	24.06	24.93	22.32	57.97	58.67	54.81	62.8
Thessaloniki	59.88	26.04	48.88	45.6	50.47	44.69	49.11	46.05	45.58	55.5
Genoa	33.36	17.71	29.19	28.68	30.76	29.1	36.17	39.21	35.04	40.8
Messina	14.51	34.71	8.69	8.77	9	8.62	48.19	51.16	46.05	53.88
Naples	31.11	23.89	22.1	21.59	23.72	20.94	40.79	42.26	38.25	44.8
Palermo	13.22	29.64	6.96	6.77	7.84	6.59	43.22	44.06	41.01	46.44
Pisa	46.55	17.55	36.88	35.9	38.15	35.17	30.88	33.21	29.97	35.71
Rome	31.77	21.91	23.71	23.57	25.11	22.88	36.16	38.34	34.48	40.24
Venice	76.06	13.08	62.19	61.88	64.79	61.36	29.38	32.32	28.63	34.67
Barcelona	37.43	15.45	26.55	24.75	28.07	24.79	29.71	32.8	29.51	33.41
Valencia	24.83	23.89	22.82	22.63	22.79	20.22	48.93	51.26	47.55	53.31
Izmir	43.27	33.90	33.96	33.96	34.54	31.09	59.08	59.07	55.67	66.19

	Today		**2065**							
	Heating	**Cooling**	**Heating [kWh/m^2]**				**Cooling [kWh/m^2]**			
	[kWh/m^2]	**[kWh/m^2]**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
Marseille	43.33	24.98	31.44	29.47	27.27	22.46	46.73	52.74	50.65	65.99
Montpellier	43.80	18.78	33.32	31.42	28.76	23.9	40.37	47.54	44.8	61.42
Nice	30.97	16.33	19.42	17.63	14.95	11.78	34.61	40.48	40.18	54.45
Athens	33.18	35.65	23.73	20.69	18.94	14.58	59.71	65.25	66.55	79.75
Thessaloniki	59.88	26.04	48.69	43.45	39.21	32.84	48.98	56.61	53.03	73.8
Genoa	33.36	17.71	28.15	25.49	24.9	20.06	38.52	45.09	41.64	57.64
Messina	14.51	34.71	8.49	7.34	6.03	5.12	51.99	56.94	55.15	71.21
Naples	31.11	23.89	21.1	18.77	17.37	13.89	42.67	47.75	46.98	62.35
Palermo	13.22	29.64	6.34	5.21	4.49	3.12	45.93	49.5	49.92	62.22
Pisa	46.55	17.55	34.37	31.88	31.21	24.43	33.5	38.34	37.47	50.78
Rome	31.77	21.91	22.52	20.4	19.09	14.99	38.53	43.38	42.28	56.1
Venice	76.06	13.08	60.56	56.1	55.73	47.62	31.8	37.39	36.03	49.45
Barcelona	37.43	15.45	24.32	21.49	20.28	15.05	33.02	37.52	35.56	48.09
Valencia	24.83	23.89	20.89	19.78	18.26	13.71	52.57	59.12	59.04	76.56
Izmir	43.27	33.90	32.41	30.49	28.15	21.78	60.53	66.76	68.29	81.94

	Today		**2090**							
	Heating	**Cooling**	**Heating [kWh/m^2]**				**Cooling [kWh/m^2]**			
	[kWh/m^2]	**[kWh/m^2]**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**	**RCP2.6**	**RCP4.5**	**RCP6.0**	**RCP8.5**
Marseille	43.33	24.98	30.34	27.5	24.38	20.87	45.86	54.51	61.47	78.97
Montpellier	43.80	18.78	31.42	29.83	26.01	22.41	39.94	49.05	56.37	76.71
Nice	30.97	16.33	17.98	16.18	12.05	10.39	34.58	41.83	50.47	67.44
Athens	33.18	35.65	22.58	18.4	14.95	11.33	60.88	70.09	74.94	96.34
Thessaloniki	59.88	26.04	46.57	40.11	37	26.42	51.71	61.9	66.66	93.21
Genoa	33.36	17.71	27.44	23.75	22.43	17.95	37.46	46.41	53.28	70.43
Messina	14.51	34.71	8.39	5.87	5.76	3.84	51.62	59.07	65.06	81.23
Naples	31.11	23.89	20.64	16.52	15.23	11.1	42.26	51.01	55.71	73.97
Palermo	13.22	29.64	6.27	4.29	3.71	2.22	45.4	52.74	57.29	70.63
Pisa	46.55	17.55	34.06	29.78	27.31	21.62	32.53	40.16	45.22	61.2
Rome	31.77	21.91	22.24	18.32	17.14	12.7	38.05	45.77	50.65	66.93
Venice	76.06	13.08	60	53.64	49.46	43.43	31.37	40	44.91	62.1
Barcelona	37.43	15.45	24.2	19.95	18.13	12.39	31.55	39.12	44.41	58.68
Valencia	24.83	23.89	21.77	18.55	14.9	10.95	51.68	66.57	71.08	96.08
Izmir	43.27	33.90	31.99	27.48	23.73	17.51	61.69	71.86	76.97	102.16

The immediate trend easily recognizable leads to a large increase in cooling in the next years with a sizable reduction instead in heating requirements as well. Table 2, in particular shows very variable results: the simulations for 2035 identify a high increase in cooling, reaching on average 81% for RCP 2.6, 91% in the case of RCP 4.5, 75% for RCP 6.0 and 104 % in the scenario RCP 8.5, if compared to current standards. On average, RCP 2.6 scenarios show an **average increase** in cooling requirements of 20.2 kWh/m^2 while for the 8.5 scenarios, this value reaches 53.5 kWh/m^2.

A similar but reversed trend is to be expected for heating demand, with reductions in impact for heating variable on average between 24.6% for the RCP 2.6 scenario up to 29.1% for scenario RCP 8.5 for 2035. For 2090 instead, on average, the decrease in heating requirements is thus expected to be reduced by 18.5% in scenario RCP 2.6, and by 27.9%, 33.8 and 58.3% respectively for the other scenarios (RCP 4.5, 6.0, 8.5).

As reported in Table 3, previous studies already analyze the effect of a warmer climate on building energy performances (Jiang, Liu, Czarnecki, & Zhang, 2019; Kikumoto, Ooka, Arima, & Yamanaka, 2015; Liu et al., 2020) in the USA (Shen, 2017; Shen & Lior, 2016), in Canada (Berardi & Jafarpur, 2020; Robert & Kummert, 2012), in Australia (Wang, Chen, & Ren, 2010), in Asia (Chan, 2011; Huang & Hwang, 2016) and in Europe (Farrou, Kolokotroni, & Santamouris, 2016; Jentsch, Bahaj, & James, 2008; Roux, Schalbart, Assoumou, & Peuportier, 2016) using as input different GCMs, climate change scenarios, future time slices. In this context, the scientific community seems to agree that climate change will have a negative effect on the energy performance of buildings (Ivan Andrić, Le Corre, Lacarrière, Ferrão, & Al-Ghamdi, 2021), but regardless of building sizing and modeling assumptions, the common perspective is that cooling in buildings is going to have a more relevant impact on building energy performances in the next decades than today.

Table 3: Summary of research on the effect of the climate change on building energy performances.

Country	Future time slices	Climate change Scenarios	Main research findings	Ref.
Southampton (UK)	2020, 2050 and 2080	UKCIP02	The study describes a method for the integration of future UK climate scenarios into the EnergyPlus weather file formats and demonstrates the importance of climate change analysis through a case study example. Simulations of a case study building (university of Southampton office building) highlight the potential impact of climate change on future summer overheating hours inside naturally ventilated buildings.	(Jentsch et al., 2008)
25 locations throughout the world	2100	IPCC TAR	The study presents a methodology to create weather files which represent climate change scenarios in 2100 and heat island impacts today, considering 25 locations throughout the world. Moreover, examples of how heat island and climate change scenarios affect the annual energy performances of small office building case study for three (cold, tropical and temperate cliomates) of the 25 locations investigated haare showed. In cold climates, the net change to annual energy use due to climate change will be positive – reducing energy use on the order of 10% or more. For tropical climates, buildings will see an increase in overall energy use due to climate change, with some months increasing by more than 20% from current conditions. Temperate, mid-latitude climates will see the largest change but it will be a swapping from heating to cooling, including a significant reduction of 25% or more in heating energy and up to 15% increase in cooling energy.	(Crawley, 2008)
Alice Springs, Darwin, Hobaùrt, Melbourne and Sydney (Australia)	2050 and 2100	IPCC TAR	The study investigates the potential impact of climate change on the heating and cooling energy requirements of residential houses in five regional climates varying from cold to hot humid in Australia.. The total heating and cooling energy requirements would vary significantly under different climate change scenarios. In the temperate climates of Sydney, for example, in 2100 the increase in the total heating and cooling energy consumption would be 120% and 530% when the global temperature increases by 2 °C and 5 °C, respectively.	(Wang et al., 2010)

Hong Kong (China)	2011-2030, 2046-2065, 2080-2099	IPCC TAR	The aim of the study is to develop a set of Hong Kong hourly weather data files for building energy simulation use, incorporating the future climate change. Moreover, the impact of climate change on building energy consumption in office and residential buildings under different emission scenarios are also evaluated. The results indicate that there will be substantial increase in air-conditioning energy consumption under the impact of future climate change, ranging from 2.6% to 14.3% and from 3.7% to 24% for office building and residential flat, respectively.	(Chan, 2011)
Montréal and Massena (Canada)	2020 - 2050	IPCC TAR	The research investigates the use of the downscaling method to generate hourly future weather data files. The impact of using these weather files on the energy performance of an NZEB case study is then assessed. The results show that the net-zero target is missed for most of the future climate change scenarios investigated.	(Robert & Kummert, 2012)
10 different cities (USA)	2040-2069	IPCC TAR	In the study, future hourly weather are used to predict future performance of renewables energy systems for low energy residential buildings in 10 different climate zones in the USA. The results show that buildings with the present configurations of renewable energy systems will be losing their capability to meet the zero-energy goal in half of the considered climate zones.	(Shen & Lior, 2016)
Taipei (Taiwan)	2020, 2050 and 2080	IPCC TAR	Hourly future weather year series for Taipei, Taiwan, are constructed. Using these future weather data, buildings thermal performances are assessed considering an ideal residential apartment building. The simulations reveale increases in cooling energy by 31%, 59%, and 82% in the three time slices investigated (2020, 2050 and 2080).	(Huang & Hwang, 2016)
Iraklio, Thessaloniki and Patra (Greece)	2020, 2050 and 2080	IPCC TAR	This paper presents results of a study of the impact of future climate change scenarios for the three climatic regions of Greece on the design of the envelope of a hotel building.The simulation results indicate a mean increase in the cooling energy demand by 34% in 2050 and 63% in 2080 if compared to today. On the other hand, heating energy demand is expected to decrease by 29% in year 2050 and 46% in year 2080.	(Farrou et al., 2016)
Macon (France)	2035, 2055, 2085	IPCC AR5	The objective of this study is to evaluate life cycle impacts of residential buildings, integrating climate change and evolution of the energy mix on the long term. The results show that heating energy demand could decrease from 24 to 44%, whereas cooling energy demand could increase also by a factor 8.	(Roux et al., 2016)
Lisbon (Portugal)	2050	IPCC TAR	The main goal of this paper is to develop a methodology for assessing the future heat energy demand on a large scale (districts/cities), taking into account both direct and indirect impacts of climate change on district heat demand. The results suggest that heat demand density could decrease within the range of 22.3–52.4% in 2050 compared to 2010, depending on weather and renovation scenario studied.	(I Andrić et al., 2016)
Philadelphia, Chicago, Phoenix and Miami (USA)	2040 - 2069	IPCC TAR	The goal of this research is understand building energy use pattern to the year of 2050 in United States by means of projecting future hourly weather data for building simulation tools. Case studies in four representative cities in the U.S. show that climate change is to have great impacts on residential and office building energy use during the years of 2040–2069. The change of yearly energy use is predicted to be variable from -1.64% to 14.07% for residential building. Moreover, the growing peak electricity load during cooling seasons is going to exert greater pressure for the future grid.	(Shen, 2017)
Guangzhou (China)	2020, 2050 and 2080	IPCC TAR	This study investigated the potential impact of climate change on the total energy consumption of housing sector in Southern China. The indoor temperatures in 2020s, 2050s and 2080s will increase by 0.82 °C, 1.91 °C and 3.41 °C, respectively. The total heating and cooling energy use of 3.5 and 5.5 star-buildings are projected to increase by 25% and 20% respectively with a 1.0 °C global warming.	(Song & Ye, 2017)
Geneva (Switzerland)	2010-2039, 2040-	IPCC TAR and IPCC AR5	The study provides an overview of the major approaches to create future weather data sets based on the statistical and dynamical downscaling of climate models. A number of weather	(Moazami et al., 2019)

	2069 and 2070-2099		data sets for Geneva were synthesized and applied to the energy simulation of 16 ASHRAE standard reference buildings (non-residential buildings), single buildings and their combination to create a virtual neighborhood. Depending on the type of building, the relative change of peak load for cooling demand under near future extreme conditions can still be up to 28.5% higher compared to typical conditions. Moreover, the analysis of the virtual neighborhood revealed that the peak electric power demand for the neighborhood can increase by 4.0%, 7.6% and 16.8% under near-term, medium-term and long-term future scenarios.	
Hong Kong (China)	2035, 2065 and 2090	IPCC AR5	The study aims to evaluate the impacts of climate change on the building energy demand and indoor thermal comfort of mixed-mode residential buildings in Hong Kong using the adaptive thermal comfort model as the thermal comfort criterion. The results indicate that by the end of this century, the indoor discomfort percentage in the cooling seasons are expected to increase from 21.9% to 36.0% and 50.4% under RCP4.5 and RCP8.5 scenarios, respectively, while the annual cooling load is expected to increase up to 278.80%.	(Liu et al., 2020)
Different location (Belgium)	2080	IPCC AR5	The study presents Heating Degree Days (HDD) and Cooling Degree Days (CDD) maps for Belgium for the current and future climate perspective considering the RCP8.5 climate change scenario. The results show a decrease of the HDDs with 27% between 1976–2004 (3189 HDD) and 2070–2098 (2337 HDD). In contrast, the CDD were found to increase with a factor 2.4 from 167 CDD to 401 CDD in the same timeline. Smaller reductions in average HDD were moreover found in urban areas compared to rural areas. For the CDD, a higher absolute increase was found for urban areas and the Northeast of Belgium.	(Ramon, Allacker, De Troyer, Wouters, & van Lipzig, 2020)
Toronto (Canada)	2070	IPCC TAR and IPCC AR5	The study investigates the effects of climate changes on the heating and cooling energy demand of buildings in the city of Toronto using ASHRAE standard reference buildings (non-residential buildings) as building models . The results show an average decrease of 18%–33% for the heating energy use intensity, and an average increase of 15%–126% for the cooling energy use intensity by 2070, depending on the baseline climatic file of use and building typology. The results also demonstrate the need to perform building modelling with sensitivity analysis of future climate scenarios in order to design more resilient buildings.	(Berardi & Jafarpur, 2020)
10 different cities (China)	every year for 2020 to 2099	IPCC AR5	The study used a building simulation-based method to predict the life cycle energy performance of residential buildings in different climate zones of China. It finds that compared with the data of the current weather files, the average temperature will increase from 5.36 °C to 2.72 °C and 2.53 °C to −0.21 °C by the end of this century in RCP 8.5 and RCP 2.6, respectively. Moreover, compared with the energy demand under the weather conditions of the current weather files, the changes in life cycle heating energy and cooling energy will be 33.9 kWh/m2 and 11.2 kWh/m2 in RCP 2.6, 40.2 kWh/m2 and 17.4 kWh/m2 in RCP 8.5.	(Zou, Xiang, Zhan, & Li, 2021)

Cooling requirements may double or triple if compared to current trends, with corresponding reductions in heating requirements. This will potentially result in a reduced use of natural gas and other fossil fuels combusted for heating and, at the same time, in the increase in electricity demand used to power cooling systems. For countries with a predominantly coal-based electricity mix, this evolution will lead to increasing levels of GHG emissions associated with building operation, if the current carbon intensity of their mix remains unchanged in the future.

These trends can also have unforeseen consequences. It is possible to expect i.e. relevant cooling in traditionally “cold” countries, with unexpected increases also of embodied energy tied to the production and acquisition of new cooling machines and HVAC systems.

This will also result in other impacts related to the ongoing global warming, resulting a vicious cycle that may lead to increase of carbon emissions and heat island effect pushed by an increase in cooling demand and thus further contributing to global warming.

Besides the provisional nature of the studies previously discussed, it is also worth discussing another relevant aspect within the methodologies of energy use assessments and in particular within morphing modeling.

It has already been previously mentioned that several provisional models exist, within the Global Circulation approaches. Choosing one model over another means to have a second layer of uncertainty which is based upon the assumptions and modeling choices performed at the GCM modeling stage, which are translated into the air temperature provisional trends and also on the energy uses for air conditioning assessments.

Figure 5 shows an example of variability between average temperature during the years in the future in the time slice investigated by RCP scenarios, by showing the monthly future projections developed by different GCM, chosen in a limited number for the sake of brevity. Increases in air temperature between the various models for e.g. RCP 4.5 amount to 2.4 °C in the case of ACCESS 1.3 and 3.3 for HadGEM”-CC at the end of the century, while these values are higher for RCP 8.5 reaching +5°C in the case of ACCESS 1.3 and HadGEM2-CC.

It is worth mentioning that while the trend in air temperature is rather common among all results from the alternative models, relevant different can be traced up to +2°C between the outputs of different models. Moreover, model ACCESS 1.3 performs forecasts that are higher than the others for about 50% of the months of investigation, while ACCESS 1.0 shows the most moderate data. This of course does not in any way aim at giving substantial and quantitative indications on the aforementioned models, since the data used refer to a specific point in a grid which covers in most cases the whole world and on a specific climatic parameter among a very wide range. However, since the focus is on the modeling of consequences in relation to global warming within the building and real estate sector, these uncertainties on one of the more relevant parameter to building energy performances need to be taken in consideration.

If dynamic building energy simulation is performed, the results from the lower section of Figure 5 can be found. The same substantial variability between energy uses for heating and cooling can be traced for both RCP 4.5 and 8.5 that was envisaged in Figure 5. In this specific case for example, RCP 4.5 results can vary as much as 35% simply by choosing one data source or another, if cooling is concerned.

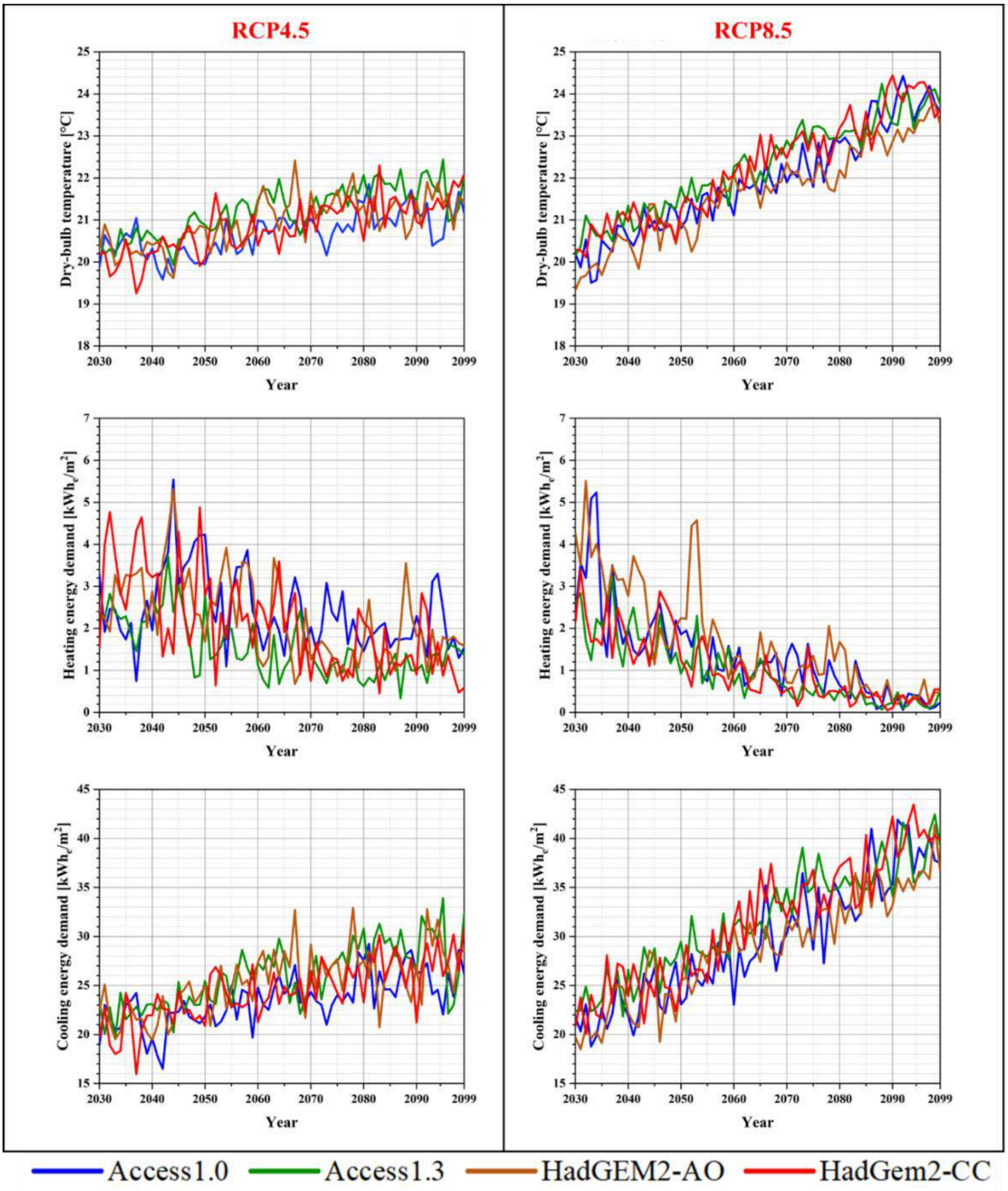

Figure 5: Variation in temperature trends between 2030 – 2090, RCP 4.5 and 8.5 for the city of Palermo – Italy and future heating and cooling energy demand within the RCP4.5 and RCP8.5 scenarios.

5. Final Remarks

Predicting the evolution of global warming in the next decades is by itself a very complicated matter with considerable implications and potential ramifications for the political, technical, environmental domains. The application to the construction and real estate sector of climate change analyses are paramount: since buildings usually have an expected life span of around a century, meaning what is being built today needs to be able to withstand the evolution of climate in the coming decades/century, therefore pointing to the research gap of climate resilience which needs to be integrated and considered in building and energy systems design for the future. Furthermore, appropriate modeling and techniques which are able to quantitatively integrate these considerations early in the design phase in order to correctly size systems and design buildings.

The approach towards the modeling of the effects of climate change is usually performed through the use of specific modeling techniques, mostly developed within climate science research with coarse resolution and mostly oriented to large scale variations of the parameters of interest. Specific techniques of downscaling are able to derive averaged values for use in more specific applications for site specific analyses, otherwise other techniques involving more refined and detailed meshing and calculations are available and usable, either making a combined use of GCM and RCM or through statistical trend analyses and future projections. The techniques used for future climate assessment in the building sector include statistical means and morphing of existing and available datasets, with a wide range of variability and different potential results in using all these techniques.

Nevertheless, the approaches proposed are most of the time limited to the use of specific research domains, where it is now in most cases accepted that the constraints coming from global warming should be included in the design of buildings, but these are concerns that do not properly invest the practitioner’s community. This is for sure due to the limited availability of easy to use (and not time-consuming) tools that may allow practitioners to simply implement these kinds of analyses into their design.

While this is understandable, it is of undeniable concern in the near future that severe spikes in cooling needs could put the current energy systems in crisis. Furthermore, this aspect could be more severe in countries with the highest construction rates (especially in northern Africa and in Asia), which tend to often use well known 'International' architectural styles without including bioclimatic aspects in the design.

Climate change could cause worsening of current issues of high performance buildings such as overheating even in non-traditionally cooling dominated countries, coupled with a large increase in power generation needs for cooling. Moreover, this aspect could also lead to an increase in the buildings embodied energy, due to a greater use of new systems and solutions to counteract overheating. Therefore, future research should not only focus on studying the effects of climate change on the buildings energy use, but extend these boundaries and investigate the relationships between climate change and the entire building life cycle. Thus, it becomes of fundamental importance to integrate, as well as the effects of climate change, the life cycle perspective in an integrated and multidisciplinary design approach of buildings, through the use of the Life Cycle Assessment method, a well-established methodology for assessing the environmental impacts along the building life cycle from extraction, manufacturing, transportation, operation, maintenance and end of life.

LCA is an important instrument to help reduce the overall environmental burden of buildings and provide insights into their overall energy and environmental performance. Since LCA approaches cover the whole lifespan of a building, the assessment of its long-term performances and its related impacts are challenging, especially so if climate change is considered.
As such, approach Life Cycle Assessment using merely one average year means neglecting the variability of the impact an evolving climate might have on the building, which was shown to be significant in previous

chapters. For these reasons, the impact of future climate change on the energy performance of buildings, according to projections of future weather data, is relevant and shall be considered in building LCA.

It is thus crucial to develop corresponding official scenarios and datasets for future climate evolution. Datasets should be based on future climate scenarios aiming at achieving the resilience of buildings to climate change.
This will have a significant impact on the results and might lead towards a shifting towards cooling for heating dominated countries and a reduction in heating energy use which may have additional repercussions also on the Life Cycle performances of the building (e.g. increase in use of cooling equipment).

To conclude, the methodologies proposed are in all cases valid and efficient with slightly different strengths and applicability suggestions: it is however necessary for the future of building energy simulation, either practitioners or in research, to adopt one. Results can vary slightly according to the modeling choices performed, however global warming will vastly impact also the energy uses of the building sector in the close future: not fully addressing it from the early stage of the building design will not solve the problem and could potentially – as already mentioned – worsen it.

6. References

Andrić, I, Gomes, N., Pina, A., Ferrão, P., Fournier, J., Lacarrière, B., & Le Corre, O. (2016). Modeling the long-term effect of climate change on building heat demand: Case study on a district level. *Energy and Buildings*, *126*(Supplement C), 77–93. https://doi.org/https://doi.org/10.1016/j.enbuild.2016.04.082

Andrić, Ivan, Le Corre, O., Lacarrière, B., Ferrão, P., & Al-Ghamdi, S. G. (2021). Initial approximation of the implications for architecture due to climate change. *Advances in Building Energy Research*, *15*(3), 337–367.

Belcher, S. E., Hacker, J. N., & Powell, D. S. (2005). Constructing design weather data for future climates. *Building Services Engineering Research and Technology*, *26*(1), 49–61. https://doi.org/10.1191/0143624405bt112oa

Berardi, U., & Jafarpur, P. (2020). Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews*, *121*, 109681.

Berrisford P, Dee DP, Poli P, Brugge R, Fielding K, F. M. (2011). *The ERA-Interim archive Version 2.0*. *Era Report series*.

Bessoudo, M., Tzempelikos, A., Athienitis, A. K., & Zmeureanu, R. (2010). Indoor thermal environmental conditions near glazed facades with shading devices - Part I: Experiments and building thermal model. *Building and Environment*, *45*(11), 2506–2516. https://doi.org/10.1016/j.buildenv.2010.05.013

Cabeza, L. F., Castell, A., & Pérez, G. (2014). 13 - Life cycle assessment (LCA) of phase change materials (PCMs) used in buildings. In F. Pacheco-Torgal, L. F. Cabeza, J. Labrincha, & A. de Magalhães (Eds.), *Eco-Efficient Construction and Building Materials* (pp. 287–310). Woodhead Publishing. https://doi.org/http://dx.doi.org/10.1533/9780857097729.2.287

Cellura, M., Guarino, F., Longo, S., & Tumminia, G. (2018). Climate change and the building sector: Modelling and energy implications to an office building in southern Europe. *Energy for Sustainable Development*, *45*. https://doi.org/10.1016/j.esd.2018.05.001

Chan, A. L. S. (2011). Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong. *Energy and Buildings*, *43*(10), 2860–2868. https://doi.org/https://doi.org/10.1016/j.enbuild.2011.07.003

CIBSE. (2022). CIBSE Weather Data. Retrieved November 10, 2022, from https://www.cibse.org/weatherdata

Crawley, D. B. (2008). Estimating the impacts of climate change and urbanization on building performance. *Journal of Building Performance Simulation*, *1*(2), 91–115. https://doi.org/10.1080/19401490802182079

DWD. (2022). DWD Testreferenzjahre (TRY). Retrieved November 10, 2022, from https://www.dwd.de/DE/leistungen/testreferenzjahre/testreferenzjahre.html;jsessionid=316A5BF0759A8E9712101A5B2E5C7F77.live21064?nn=507312

Eames, M., Kershaw, T., & Coley, D. (2010). On the creation of future probabilistic design weather years from UKCP09. *Building Services Engineering Research and Technology*, *32*(2), 127–142.

https://doi.org/10.1177/0143624410379934

Edenhofer, O., Pichs-Madruga, R., & Sokona, Y. (2014). *Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Farrou, I., Kolokotroni, M., & Santamouris, M. (2016). Building envelope design for climate change mitigation: a case study of hotels in Greece. *International Journal of Sustainable Energy*, *35*(10), 944–967. https://doi.org/10.1080/14786451.2014.966711

Guarino, F., Tumminia, G., Longo, S., Cellura, M., & Cusenza, M. A. (2022). An integrated building energy simulation early—Design tool for future heating and cooling demand assessment. *Energy Reports*, *8*, 10881–10894.

Huang, K.-T., & Hwang, R.-L. (2016). Future trends of residential building cooling energy and passive adaptation measures to counteract climate change: The case of Taiwan. *Applied Energy*, *184*, 1230–1240. https://doi.org/http://dx.doi.org/10.1016/j.apenergy.2015.11.008

IEA. (2017). Buildings policies database. Retrieved from https://www.iea.org/policies?sector=Buildings

International energy agency. (2019a). *Global status report for buildings and construction*. Paris.

International energy agency. (2019b). *Tracking buildings*. Paris.

Jentsch, M. F., Bahaj, A. S., & James, P. A. B. (2008). Climate change future proofing of buildings—Generation and assessment of building simulation weather files. *Energy and Buildings*, *40*(12), 2148–2168. https://doi.org/https://doi.org/10.1016/j.enbuild.2008.06.005

Jiang, A., Liu, X., Czarnecki, E., & Zhang, C. (2019). Hourly weather data projection due to climate change for impact assessment on building and infrastructure. *Sustainable Cities and Society*, *50*, 101688. https://doi.org/https://doi.org/10.1016/j.scs.2019.101688

Kikumoto, H., Ooka, R., Arima, Y., & Yamanaka, T. (2015). Study on the future weather data considering the global and local climate change for building energy simulation. *Sustainable Cities and Society*, *14*, 404–413. https://doi.org/https://doi.org/10.1016/j.scs.2014.08.007

Klein, S. A. (1988). TRNSYS-A transient system simulation program. *University of Wisconsin-Madison, Engineering Experiment Station Report*, 12–38.

Levermore, G. J., Watkins, R., Cheung, H., Parkinson, J., Laycock, P., Natarajan, S., … Sanderson, M. (2012). Deriving and using future weather data for building design from UK climate change projections – an overview of the COPSE. . Manchester: University of Manchester.

Liu, S., Kwok, Y. T., Lau, K. K.-L., Tong, H. W., Chan, P. W., & NG, E. (2020). Development and application of future design weather data for evaluating the building thermal-energy performance in subtropical Hong Kong. *Energy and Buildings*, *209*, 109696. https://doi.org/https://doi.org/10.1016/j.enbuild.2019.109696

Lützkendorf, T., Balouktsi, M., Frischknecht, R., Peuportier, B., Birgisdottir, H., Bohne, R. A., Cellura, M., Cusenza, M. A., Francart, N., García, A., Gomes, V., Gomes da Silva, M., et al. (2023). *Context-specific assessment methods for life cycle-related environmental impacts caused by buildings*. treeze Ltd. ISBN: 978-3-9525709-0-6; DOI: 10.5281/zenodo.7468316

Moazami, A., Nik, V. M., Carlucci, S., & Geving, S. (2019). Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions. *Applied Energy*, *238*, 696–720. https://doi.org/10.1016/J.APENERGY.2019.01.085

Mylona, A. (2012). The use of UKCP09 to produce weather files for building simulation. *Building Services Engineering Research and Technology*, *33*(1), 51–62. https://doi.org/10.1177/0143624411428951

Ramon, D., Allacker, K., De Troyer, F., Wouters, H., & van Lipzig, N. P. M. (2020). Future heating and cooling degree days for Belgium under a high-end climate change scenario. *Energy and Buildings*, *216*, 109935.

Robert, A., & Kummert, M. (2012). Designing net-zero energy buildings for the future climate, not for the past. *Building and Environment*, *55*, 150–158. https://doi.org/https://doi.org/10.1016/j.buildenv.2011.12.014

Roux, C., Schalbart, P., Assoumou, E., & Peuportier, B. (2016). Integrating climate change and energy mix scenarios in LCA of buildings and districts. *Applied Energy*, *184*(Supplement C), 619–629. https://doi.org/https://doi.org/10.1016/j.apenergy.2016.10.043

Sachs, J., Tubiana, L., & (IDDRI), and I. for S. D. and I. R. (2014). *Pathways to deep decarbonization*.

Shen, P. (2017). Impacts of climate change on U.S. building energy use by using downscaled hourly future weather data. *Energy and Buildings*, *134*, 61–70. https://doi.org/http://dx.doi.org/10.1016/j.enbuild.2016.09.028

Shen, P., & Lior, N. (2016). Vulnerability to climate change impacts of present renewable energy systems designed for achieving net-zero energy buildings. *Energy*, *114*(Supplement C), 1288–1305. https://doi.org/https://doi.org/10.1016/j.energy.2016.07.078

Song, X., & Ye, C. (2017). Climate Change Adaptation Pathways for Residential Buildings in Southern China. *Energy Procedia*, *105*(Supplement C), 3062–3067. https://doi.org/https://doi.org/10.1016/j.egypro.2017.03.635

Wang, X., Chen, D., & Ren, Z. (2010). Assessment of climate change impact on residential building heating and cooling energy requirement in Australia. *Building and Environment*, *45*(7), 1663–1682. https://doi.org/http://dx.doi.org/10.1016/j.buildenv.2010.01.022

Zhu, M., Pan, Y., Huang, Z., & Xu, P. (2016). An alternative method to predict future weather data for building energy demand simulation under global climate change. *Energy and Buildings*, *113*, 74–86. https://doi.org/10.1016/J.ENBUILD.2015.12.020

Zou, Y., Xiang, K., Zhan, Q., & Li, Z. (2021). A simulation-based method to predict the life cycle energy performance of residential buildings in different climate zones of China. *Building and Environment*, *193*, 107663.