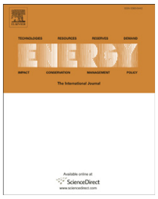
Energy 240 (2022) 122479

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)?

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ARTICLE INFO

Article history:
Received 21 December 2020
Received in revised form
25 October 2021
Accepted 28 October 2021
Available online 6 November 2021

Keywords:
Building design
Building energy performance
Building modeling
Climate change
Energy efficiency measures
Nearly zero energy buildings (NZEBs)
Renewable energy production
Weather datasets

ABSTRACT

Climate change, driven by greenhouse gas emissions, is a growing global concern, threatening worldwide environment, health and economy. Energy needs for buildings are a large source of greenhouse gas emissions. As the energy needs of buildings strongly depends on weather patterns, this paper investigates how climate change may impact building heating and cooling loads, cost-optimal efficiency measures, and renewable energy production. Eight locations (Stockholm, Milan, Vienna, Madrid, Paris, Munich, Lisbon, and Rome) highlight differences among European climates. Weather datasets, commonly used in building energy simulations, are evaluated to see how climatic parameters have changed over recent decades. A future climate change scenario (with uncertainties) is analyzed for the year 2060. Weather files are used to drive building energy simulations for a standard baseline and a (Nearly Zero Energy Building) NZEB residential building whose design is improved using a cost-optimization approach.

The analysis indicates most currently available weather datasets cannot assure reliable results with building simulations. We find the energy balance in European buildings will significantly change under future conditions: heating will decrease by 38%–57%, while cooling will increase by +99%–380% depending on location. In future NZEBs, efficiency measures to reduce cooling needs and overheating will be favored (e.g. roof insulation, window type, solar shading, envelope finishes), illustrating how improving energy efficiency will be more crucial within climate change scenarios. Compared to the baseline, more efficient NZEBs will enable renewable energy to much better cover building needs. There will also be advantages from reducing winter and summer peak demand, particularly when coupled to short-term electrical storage. When solar resource is limited in winter, more airtight, better-insulated NZEBs improve PV self-consumption.

1. Introduction

Accounting for about 40% of final energy consumption, 36% of associated CO_2 emissions and 55% electricity consumption [1], buildings are a key factor to achieve the European (EU) 2030 updated Energy and Climate targets of reducing greenhouse gas emissions (40%), increasing energy efficiency (32.5%) and renewables (32.5%) [1,2]. Recent political EU Guidelines (2019–2024) aim at a more rapid cut in greenhouse gas emissions of at least 55% in 2030 [3]. More ambitious is the European Green Deal strategy to realize no net greenhouse gas emissions by 2050 [4]. In line with the Paris agreement to keep the global temperature increase to well below 2 °C [5,6], the Energy and Climate Union strategy supports the EU climate neutral transition. This established energy efficiency as one of its strategic objectives [7].

A core policy is decarbonising the energy sector by ensuring buildings are more efficient. Nearly zero energy buildings (NZEBs) play a key role in the strategy combining energy efficiency with the deployment of renewables [8]. According to the Energy Performance of Building Directive (EPBD recast), Member States shall ensure that all new buildings are NZEBs by December 31, 2020. A

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https://doi.org/10.1016/j.energy.2021.122479

NZEB is a building that “has a very high energy performance with the nearly zero or very low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby”. Extensive literature on NZEBs has been produced [9–15], where a cost-optimal approach is to be adopted in relation to the choice of implemented energy efficiency measures [16–21]. The establishment of NZEB criteria is a debated topic and appear to be quite different among countries [22]. Energy calculations are performed to derive global costs, and to identify the cost-optimal solutions within an established methodology [23]. Previous work has shown the proper combination of cost-effective thermal efficiency measures, equipment, appliance and renewables can readily achieve the NZEB objective using a cost-optimal approach [24,25].

To achieve the outlined climate policy, the strategy aims to enhance both NZEBs and building renovation, through the recent Renovation Wave initiative [26]. With a future focused perspective, this paper aims to investigate climate change implications for buildings to be constructed or renovated.

1.1. Climate change and buildings

Climate change is globally recognized as one of the largest threats of this century, with harsh and complex interconnected consequences affecting environment, to health, and economy [27]. The European Climate Law identifies how tackling climate change is an urgent challenge [28]. Over last decade, unusual and extreme weather events occurred worldwide with increasing frequency and severity, especially during summer heat waves, with temperatures above 35 °C. Not only is temperature varying within climate change, but also precipitation, humidity, wind and solar irradiance [29]. Although some environmental effects are almost certain (e.g. sea level rise, change in ecosystem species), further effects, links and implications, are still not fully known [30].

Since buildings are the human interface between the outdoors and indoors, where occupants seek to be safe and comfortable, it seems certain that climate change will affect this sector profoundly [31]. Consequences range from changes in heating and cooling energy balance and capacity mismatch, inability to mitigate extreme weather events and increased greenhouse gas emissions, and even flooding, structural, and urban fabric issues [32]. Although not commonly taken into account [33], effects on occupants could be alarming as well (e.g. discomfort, heat stress, reduced productivity, financial costs, illness and increased mortality) [34,35].

1.2. Building simulations and weather datasets

Building energy simulations are a powerful modeling tool used for varied purposes [36]. Among applications, there are: the establishment of the building design [37], the selection of cost-optimal technology measures [38], the forecast of building energy performance and stock renovation [39], the determination of comfort and indoor air quality conditions [40], the assessment of building certification [41], and the estimation of future savings scenarios on which define specific policy initiatives [42].

However, building energy simulations can be affected by numerous uncertainties. Some of these can be controlled by the modeler (e.g. building specification, geometry details, technical parameters, costs, operational schedules and set-points and simulation algorithms), while others are not easily addressed. Among the latter category are the weather files related to the location under investigation [43]. Different datasets can result in unsuspected shortfalls in output accuracy, increasing the gap between simulated and operational energy consumption [44]. Sensitivity analysis and model calibration can help to improve simulation accuracy [45–47], but the choice of the weather datasets remain a crucial point in model development [48]. The use of past datasets to predict energy loads in buildings can be misleading since climate data drivers from the past are projecting future building energy use [49,50].

The use of poorly representative weather datasets can lead to unsuspected consequences, such as designing a building in which energy loads and comfort conditions are not properly estimated, increased energy consumption, added extra costs, lower efficiencies, and an inadequate heating and cooling systems size [51,52]. Improvements are necessary to overcome the limitations of old methods to construct weather datasets [53–55]. Very often these have been based on data recorded more than half century ago.

Due to the current climate change, basing simulation on such data may produce misleading results especially related to the balance of heating and cooling [56,57]. Moreover, in building energy simulations, energy use is typically projected out with economic assumptions of 30–50 years. This is acceptable only if the driving weather is relatively stable, with little change over long intervals. This does not reflect recent experience in Europe.

As example, Robert and Kummert [29] show that NZEBs using obsolete weather datasets can miss energy savings targets of future decades. A favored alternative is to use “morphed” weather datasets modified to fit anticipated conditions from IPCC (Intergovernmental Panel on Climate Change) [58] scenarios using the downscaling methods proposed by Belcher et al. [59] or the equivalent method of Crawley et al. [56]. The advantages of these weather datasets will be further considered in Section 2.2.

1.3. Research aim

This paper aims to investigate the relationship between climate change and buildings. A particular focus is given to NZEBs, the EU building target mandatory as from 2021 onwards. As different weather datasets in building simulations can lead to potentially important differences in predicted building energy results, our analysis includes main commonly used weather files (e.g. IWEC, TMY). We also composed future-looking weather files to simulate how buildings will respond to a changing climate, through the use of morphed weather files for the year 2060 under the IPCC 50% percentile level of anticipated warming potential (Representative Concentration Pathways –RCP- 8.5). Sensitivity analysis also examined the 10% and 90% lower and upper bound cases for this scenario and how they influence the selected energy efficiency measures of future buildings. The paper also investigates how these changes affect building energy loads, the selection of the efficiency measures in NZEBs, photovoltaic (PV) output, also including the role of electrical energy storage. Although the research is performed for the main European climates and locations, the outlined methods can be extended globally.

2. Methodology

Due to the large data amount that characterize this research, we divide the methodology in different sections. In each of them, we aim to answer specific questions to evaluate the implications of how climate changes might impact buildings.

2.1. Weather data analysis

To explore how climate influences building simulations, energy performance and NZEBs design, we first examined the changes in different weather datasets, as reflected in hourly files used in building energy simulation.

In a preliminary analysis, we composed a preliminary evaluation for Milan, which is updated in this research with both longer term and more recent meteorological data [61]. We refined and extend this work to eight European locations with very different climates:

- Stockholm (Sweden)
- Milan (Italy)
- Vienna (Austria)
- Madrid (Spain)
- Paris (France)
- Munich (Germany)
- Lisbon (Portugal)
- Rome (Italy)

We collected and analyzed yearly weather datasets for all studied locations from 2003 to 2018. Included in the analysis were the International Weather for Energy Calculations (IWEC) and typical metrological year (TMY) datasets as commonly used in building simulations. In particular, many energy-based simulations used IWEC and IWEC2 hourly weather datasets which represent average weather observed, or TMY, typically related to the last 15–25 years [62,63]. Single years cannot properly represent typical long-term weather patterns, although providing a tendency of occurring conditions [64,65]. The IWEC represents data from 1984 to 2001, while the more recent IWEC2 represents similar data from 1994 to 2011. Recently, more up to date TMYs became available [66], including data since 2011 based on satellite data [67].

To address for climate change in the simulations, we utilized an hourly weather file modification methodology based on climate projections for the IPCC 5th assessment [68]. This scheme used the down-scaling calculation methods of [59] to “morph” most recent TMY file (2004–2018) to anticipate the future climate in the year 2060 in the studied locations. This is accomplished by means of a mathematical transformation (morphing) to produce a future weather time series based upon the historic weather observations. Thus, the approximate seasonal harmonics and diurnal shape and stochastic distribution of the historical weather data is thus maintained, but with adaptation to the expected changes in temperature and other meteorological characteristics then used to modify the weather files. A description of the methods used for this technique are summarized in a comparative evaluation by Herrara et al. (2017) [60]. The commercially available Weather-Shift implementation of the Belcher et al. calculation [59] allows the selection of different greenhouse gas emission scenarios by the IPCC definitions (WeatherShift, 2020) This includes the RCP and the various associated warming potential percentiles [58]. For our evaluation, we utilized the RCP 8.5 pathway (suggesting additional radiative forcing of 8.5 W/m^2 towards 2100), which largely represents business as usual scenario with limited mitigation in the near term. Although mitigation strategies are underway worldwide [69], latest evidence suggests that greenhouse gas emissions are closely following this IPCC pathway [68].

The median 50% RCP 8.5 TMY 2060 weather file represents the hourly weather dataset used in our building energy simulation in the studied locations to account for climate change. The IPCC projections are constructed following many different climate change models. We adopted a 50% percentile that indicates that the half of the models and leads to a temperature offset that is minor or equal to the offset specified in the scenario. In particular, many energy-based simulations used IWEC and IWEC2 hourly weather datasets, which represent average weather observed, or TMY, typically related to the last 15–25 years [68]. These were included within our analysis to account for the uncertainty in the predicted future climate.

Specific questions we aim to answer within this analysis are:

- How does recent year weather data relate to IWEC, IWEC2, or TMY?
- How do TMY weather datasets “morphed” to account for climate change compare to current available weather files? We also look to examine how peak summer temperatures might be elevated and how will they vary in a climate change scenario when compared with winter lows and associated extremes.

2.2. Building energy simulations

After analyzing the differences among the considered weather datasets, we evaluated how these files impacted predicted energy demand in the studied locations. We first carried out energy simulations for a baseline building prototype. This is a two-story residential building of 120 m^2 floor area with a full cellar (Fig. 1).

A similar building was used in a study by Ecofys GmbH and the Danish Building Research Institute [70], as well as in D'Agostino et al. [24]. Its key characteristics are summarized in Table 1, with system properties, insulation levels, airtightness and equipment efficiencies given:

The building prototype is representative of the European national building [71], representing a baseline energy performance building with standard levels of insulation and air tightness with standards for U-values and appropriate measures in concordance with the Energy Performance of Buildings Directive (EPBD) as published by the Danish Buildings Institute [70]. A minimum air exchange at maximum occupation rate was considered, coherent with occupation levels and ventilation rates proposed by Standard EN 15251 [72] for high air quality buildings (0.5 h^{-1} for residential buildings). The installed 6 kW PV system is related to the available roof space facing south with current module efficiencies and safety access around the array perimeter.

We made two important changes in the current research compared to previous investigations [73]: we changed the building to all-electric, in line with the EU strategy of a future electrification of the European residential sector and the use of renewable sources to satisfy building loads. We also altered the cooling setpoints upwards to 25.6 °C for the simulated interior control air node operative temperature within EnergyPlus in accordance with ISO Standard 7730. An standard air-source heat pump with electric resistance back up with a Seasonal Coefficient of Performance (SCOP = 2.4) at rating conditions was assumed in the analysis for electric heating as evaluated at multiple temperature conditions in EN 14511 and EN 14825. The heat pump utilizes mixture of supplemental resistance and heat pump at lower temperatures depending on building heat loads and heat pump capacity balance point. Thus, the operating SCOP at the evaluated locations varies both depending on prevailing temperature conditions and building characteristics.

A much more efficient heat pump (SCOP = 3.1) was also simulated for each climate and made available within the optimization process. It is often selected, particularly in extreme heating or cooling climates. Still more efficient geothermal heat pump system are available, although the study seeks to examine changes to the building envelope elements brought about by climate change and not just justification for improving heating and cooling systems. Building envelope decisions generally have long impact due to differing lifetime time horizon relative to equipment.

We used the NREL BEopt software [74] which features an exhaustive analysis of the energy and costs of the building, powered by the EnergyPlus simulation engine. This allows hourly building energy simulation to derive annual heating, cooling, water

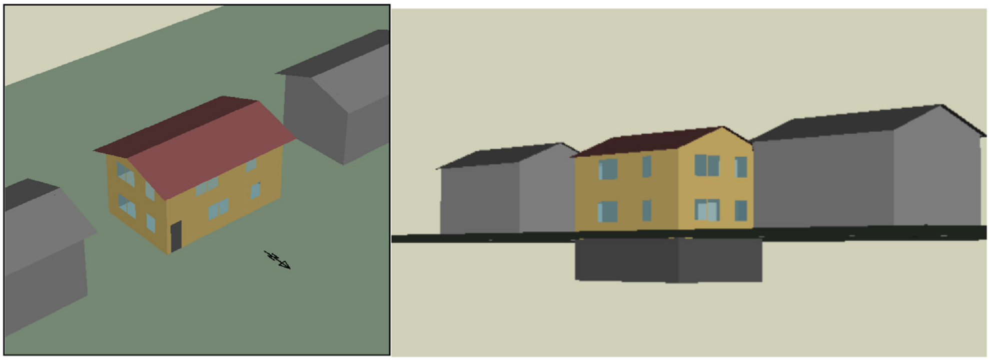

Fig. 1. Two-story prototype residential building as rendered for EnergyPlus.

Table 1
Characteristics of the baseline building.

Building type	New residential building
Building dimensions	120 m^2 over a 2.5 m cellar; volume: 290 m^3
Neighbours	Similar neighboring buildings on the two sides
Envelope	
Windows	23 m^2 with double clear glass (2.2 W/m^2K)
Walls	149m^2, net area; R 1.3 Insulated perlite filled masonry walls (~0.8 W/m^2K)
Roof	120m^2, ceiling area; R-2.6 insulation (~0.38 W/m^2K)
Doors	3.7m^2 area, Insulated wood entry door (~2.3 W/m^2K)
Cellar Walls	R-0.9 insulation (~1.1 W/m^2K)
Air leakage	Standard construction (4 ACH at 50Pa blower door pressure)
System	
Heating	Heat pump heating system; SCOP = 2.4; fully electric resistance heat below −12C; mix of supplemental resistance and heat pump at lower temperatures depending on building/heat pump capacity balance point
Cooling	SCOP 4.1 mini-split cooling system
Hot Water	155 l insulated electric boiler in cellar providing 120 l per day at 55 °C; 2 cm insulated piping assumed for distribution system.
Mechanical ventilation	20.3 l/s continuous per floor; 40.6 l/s total with 72% efficient ERV; 50 W; provides ~0.5 l/m^2 fresh air
Lighting/Appliances	Standard incandescent lighting, refrigerator, clothes washer, dishwasher, resistance cooktop[a]
PV	6.0 kW (DC) with crystalline silicon modules, 96% efficient inverter

[a] Details of energy-using appliances, baseline to NZEB are given in Ref. [24], but here we summarize them for both the standard and energy efficient cases: (typically A+++). Resulting annual energy: Refrigerator: 340 and 201 kWh; Clothes Washer: 300 to 169 kWh, Dishwasher: 194 to 151 kWh, Dryer: 442 and 281 kWh and cooktop: 334 to 300 kWh (induction); Lighting 551 kWh to 158 kWh (solid state), miscellaneous electricity use: 723 kWh.

heating and appliance electricity consumption as well as resulting costs given a representative electricity price of € 0.23/kWh. A series of 19 weather datasets (e.g. IWEC, IWEC2, TMY, yearly datasets from 2003 to 2018, TMYshift_2060) were considered for the studied locations, for a total of 152 simulations for the baseline building.

This section aims to answer the following questions:

- Which will be the total, heating and cooling electric demand in the baseline building prototype using different weather datasets?
- What differences can be found among the studied locations?
- How will the building energy balance be altered in a climate change scenario?

2.3. Climate change and energy efficiency measures selection

After analysing the baseline building, using a cost-optimal process, we improved it to reach the NZEB target (90% reductuion of primary energy) as more thoroughly described in previous research [25]. The optimization algorithm seeks to achieve NZEBs at lowest possible cost in specific locations. Changes in the annual balance of heating and cooling are important in the NZEB design as well as the relative weight of cooling compared with heating measures in the cost-optimization.

Certain measures are inherently sensitive to the balance of heating and cooling. These include roof and wall solar reflectance as well as window glazing solar heat gains measures. The analysis aimed at verifying if measures like low solar gain windows are more effective than high solar gain glazing depending on location. This is evaluated across climates within this study for the first time.

This section aims to answer the following questions:

- How might climate change influence the NZEBs design?
- How does climate change translate into differences in the chosen energy efficiency measures obtained from a cost-optimal approach?

2.4. Renewable energy generation in baseline and NZEB buildings subject to climate change

We considered the baseline and NZEB buildings to investigate how the renewable production from PV might change using different weather datasets in a climate change scenario. Some difference is expected since one expectation for a future warmer climate is a slight reduction in prevailing cloud cover.

We simulated total electricity consumption for heating and cooling, as well as electric demand on winter and summer peak days for both buildings. We compared results for 2018 and 2060 weather datasets as well as the PV output and the estimated needs in the baseline (6 kW dc PV array) and NZEB buildings.

The research also considers that, in recent years, on-site short-term electrical storage systems are becoming widely available and increasingly affordable. Assuming that daily electrical storage with PV systems will spread in next decades, the match of loads to renewable resource will be particularly critical over the daily cycle. The seasonal equivalence of daily energy demand to renewable energy generation is most challenging in winter when the daily energy needs of many buildings are highest while solar energy production is lowest.

The questions we aim to answer in this section are:

- How will the annual PV output change from the baseline to the NZEB building in different locations?
- How will NZEBs impact an increased cooling need in a climate change scenario, particularly during peak electrical demand periods?
- What might be the role of short-term energy storage in a future climate scenario?

3. Results

3.1. Weather data analysis

We analyzed a comprehensive weather dataset for Milan-Malpensa, Italy for the period ranging from 1973 to 2018. This is the maximum the length of the continuous weather stream available for the site. This consists of nearly half a million recorded weather data points. These records contain many climatic variables, such as dry and wet bulb temperature, dew-point, relative humidity, atmospheric pressure, wind direction and speed, global and diffuse horizontal radiation, precipitation and sky cover. In Fig. 2 we plot the hourly outdoor dry bulb temperature which exacts a key influence on building heating and cooling needs in Milan.

A changing temperature trend can be observed in Fig. 2. The plotted red line is the estimated linear trend for the period, showing that the average annual temperature increased by 0.056 °C per year (±0.021) at a 95% confidence. Thus, in 1973, the average temperature was ~10.8 °C which increased to ~13.3 °C by 2018.

An ANOVA/regression analysis indicates that air temperatures in Milan grew over the period, averaging an increase at rate of 0.56 (±0.21)°C per decade, when evaluated at a 95% confidence interval. This strong trend is statistically significant, with changes to minimums visible in the plotted years.

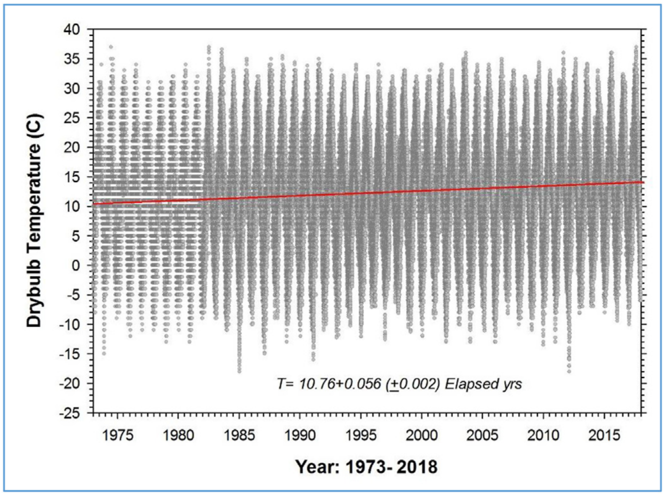

Fig. 2. 47-year time series of hourly outdoor dry bulb temperature at Milan from 1973 to 2018.

To facilitate the interpretation of the plot in Fig. 2 (403 K hourly data points), we created a boxplot showing the medians and inner-quartile ranges for the same data, binned over five years during the same period.

Fig. 3 shows a visible increase in outdoor median dry bulb temperature, particularly after 1985. The real change in medians begins in 1985/1990 and progresses after that point. The most recent bin is strongly atypical with higher values, minimums, and medians. Recent years show larger changes which fit the experience of many people living in Milan. The increase is likely related to climate change as well as urbanization from the heat island effect. The heat island effects arise due to increases to the built environment to the neighborhood around the Milan-Malpensa airport [75].

Table 2 shows measured meteorological data in Milan obtained from composite weather files from 2003 to 2018. The Table includes annual average outdoor dry bulb temperature, minimum, maximum as well as July and January day and night average conditions for each year. Such data were obtained for each studied location.

In Table 2, weather data related to the year 2003 are shown to provide context to the heat wave emergency occurred in that year. Peak summer temperatures since 2010 are shown to be as hot as the heat wave from 2003. There were an observable increase in temperature, particularly in winter over the last seven years, when low temperatures are monitored as higher. For instance, in Table 2 the data show that air temperatures below −10.5 °C were not recorded at the site since 2012.

The morphed weather files for Milan across the various probability scenarios suggest that the average temperature will rise from 12.8 °C to a range varying from 14.6 °C to 17.2 °C (median = 16.0 °C) by 2060 under the RCP 8.5 assumptions. The average temperature difference between 1984-2001 and 2004–2018 increases by 1.6 °C, whereas an increase in temperature of 1.8–4.4 °C is estimated over the 42 years due to both climate change and urbanization.

Fig. 4 reports a yearly cumulative distribution frequency of the outdoor temperature in Milan from 2004 to 2017, the IWEC, TMY and the 2060 morphed weather-shift datasets.

The predicted future climate in Milan shows much longer tails of high temperatures in the 50% (median) and 90% (upper) projections. Peak summer temperatures under the 90% upper bound become 40 °C or higher by 2060. A more detailed comparison between hourly temperatures in Milan obtained from 2018 TMY (2004–2018) and the 2060 morphed weather dataset is depicted in Fig. 5.

Examining Fig. 5, it is possible to observe that minimum night-time outdoor air temperatures increase in the predicted future climate. Lines also show increases to mains water inlet temperatures that are important determinants of water heating energy. It is known that the average annual mains (community supply) water temperature is slightly greater than the annual average temperature in a given location from solar heating of the upper ground where pipes are buried [76]. However, there is a strong seasonal variation in the inlet water temperature from the ground which can also be affected by climate change. We used the detailed algorithm of Burch and Christensen [74] to predict the community water supply temperature against a lagged sinusoidal solution for the specific location using the maximum and minimum daily average air temperatures. The sinusoidal regression fit showed excellent agreement to measured supply water temperatures in nine highly varied climate locations as documented in the original research. We accounted for this impact in our building simulations (Section 3.2) [77]. The annual temperature increase from climate change and is

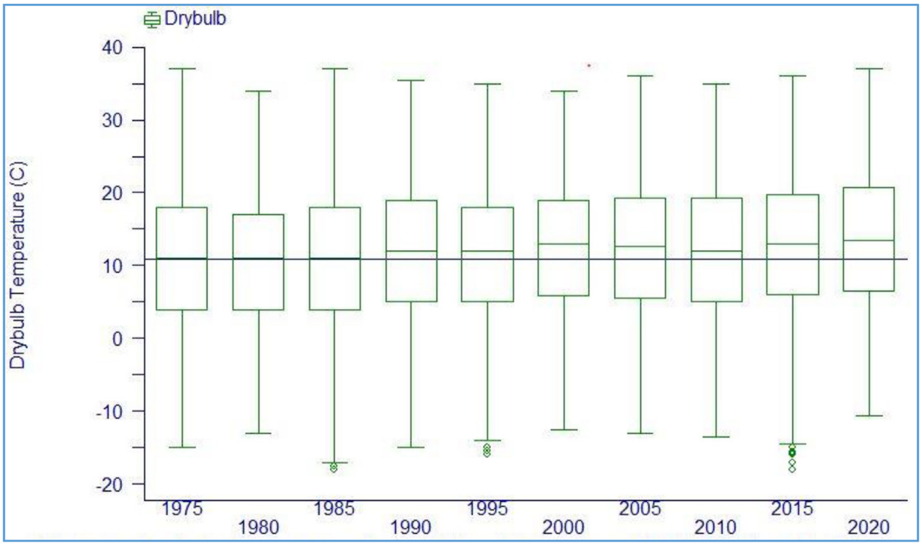

Fig. 3. Boxplot of outdoor dry bulb temperature at Milan from 1973 to 2018 by 5-year bins. The blue horizontal line at 10.8 °C is the median temperature of the first five-year bin. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Measured outdoor dry bulb temperature, Milan: 2003–2018 and composite 2060 weather files.

Weather datasets	Yearly Avg. T (°C)	Yearly Min. Avg. T (°C)	Yearly Max. Avg. T (°C)	Monthly January Avg. T day (8am-8pm) (°C)	Monthly January Avg. T night (8pm-8am) (°C)	Monthly July Avg. T day (8am-8pm) (°C)	Monthly July Avg. T night (8pm-8am) (°C)	Heating Degree Days (hdd)	Cooling Degree Days (cdd)
2003	13.2	−13.0	36.0	4.5	−0.3	29.6	22.0	2710	763
2004	12.1	−8.4	34.0	3.7	−0.3	25.6	19.3	2802	460
2005	11.9	−13.0	34.0	4.1	−0.9	23.8	17.7	2879	479
2006	12.3	−13.0	35.0	1.8	−4.3	23.5	17.5	2772	498
2007	12.5	−11.0	33.0	5.7	1.5	23.9	17.8	2663	469
2008	12.5	−9.0	32.0	5.2	1.1	26.1	19.7	2659	475
2009	12.6	−13.5	34.4	1.4	−2.6	27.8	21.4	2764	608
2010	11.8	−13.0	33.0	1.8	−0.6	24.7	19.0	2942	497
2011	13.1	−8.0	36.0	2.4	−0.6	27.7	20.5	2555	594
2012	12.8	−18.0	35.0	4.5	−1.3	28.9	21.6	2682	613
2013	12.4	−7.0	34.1	4.9	1.3	27.0	19.3	2746	520
2014	13.2	−8.0	33.0	5.9	2.2	22.8	17.8	2300	377
2015	13.2	−7.0	36.0	6.2	0.4	25.9	19.7	2537	614
2016	13.2	−9.7	32.4	5.0	−0.5	26.2	19.8	2468	543
2017	13.5	−9.4	36.7	3.2	−2.2	28.6	21.2	2501	686
2018	14.1	−10.3	34.2	6.7	3.1	27.3	22.4	2274	731
IWEC 1984 –2001	11.2	−11.2	33.0	2.2	−2.3	24.7	17.3	3049	367
IWEC2 1994 –2011	12.2	−10.0	32.6	4.67	0.7	25.9	19.5	2770	462
TMY2004-2018	12.8	−8.2	32.2	3.48	−0.1	26.3	21.3	2561	534
TMYshift _2060_50%	16.0	−5.1	38.1	6.03	3.1	31.2	26.1	1902	1046
TMYshift 2060_10%	14.6	−6.8	34.9	4.61	1.6	28.1	24.1	2152	904
TMYshift 2060_90%	17.2	−3.9	40.0	6.49	4.0	32.7	28.3	1711	1310

reflected both in deep wells and surface water sources with ground and pipe water temperatures increased as a consequence [78]. We found the EnergyPlus predictions for changing seasonal service water temperature to largely fall in line with these empirical results. Results indicate that the relative energy needs for water heating in buildings will decrease, as our building simulation confirms (Section 3.3). However, the seasonal increase is greater in summer than in winter, meaning that water heating energy use will remain important to be reduced in winter to obtain best match with the limited solar resource at that time.

Fig. 6 shows the relative change in the hourly temperature in 2018 TMY weather dataset (2004–2018) compared to the 2060 morphed weather-shift dataset in Stockholm.

As in Milan, in Stockholm it can be observed that the minimum night-time temperature are higher than daytime increases in the predicted future climate (Fig. 6). Looking at air temperatures, we

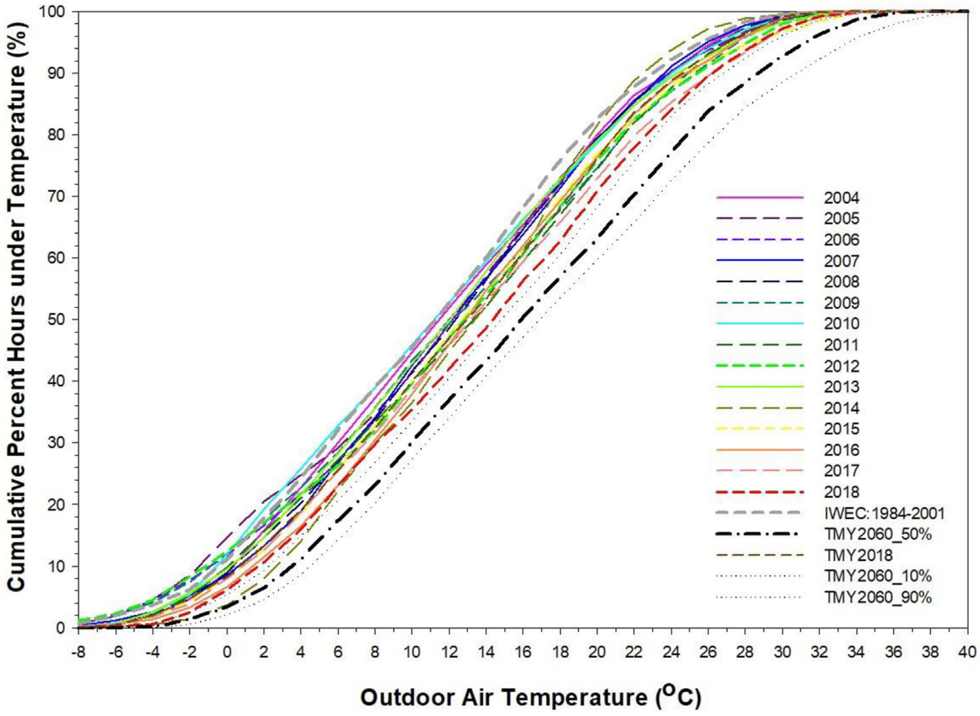

Fig. 4. Cumulative distribution frequency of outdoor temperatures for Milan, from 1984 to 2018 for each year, the IWEC file and the 2060 morphed weather dataset which shows both the 50% median case as well as the 10% lower bound and 90% upper bound cases (dotted lines) in the model projections.

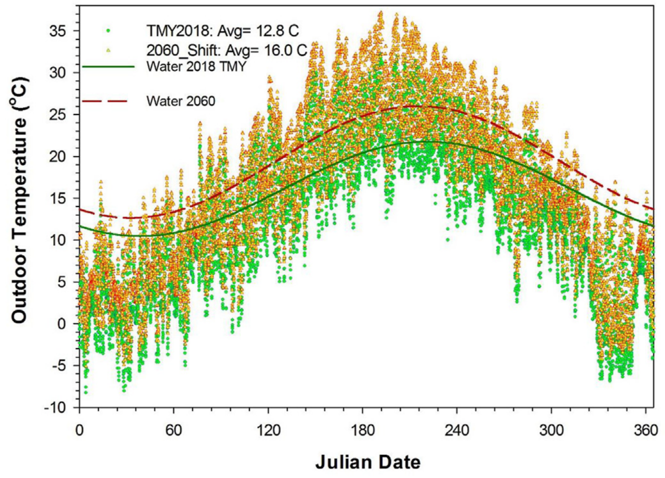

Fig. 5. Hourly outdoor and water temperatures in Milan, obtained from 2018 TMY compared with the 2060 morphed weather-shift datasets in accordance with the median 50% IPCC RCP 8.5 pathway.

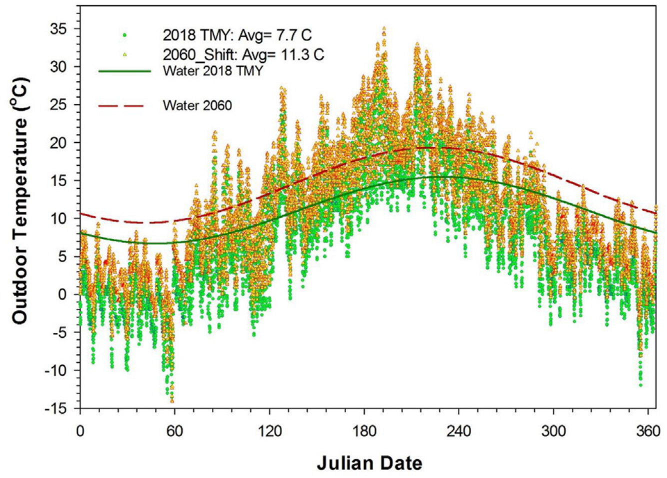

Fig. 6. Hourly outdoor and water temperature in Stockholm obtained from 2018 TMY and 2060 morphed datasets in accordance with the median 50% IPCC RCP 8.5 pathway.

note that the greatest winter extremes are unaffected, while summer temperatures are considerably higher. As in Milan, seasonal inlet water temperatures are increased in the climate change scenario.

We also report results indicating how peak summer and winter conditions might be altered by climate change. We evaluated the hottest daily temperatures and the relative increase as basis to investigate changes on future buildings and energy efficiency selection (Section 3.4).

In Fig. 7 we report the coldest and hottest individual days in 2018 and 2060 for Milan, showing how dry bulb temperatures are changed. The coldest and hottest days were January 6th for winter and July 11th for summer.[1]

In Fig. 7 it can be observed how the winter peak day temperature increased by an average of 3.1 °C from 2018 to 2060, while the summer peak day exhibits a 4.3 °C increase.

A key implication of this result for buildings is that the increase of summer night-time temperature reduces the effectiveness of many passive cooling strategies. This includes night-time

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[1] The specific peak days come from the 2018 TMY weather file that is the basis of the 2060 predictions. Thus, the 2060 peaks are “morphed” changes to the temperature magnitude in 2018 which is the starting point of the calculation method [59].

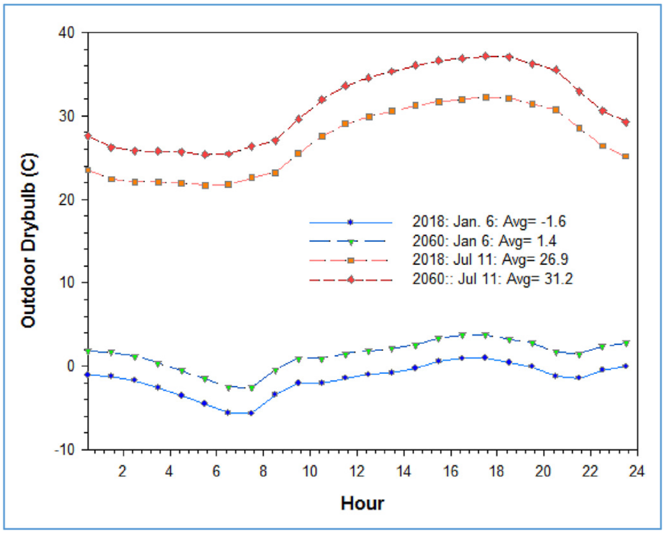

Fig. 7. Winter and summer peak days in weather datasets for Milan (2018 and 2060 morphed 50% median case). Coldest day is January 6th; hottest day is July 11th.

ventilation, either natural or active driven by mechanical fans. Such changes can have an influence on future space conditioning loads. This was verified within the simulations by examining how much cooling could be reduced by opening windows for natural ventilation in current and future climate. EnergyPlus, as implemented in BEopt, has a rigorous algorithm for estimating building ventilation against operable windows, wind and thermal buoyancy. For instance, in Milan, using the 2018 TMY, opening windows at night in summer was able to reduce annual cooling (539 kWh) by 9.3%, but by only 5.0% with the 2060 morphed weather file. In Rome, with much greater cooling (1659 kWh in 2060), opening windows nightly in summer reduced air conditioning by 7.6% in 2018, but only 3.9% in 2060.

3.2. *Energy simulation outputs: past, present, and future energy loads in different locations*

In Table 3 we show how simulated energy use varies using yearly weather datasets from 2004 to 2018 as well as using TMY datasets in the baseline building. In the same table, we also show how energy use compares in the 2018 TMY to the 2060 morphed weather-shift dataset in Milan.

Simulation results show that the balance of heating and cooling in Milan has already substantially changed from that prevailing in the 1980s. We found that recent weather datasets, and particularly the morphed future weather data, evidence reduced heating loads and increased cooling loads. These results are in agreement with the analysis of building energy loads against morphed weather data by Troup and Fannon [79]. In Milan, the total energy use declined slightly, but with a large increase in the balance of cooling against heating. The morphed data also suggests that spring and autumn will exhibit considerably warmer conditions by 2060 under the IPCC RCP 8.5 scenario. Indicated peak summer temperatures are upwards to 38 °C, and 40 °C in the 90% upper bound scenario.

Simulations using TMY (2004–2018) weather datasets from showed a reduction in the average heating needs by 27% using IWEC (1984–2001), while cooling increased by 70% over the same period. IWEC2 datasets (1994–2011) showed closer agreement to the most recent 15-year weather averages. Older TMYs and IWEC datasets do not appear adequate to derive reliable results in building energy simulations. Most recent TMYs are better for a more appropriate analysis of building energy consumption. However, considering that NZEBs designed today will likely be occupied over the next century, current TMY weather datasets may not be adequate to predict energy consumption over the life of the structure. A changing climate calls for further adaptation of even recent TMY files.

The 2060 morphed weather datasets (50% median case) suggests important changes that have to be considered. For instance, the future energy balance in Milan will become even more skewed, moving from a heating-dominated climate to one with mixed heating and cooling. Simulation predicts cooling to increase by 107% over the 2018, 15-year average while heating drops by 37%. The 90% upper bound shows even greater changes: a 47% drop in annual space heating and a 161% increase in space cooling.

Full results were also detailed for the other studied climates for all locations in Fig. 8 and Table 4.

As anticipated in Section 3.1, water heating decreases with newer climate datasets, particularly those projected to the future. In a climate change scenario, it will be easier to reach the NZEB target in colder locations, which show significantly reduced heating. However, very mild locations, such as Rome, will become more difficult given increased energy use for summer cooling electrical demand.

As depicted in Fig. 8, the studied locations show differing future heating and cooling loads. All locations show decreases to heating and increases to cooling, but the impact differs markedly by geographic location. Stockholm, Munich and Austria will have important lower seasonal heating requirements (−57%, −48% and −36%, respectively), although with the increased cooling needs. On the other hand, climates such as the one of Rome see considerably increased annual space energy needs since cooling needs approximately double. Such changes, as illustrated in Section 3.3, will deemphasize heating measures while increasing the importance of addressing cooling loads in future European buildings.

A key finding shown in Table 4 is that with climate changes associated with the 2060 horizon, all NZEBs, even in Stockholm, become positive energy buildings (PEBs). Thus, this shows a key advantages of the NZEB efficiency concept in addressing climate change.

3.3. *Impact of climate change on energy efficiency measures selection*

Section 3.2 showed how heating reduced and cooling increased in the evaluated locations. So we examined how selected energy efficiency options in NZEBs may change across climates comparing the 2018 to 2060 morphed weather-shift datasets.

Fig. 9 depicts an example of the cost-optimization process for Milan where several options are sequentially evaluated over hundreds of simulations (gray dots) to locate those having the best energy performance at the lowest cost, as foreseen by the cost-optimal methodology. Costs are evaluated taking into account the lifecycle expense of the specific measures over their useful life, operation and maintenance as well as the cost of building components and impacts on building energy consumption over time. Cost data sources are elaborated in previous work [24,25]. The black symbols indicate the selected measures at each step of the sequential optimization process. Note that to reach an objective >90% source energy savings, the lifecycle costs are shown to be slightly higher than the minimum cost, but significantly lower than the starting point.

The optmized NZEB characteristics are given in Table 5. We note that most of the cost optimal NZEB options were not sensitive to location—particularly efficient lighting and appliances as well as

Table 3
Simulated energy loads obtained using different weather datasets in a baseline building located in Milan.[a].

	Heating and cooling loads in a standard building located in Milan[b]									Variances from 15-year average			
Year	HP Heat (kWh) (a)	Supp. Resistance Heat (kWh) (b)	Heat fan (kWh) (c)	Heating total (kWh) (d)	Cooling (kWh) (e)	Cooling fan (kWh) (f)	Cooling total (kWh) (g)	Total Heating and Cooling (kWh)[c]	Solar PV (kWh)	Heat deviation (%)	Cooling deviation (%)	Total deviation (%)	PV deviation (%)
2004	2409	372	465	3256	478	167	645	3901	7576	4.3	−18.6	−0.3	−0.0
2005	2436	721	481	3638	466	164	630	4268	7699	16.5	−20.5	9.0	1.7
2006	2301	633	448	3382	440	149	589	3971	7755	8.3	−25.7	1.4	2.4
2007	2163	346	419	2928	410	141	551	3479	7834	−6.2	−30.5	−11.1	3.4
2008	2292	428	448	3168	522	185	707	3875	7242	1.5	−10.8	−1.0	−4.4
2009	2394	742	475	3611	706	255	961	4572	7579	15.7	21.3	16.8	−0.1
2010	2743	677	545	3965	548	196	744	4709	7192	27.0	−6.1	20.3	−5.0
2011	2113	314	422	2849	648	234	882	3731	7831	−8.8	11.3	−4.7	3.4
2012	2169	777	437	3383	759	273	1032	4415	7644	8.4	30.2	12.8	0.9
2013	2456	413	487	3356	574	202	776	4132	7183	7.5	−2.1	5.6	−5.1
2014	1885	152	363	2400	314	106	420	2820	7055	−23.1	−47.0	−28.0	−6.8
2015	2055	264	404	2723	739	258	997	3720	7819	−12.8	25.8	−5.0	3.3
2016	2052	275	402	2729	601	214	815	3544	7570	−12.6	2.9	−9.5	−0.0
2017	2025	328	399	2752	771	273	1044	3796	8016	−11.9	31.8	−3.0	5.9
2018	2049	243	402	2694	803	290	1093	3787	7597	−13.7	37.9	−3.3	0.0
Average 2004 −2018	2236	446	440	3122	585	207	792	3915	7573				
TMY 2004 −2018	2230	381	443	3054	525	188	713	3767	7623	−2.2	−10.0	−3.8	0.7
IWEC2	2075	275	413	2763	595	214	809	3572	7315	−11.5	2.1	−8.8	−3.4
IWEC	2846	838	566	4250	346	120	466	4716	5404	36.1	−41.2	20.5	−28.6
TMY 50% 2060	1591	56	305	1952	1213	431	1644	3596	8104	−37.5	107.5	−8.1	7.0
TMYshift 2060_10%	1835	138	360	2333	806	287	1093	3426	7849	−25.3	37.9	−12.5	3.6
TMYshift 2060_90%	1375	23	261	1659	1536	530	2066	3725	8414	−46.9	160.7	−4.8	11.1

[a] Simulation results for a 120 m^2 prototype. Thus, the results for the total heating and cooling for 2004–2018 (7573 kWh) equates to 63.1 kWh/m^2/y.

[b] Estimated heating and cooling energy use includes the heat pump air circulation fan energy during heating (heating fan) and during cooling (cooling fan).Total Heating (d) = Heat Pump compressor heating energy (a) + supplemental resistance heat (b) + fan energy (c)Total Cooling (g) = Heat Pump compressor cooling energy (e) + fan energy (f).

[c] Total annual ventilation fan energy from a continuously operating 50 W HRV fan adds an annual electricity use of 438 kWh.

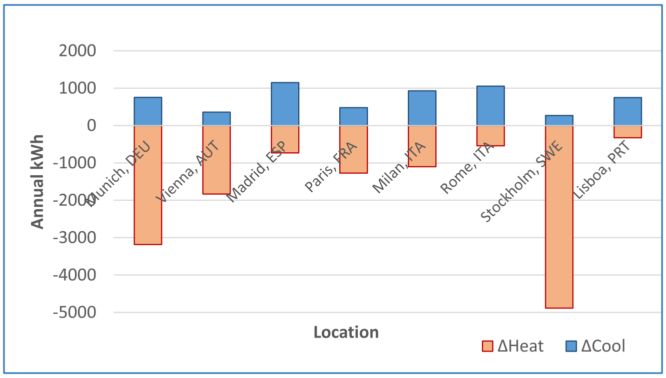

Fig. 8. Predicted decrease in heating and increase in final cooling electricity consumption by location from 2018 to 2060.

heat pump water heating. (The optimal order with which measures were selected could be quite different with climate, but the final selection often differed little.) Due to its low incremental cost, high levels of infiltration control were uniformly cost effective. For necessary outdoor air ventilation, a 90% efficient energy recovery ventilator is assumed in all evaluated cases.

Similarly, higher efficiency reversible air-source heat pumps with a heating seasonal COP of 3.1 and a cooling season COP for 6.4 were found uniformly cost-effective compared to standard efficiency systems. These levels are calculated at six different ambient air temperatures (A-F) within regulations EN 14511 and EN 14825. These procedures include standby electric power and operating system losses. However, no duct systems or radiators are included as air-to-air systems are assumed. In heating mode, heat pumps can use supplemental electric resistance heat when outdoor temperatures to not provide sufficient heating capacity; heat pump goes to full resistance below temperatures of −12C. EnergyPlus simulates compressor, fans and supplemental resistance heat in detail for heat pump systems depending on the operating building loads at a given temperature as well as the heating and cooling capacity at that outdoor condition.

As shown in Fig. 9, the NZEB building has efficient appliances and lighting as well as a high insulation levels for walls, foundation and ceilings. Other important measures are advanced windows and tight construction with a very high efficiency heat pump for space conditioning as well as a dedicated COP 3.0 heat pump water heater with an insulated hot water distribution system. The optimized building for 2018 includes high gain windows and walls.

We found that the morphed 2060 data, had an influence on the optimal roof insulation, with solar control becoming more important for milder locations. Table 6 shows the results by location for both the 2018 and 2060 weather datasets used in the building simulations.

Legend: Dk = Dark: Solar reflectance = 0.3; Med = Medium reflectance = 0.5, Lt = Light color & reflective, reflectance = 0.7; Glazing: G-factor = 0.4 for high (Hi) solar transmittance; 0.25 for low (Lo) transmittance. Seasonal exterior window

Table 4

Heating, cooling, and water heating energy consumption in baseline and NZEB buildings, in the studied locations.[a]

Weather dataset	Heating (kWh)	Cooling (kWh)	Total Heating and Cooling (kWh)	Hot Water (kWh)	Total (kWh)	PV (kWh)	Renewable (%)	Heating (kWh)	Cooling (kWh)	Total Heating and Cooling (kWh)	Hot Water (kWh)	Total (kWh)	PV (kWh)	Renewable (%)
	Rome: Base Building							Rome: NZEB Building						
IWEC	1216	1099	2315	1846	7521	7471	99%	332	284	616	680	3643	7471	205%
IWEC2	979	1093	2072	1838	7268	7784	107%	267	284	551	674	3576	7784	218%
2018 TMY	1128	1129	2257	1808	7424	9053	122%	282	299	581	668	3590	9053	252%
TMY shift 2060_50%	586	2182	2768	1577	7702	9358	122%	117	683	800	592	3690	9358	254%
	Lisbon: Baseline Building							Lisbon: NZEB Building						
IWEC	598	803	1401	1802	6562	8353	127%	138	217	355	668	3365	8353	248%
IWEC2	393	1211	1604	1714	6656	7752	116%	85	340	425	633	3385	7752	229%
2018 TMY	595	853	1448	1759	6565	8778	134%	123	217	340	654	3321	8778	264%
TMY shift 2060_50%	267	1603	1870	1586	6814	9036	133%	29	434	463	592	3356	9036	269%
	Madrid: Baseline Building							Madrid: NZEB Building						
IWEC	1767	941	2708	1964	8030	8192	102%	530	23	553	744	3904	8192	210%
IWEC2	1574	1038	2612	1952	7922	8432	106%	482	258	740	741	3872	8432	218%
2018 TMY	1779	1231	3010	1890	8259	8951	108%	507	325	832	727	3939	8951	227%
TMY shift 2060_50%	1096	2380	3476	1647	8482	9367	110%	270	750	1020	645	4006	9367	234%
	Paris: Baseline Building							Paris: NZEB Building						
IWEC	3717	226	3943	2210	9511	5533	58%	1073	53	1126	811	4382	5533	126%
IWEC2	3286	287	3573	2181	9112	5753	63%	964	76	1040	803	4285	5753	134%
2018 TMY	3505	244	3749	2151	9259	6064	65%	973	62	1035	797	4244	6064	143%
TMY shift 2060_50%	2233	724	2957	1934	8250	6215	75%	596	185	781	715	3880	6215	160%
	Milan: Baseline Building							Milan: NZEB Building						
IWEC	4250	466	4716	2131	9786	5404	55%	1137	174	1311	794	4557	5404	119%
IWEC2	2763	809	3572	2160	9062	7315	81%	903	193	1096	785	4314	7315	170%
2018 TMY	3054	713	3767	2087	9212	7623	83%	964	179	1143	774	4300	7623	177%
TMY shift 2060_50%	1952	1644	3596	1838	8793	8104	92%	587	460	1047	686	4089	8104	198%
	Vienna: Baseline Building							Vienna: NZEB Building						
IWEC	5847	293	6140	2303	11802	5844	50%	1697	65	1762	844	5108	5844	114%
IWEC2	4853	419	5272	2245	10876	6084	56%	1448	93	1541	824	4945	6084	123%
2018 TMY	5085	402	5487	2210	11055	6398	58%	1427	85	1512	818	4801	6398	133%
TMY shift 2060_50%	3251	762	4013	2025	9396	7978	85%	891	188	1079	753	4235	7978	188%
	Munich: Baseline Building							Munich: NZEB Building						
IWEC	7652	135	7787	2456	13602	5891	43%	2260	35	2295	891	5747	5891	103%
IWEC2	6005	176	6181	2386	11976	5888	49%	1737	44	1781	873	5173	5888	114%
2018 TMY	6518	170	6688	2348	12345	6550	53%	1831	38	1869	865	5234	6550	125%
TMY shift 2060_50%	3280	648	3928	2098	10147	6893	68%	1111	158	1269	783	4458	6893	155%
	Stockholm: Baseline Building							Stockholm: NZEB Building						
IWEC	7160	118	7278	2559	13209	5891	45%	3546	21	3567	909	7087	5891	83%
IWEC2	6524	143	6667	2573	12585	5879	47%	3086	29	3115	903	6618	5879	89%
2018 TMY	7101	143	7244	2474	14560	5407	37%	2495	41	2536	885	5985	5407	90%
TMY shift 2060_50%	3900	500	4400	2219	10322	6000	58%	1301	103	1404	809	4683	6000	128%

[a] The efficiency of the various equipment options for the NZEB buildings are documented in Table 5.

shade = seasonally adjusted shutters, awning or shading devices such that window solar transmittance is 0.7 in winter and 0.3 in summer. Otherwise 0.7 year round.

Our analysis in Table 6 confirms that future conditions associated with the median rates of 2060 climate change scenario in Milan will emphasize NZEB building elements to reduce cooling needs. In table values we also observe that, NZEB optimal choices vary and change by location. For instance, in locations like Paris cooling related measures begin to emerge as important in the NZEB design.

However, with the 90% upper bound, which reflects the upper limit of the accounted RCP 8.5 2060 climate change scenario, we found that Low-G factor windows and light colored walls and roofs were shown to be desireable across climates even in Munich and Stockholm. This means that solar control in future European buldings will become much more effective if higher rates of climate warming occur. For instance, medium height vegetation around facades or balconies, awnings or shutters, may help reducing solar gains while not interfering with PV production.

We found that cost-optimal appliances and lighting were selected earlier in the optimization process with the more recent weather datasets, reflecting the increased emphasis on reducing

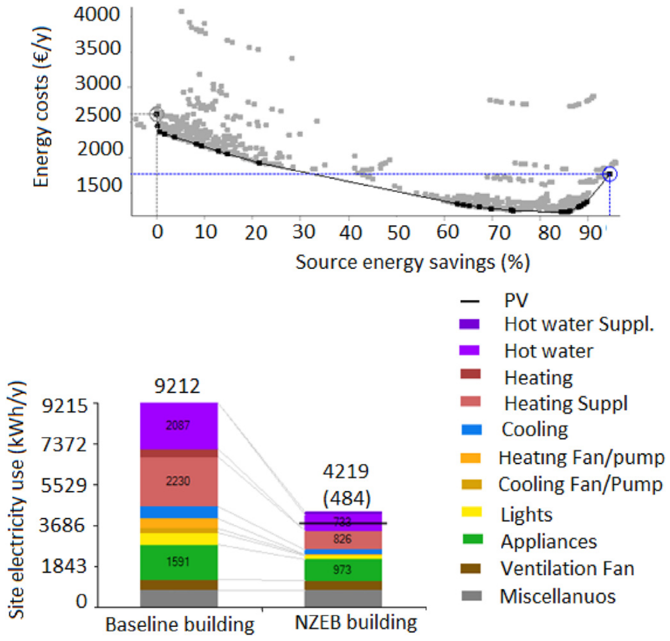

Fig. 9. Cost-optimal optimization in Milan, with 2018 TMY weather dataset to reach the NZEB target (+90% primary energy reduction). The bar chart shows the building initial energy consumption by colored end-uses (left) and the consumption at the final step (right bar).The horizontal black line shows the solar PV electric generation with the net annual energy in parentheses.

internal heat gains that significantly impact cooling. Our results mirrors those of Ferrara & Fabrizio [38] recommending slightly lower levels of insulation within a recent and future climate. Most importantly, we found that with improved building envelope, airtightness and equipment, the energy use of the NZEB building was less sensitive to weather conditions than the baseline. This is then revealed as a fundamental advantage of the NZEB concept, which shows itself more robust in performance relative to climate change.

Also, with climate change, the model also showed an increasing preference for lighter colored surfaces with higher reflectance for both roof and walls. Better solar control from windows (lower G-factor) was selected, depending on loation, together with more efficient lighting and appliances, at the beginning of the optimization process to reduce cooling needs from internal loads.

3.4. Renewable energy generation in baseline and NZEB buildings subject to climate change

Beyond building heating and cooling loads, we also explored how climate change may influence solar electric output from PV systems. In accordance with the expected drop in cloud cover with climate change [59] we can expect higher levels of direct as well as diffuse horizontal solar radiation according to the procedures described in Ref. [81]. Based on the modified weather files, we observed solar irradiance to climb modestly and with it electrical production from PV systems as simulated the highly-detailed TRNSYS simulation program [82]. Fig. 10 shows the change in total annual HVAC electricity, as well as solar PV output from 2018 to 2060 weather datasets across evaluated locations.

In all locations, the PV output increased in a climate change scenario. A 6% higher renewable energy production is found in Milan using the 2060 median morphed RCP 8.5 weather dataset. This varied from a lower increase of about 3% in Lisbon, to more than 20% in Vienna, where the morphed weather dataset predicted lower future cloud cover.

We also consider building short-term energy storage which increases self-consumption by PV production when the building loads need to be addressed in a day and the preceding day. This can be done by post processing daily building loads and PV output.

It is important to point out that the annual energy balance may

Table 5
NZEB characteristics obtained from the optimization process.

Walls	R1.3 Insulated perlite filled masonry walls with interior insulation and exterior insulation sheathing (~0.16 W/m^{2}K)[a]
Windows	23 m^2, triple selective glass (0.96 W/m^{2}K), low-e with improved frame and argon fill; G-Factor based on location
Roof	R-6.3 insulation (~0.15 W/m^{2}K)[a]
Cellar Walls	R-1.8 insulation (~0.57 W/m^{2}K)
Doors	Insulated fiberglass entry door (~0.8 W/m2K)
Air leakage	Standard construction (0.6 ACH at 50Pa blower door pressure)
Heating	Heat pump heating system; Seasonal COP = 3.1 with supplemental resistance heat (EN 14511 and EN 14825)
Cooling	Seasonal COP 6.4 mini-split cooling system (unit includes compressor and fans) (EN 14511 and EN 14825)
Hot Water	155 l heat pump water heater (COP = 3) in cellar providing 120 l per day at 55 °C; 2 cm insulated piping assuming for hot water distribution system.
Mechanical ventilation	40.6 l/s continuous with 90% efficient ERV: energy recovery ventilator ventilation system; operating system power of 50 W
Lighting/Appliances	LED lighting, A+++ rated refrigerator, clothes washer, dishwasher; Induction cooktop

[a] Note that window G-factor and wall and roof finishes are optimized for NZEB building based on analysis.

Table 6
Selected cost-optimal energy efficiency measured related to roof, wall finishes, window shading, and solar transmission factors by location for three weather datasets (IWEC 2, 2018 TMY, TMY shift 2060 50% percentile).

Location	Roof reflectance			Seasonal exterior window shade			Window G-Factor			Wall finish reflectance		
	IWEC 2	2018 TMY	TMY 2060	IWEC 2	2018 TMY	TMY 2060	IWEC 2	2018 TMY	TMY 2060	IWEC 2	2018 TMY	TMY 2060
Rome	Lt	Lt	Lt	Yes	Yes	Yes	Hi	Hi	Lo	Lt	Lt	Lt
Lisbon	Lt	Lt	Lt	Yes	Yes	Yes	Lo	Lo	Lo	Lt	Lt	Lt
Madrid	Med	Lt	Lt	Yes	Yes	Yes	Hi	Hi	Lo	Me	Med	Lt
Milan	Med	Med	Lt	No	No	No	Hi	H	Lo	Med	Med	Lt
Paris	Dk	Lt	Lt	No	No	No	Hi	Hi	Lo	Med	Med	Med
Vienna	Dk	Dk	Dk	No	No	No	Hi	Hi	Hi	Med	Med	Med
Munich	Dk	Dk	Dk	No	No	No	Hi	Hi,	Hi	Med	Med	Med
Stockholm	Dk	Dk	Dk	No	No	No	Hi	Hi	Hi	Med	Med	Med

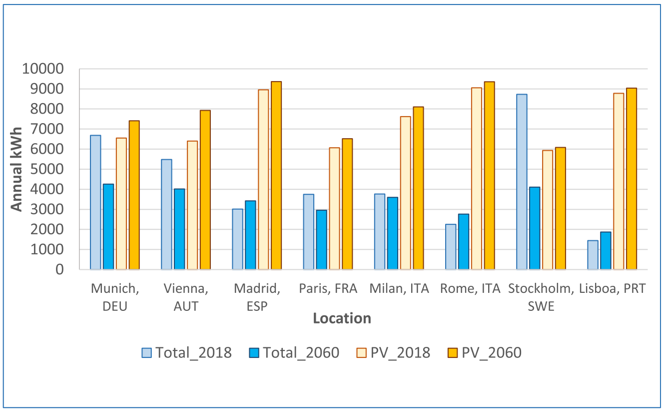

Fig. 10. Change in total heating, ventilation and air conditioning electricity consumption and PV output from 2018 weather to 2060 morphed weather datasets across evaluated locations.

not be the best indicator in terms of how space conditioning loads and solar PV output change. Although energy storage can readily meet 24-h differences in loads, periods longer than about 3 days are difficult to address [80]. Thus, the seasonal match between solar and building energy needs becomes paramount. This is because increases in PV output may come in spring and autumn when the PV production is of less benefit. On the other hand, reduced space heating will not likely occur during times of the year when the solar output is greatest.

Results for Stockholm are given to illustrate a different climate from Milan. Fig. 11 shows the hourly total electric power and PV output expected for the baseline building compared with the NZEB using the 2018 weather dataset. The comparison aims to see if and how much NZEBs might impact electrical loads and the relative match with solar PV and peak loads.

While the PV output (orange) is the same, the building loads (blue) with the NZEB are much closer to the limited winter solar resource.

Seasonal trends become more evident by taking an average of the hourly time series of Fig. 11 as monthly profiles over a 24-h cycle. This is given in 2018 for both the baseline and NZEB buildings in Figs. 12 and 13, respectively.

Figs. 14 and 15 show similar results for the baseline and NZEB buildings simulated using the 2060 morphed 50% weather dataset. We note the large reduction in average heating reflected in monthly loads in winter and the favorable effect of the NZEB design on reducing the loads so that they are closer to the average PV production in each month.

Fig. 16 illustrates the energy-end-uses that make up the baseline building demand in both winter and summer and how they compare to the PV output in 2018 in Milan.

As seen in Fig. 16, daily space heating in winter often exceeds PV output for any particular day. Thus, heating loads are out of phase with PV output in northern latitudes given seasonal variation in solar radiation and temperature. Fig. 17 shows total energy use over the year in the baseline and the NZEB buildings in 2018.

As seen in Fig. 17, the NZEB building exhibits lower amplitude in daily energy loads over the year. The PV system produces more than the energy needed by the baseline building and nearly three times as much energy as needed in the NZEB building. However, both fall short in winter although the NZEB building is much closer. Fig. 18 shows a graph related to 2060 morphed RCP 8.5/50% weather dataset.

From Fig. 18 it can be seen how winter loads fell from 2018, but summer loads are higher (blue). The NZEB building (green loads) is less sensitive to seasonal differences in temperature from climate change with a greater solar utilization. Since the 2060 weather is hotter in summer, the surplus of energy production in the NZEB prototype is not as high in the future scenario. A key result is that on both winter and summer peak days, the NZEB building shows a much better match in covering building energy loads with the solar resource. This is particularly evident in the extreme winter peak day where the portion covered by renewable energy increases from 4.5% to 8.3%.

Evaluating the loads against PV generation, the median 2060 morphed weather dataset shows a similar match of loads to PV on the coldest day, although it averages 3 °C warmer than the 2018 winter peak day. The energy efficiency measures of the NZEBs also contribute to match the building loads with the PV generation in a future climate.

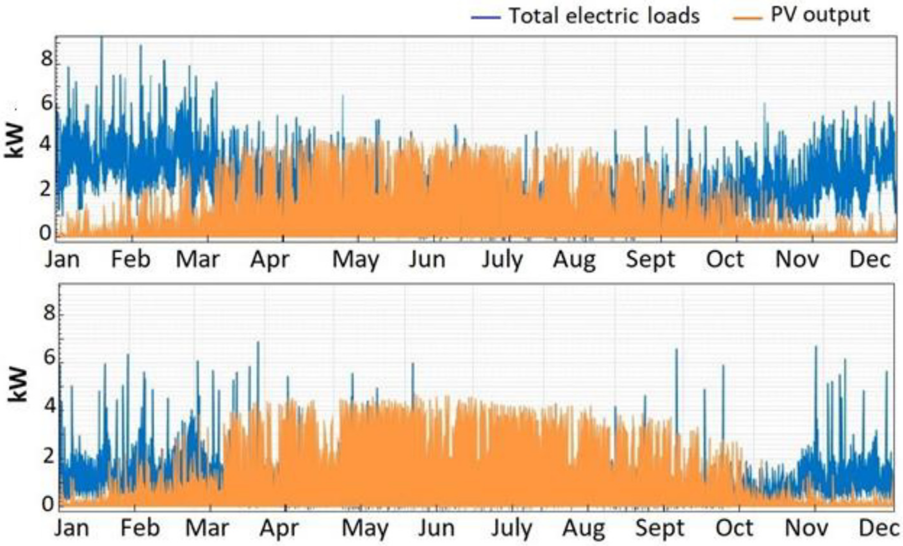

Fig. 11. Comparison of building total hourly electrical loads with PV output in Stockholm for the baseline building on the top and NZEB building on the bottom given by the sum of: heating, cooling, hot water, lighting appliances.

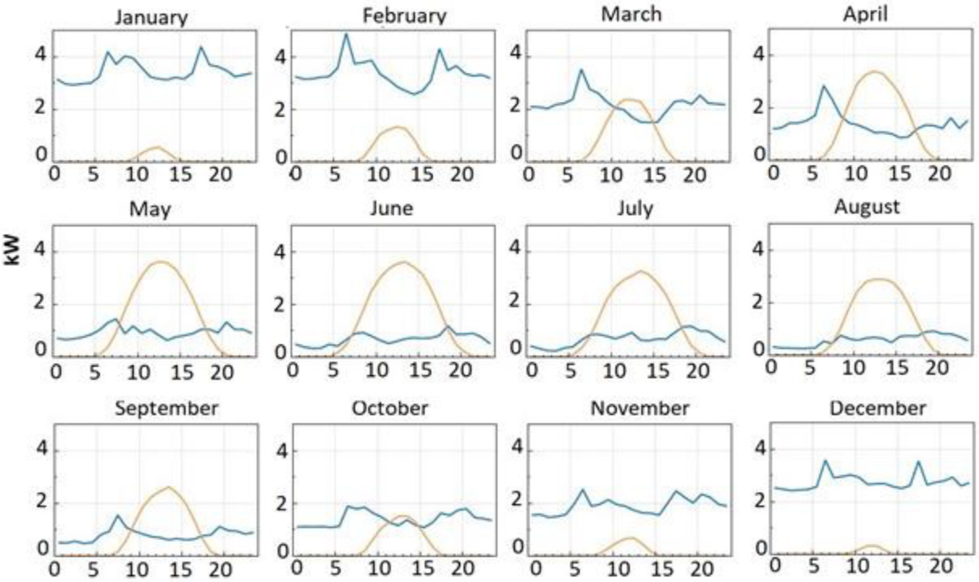

Fig. 12. Baseline residential building in Stockholm showing monthly predicted electrical loads as well as PV output in 2018 (X-axis is hour of the day with average profiles for each month).

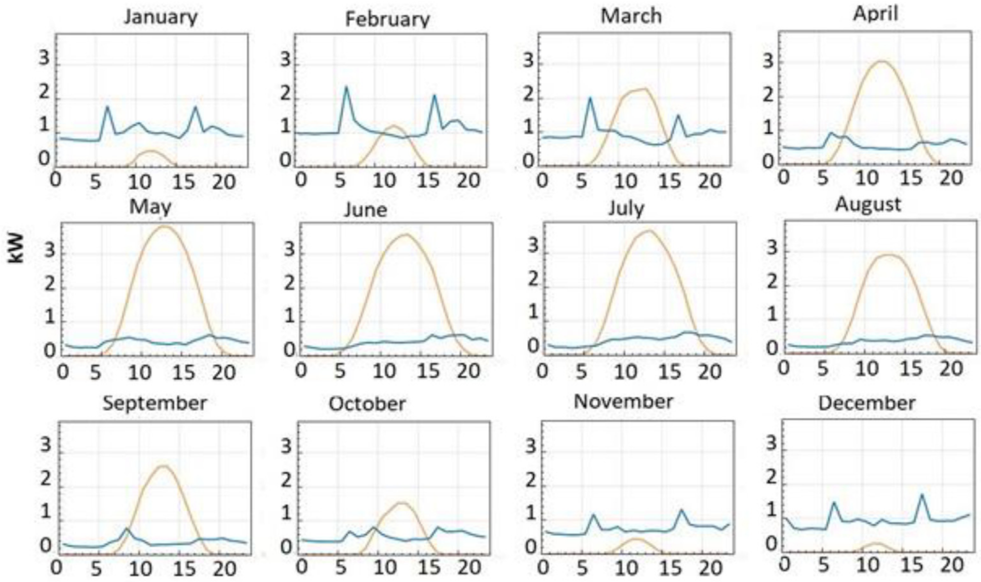

Fig. 13. NZEB residential building in Stockholm showing monthly predicted electrical loads as well as PV output in 2018 (X-axis is hour of the day with average profiles for each month).

Table 7 shows key parameters as well as simulated building performance using the 2018 TMY and the median 2060 morphed weather dataset. Peak winter and summer days are important as they occur typically when the utility experiences its highest demand associated with space conditioning for heating in winter and for cooling in summer.

The results for winter and summer impacts of NZEB in Table 7 reveal key attributes of the PV production in Milan against building loads. Considering a 24-h energy storage, on the coldest day of the year in the 2018 TMY, the PV system only produces 2.6 kWh against total building loads of 59.0 kWh—only 4.5% of the needed energy. However, NZEBs help in improving self-consumption as building loads are more synchronized with the PV production in winter. Building energy needs are cut in half and the PV is able to supply about 9% of the required energy on the coldest day of the year, twice as much as before in Milan. In northern latitudes (exemplified by Stockholm), the energy demand is higher in winter with much lower available solar energy. The NZEB efficient design, particularly increased insulation and air tightness, can intensely lower winter-time heating loads and thus considerably improve potential PV self-consumption. In summer, the PV resource coupled with daily short-term electrical storage is able to successfully address peak summer demand.

A major finding is that not only NZEBs would have greater ability to cover site building loads, but that there would also be advantages for reducing summer peak demand. With daily electrical storage,

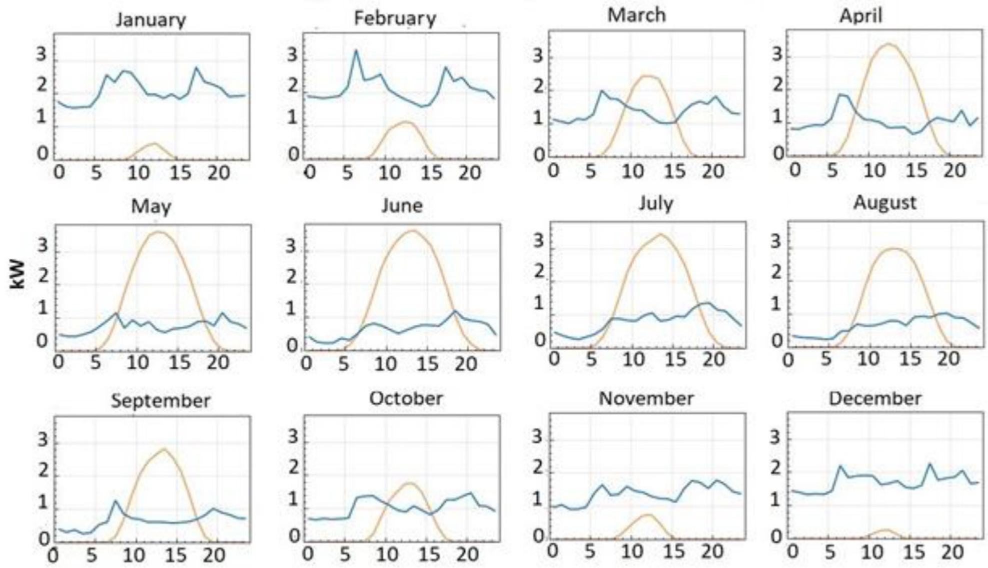

Fig. 14. Baseline residential building in Stockholm with 2060 weather dataset, showing monthly predicted electrical loads as well as PV output (X-axis is hour of the day with average profiles for each month).

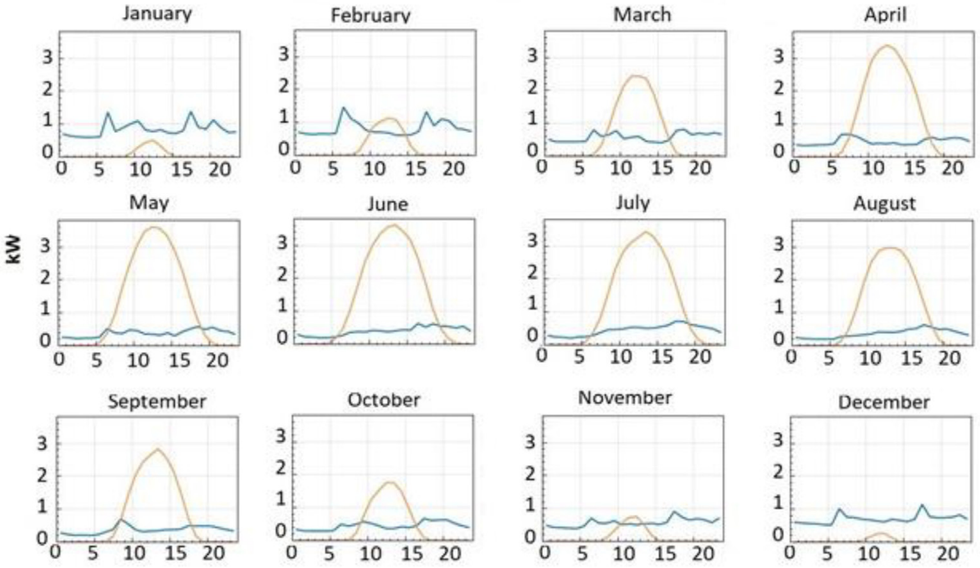

Fig. 15. NZEB residential building in Stockholm with 2060 weather dataset, showing monthly predicted electrical loads and PV output (X-axis is hour of day with average monthly profiles). Note improved match to PV resource.

the match of loads to renewable resource is much improved.

Simulated and empirical data on relative sizing and performance show that addressing building loads through electrical storage will best meet loads and be properly sized to consider not only daily PV production on the day of the loads, but also the PV available on the preceding day to produce sufficient energy capacity to address loads [83].

We posit from these considerations that a useful metric for assessing future NZEBs success could be the Fractional Renewable Energy Self-COnsumption or FRESCO which considers how the PV solar fraction varies by day. This concept mirrors the conclusions of Torcellini et al. [84] which suggest that the timing of loads is crucial for the long-term large-scale adoption success of NZEBs. Increased building self-consumption may become more important as solar PV saturation grows across Europe along with short-term electrical storage [85]. A realistic daily electrical storage is typically about twice the size of the average daily loads, while longer storage is prohibitive as site electrical energy storage costs about €1000/kWh or more.[2] Short-term electric storage in buildings will be widely available in next decades with most storage only utilizable over a 2-day period. The PV energy stored on one day becomes available for

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[2] Long term energy storage will remain a challenge for NZEBs and will tend to emphasize measures to reduce space heating needs as identified in this analysis. While the authors appreciate the need to evaluate long-term storage, here we have concentrated on how improved building characteristics and equipment can improve the utilizability of readily available short term electrical storage within NZEB dwellings as revealed in Table 7.

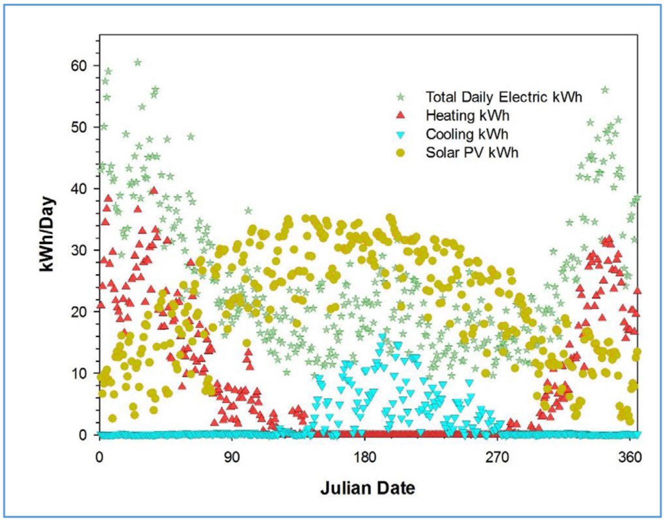

Fig. 16. Daily end use loads for the baseline building in Milan simulated with the 2018 TMY dataset. Heating is for space conditions and does not include water heating.

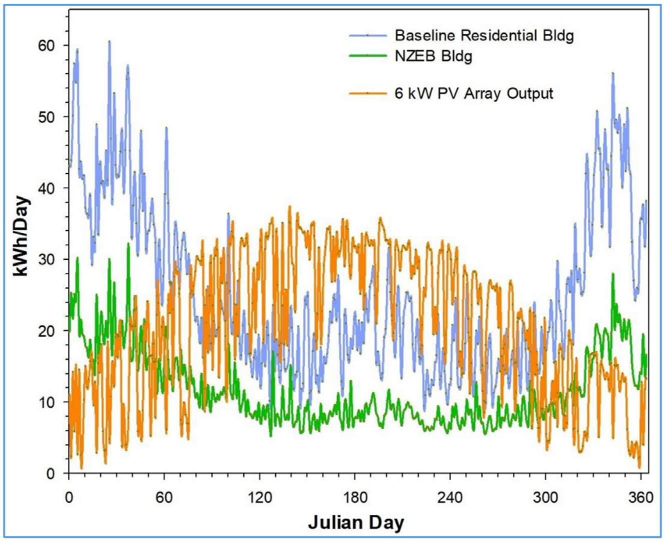

Fig. 17. Seasonal match of energy loads and PV output in 2018 TMY file in the baseline and NZEB buildings.

meeting the loads of the following day, making the daily energy loads easier to fully meet with renewable energy. Thus, the average fractional self-consumption on a particular day is the average of the PV energy on the current and preceding days, along with the loads on the two days as well.

This would represent a much more meaningful metric than simply summing up total electrical loads and PV production over the year. The currently used metric, considering annual computation the renewable energy production against annual load, can overestimate PV potentials. When applied on a large scale, how much of building electric demand can really be met by PV? We anticipate that increased building level renewable energy self-consumption will become more important in future buildings [86,87].

4. Conclusions

We analyzed weather and simulated energy use in eight highly varied climates across Europe to see how climate change will impact buildings. Beyond weather data itself, we examined how weather data influences building energy use as well as best potential energy options for energy use reductions. This effort was pursued in the context of the pressing importance of reducing building greenhouse gas emissions.

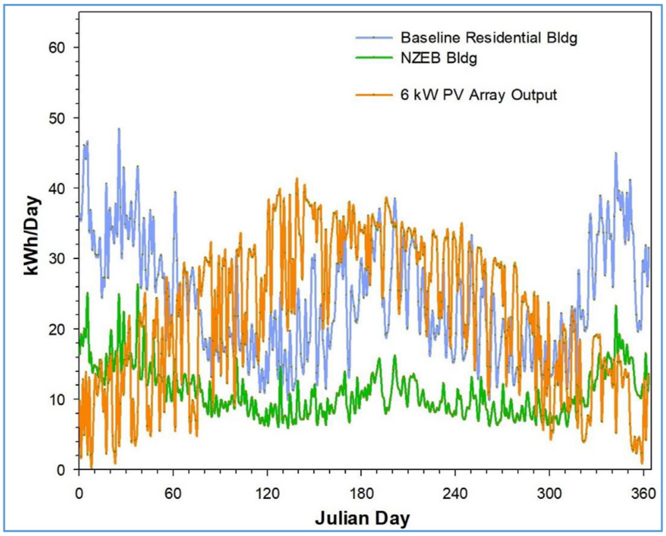

Fig. 18. Match of energy loads to PV output for median 2060 morphed weather dataset.

Analysis of the weather data revealed temperature increases over recent decades in all evaluated locations. For instance, temperature in Milan increased at an average rate of 0.56 (±0.21)°C per decade (uncertainty evaluated at a 95% confidence from 1973 to 2018). The morphed future weather datasets suggest that the average temperature will rise to 16.0 °C by 2060. Winter peak day temperature increased by an average of 3.1 °C from 2018 to 2060, while the summer peak day exhibits a 4.3 °C increase, including both effects of urbanization and climate change.

Further examination of weather data, suggested that in future years extreme summer temperatures may become much more common. A future climate with milder winters and periods of intense summer heat will impact energy demand and selected energy efficiency measures for most effective NZEBs.

We found that older IWEC weather datasets (1984–2001) do not appear adequate to obtain reliable results from building simulations (heating overpredicted, cooling and PV output underpredicted). The IWEC2 weather files (1994–2011) performed better, but most recent TMYs (2004–2018) allow a more realistic analysis of building energy consumption. However, a changing climate calls for further adaptation. Considering that NZEBs designed today will be occupied over the next century, using morphed weather datasets may be crucial to obtain representative results when projected to the future.

In all locations, the median 2060 climate change scenario shows a large decrease in heating. The colder studied locations showed large decreases to annual space heating for the baseline building compared with TMY 2018 weather datsets: Stockholm −45% (7101–3900 kWh), Munich −50% (6518–3280 kWh) and Vienna −36% (5085–3251 kWh). These sites also exhibited increased cooling needs, although large in a percentage basis (+250%, +281% and +90%, respectively), the changes were small on an absolute basis—357 to 478 kWh.

In Milan, in the median 2060 climate change scenario, predicted annual cooling more than doubled (466–1644 kWh or a +251%

Table 7

Evaluation of peak day performance of baseline and NZEB buildings in Milan, in 2018 and 2060.

Weather dataset	Peak Day	Min T (°C)	Max T (°C)	Average (°C)	Total Baseline (kWh)	Total NZEB (kWh)	PV output (kWh)	PV baseline building: total loads/peak loads (%)	PV NZEB: total loads/peak loads (%)
2018 TMY	Winter: January 6th	−5.7	0.9	−1.6	59.0	30.2	2.6	4.5	8.7
	Summer: July 11th	21.7	32.2	26.9	29.0	11.3	31.9	110	282.3
TMY shift 2060_50%	Winter: January 6th	−3.0	2.3	1.4	46.2	25.1	2.1	4.5	8.3
	Summer: July 11th	25.4	37.2	31.2	37.0	15.8	34.4	93.0	217.7

versus the IWEC dataset and by 131% compared to TMY (2004–2018). At the same time, annual heating in the baseline building in Milan decreased by 28% comparing 2018 TMY to IWEC, and by 54% comparing to the 2060 climate change scenario. The 90% upper limit of the RCP 8.5 2060 model showed even greater changes, with heating decreasing by 47% and cooling increasing by 161% compared to the 2004–2018 averages. Total annual heating and cooling decreases with climate change in Milan from 4716 kWh (IWEC) to 3767 (TMY 2018) and then to 3596 kWh (2060 median climate change scenario). The modest decrease in total HVAC energy from TMY2018 to TMY2060 masks the fact that the balance of heating and cooling changes dramatically with cooling becoming 34% of total space conditioning loads in the future period—and even more (45%) within the 90% upper bound RCP 8.5 2060 model. Thus, Milan becomes a mixed heating and cooling climate with hot summers. These changes will de-emphasize heating measures in future buildings, while increasing the importance of addressing cooling loads.

Milder locations such as Lisbon and Rome show significantly increased cooling loads and nearly no heating any longer. The largest increases to cooling are: Rome (1129 kWh to 2182 kWh) and Lisbon (853–1603 kWh). This makes reaching NZEB more difficult, as space conditioning loads increase compared to colder locations in Europe. However, warm locations also benefit strongly from NZEB efficiency measures.

The average long term temperature increase with climate change are also reflected in deep wells and surface water temperatures as being observed across Europe [78]. This leads to a decrease of water heating needs in buildings (about 10% across climates).

The NZEB design is different in a climate change scenario than estimated from current weather, having slightly lower levels of insulation, improved envelope, airtightness and equipment, lighter colored surfaces with higher reflectance roof and walls, and better solar control from windows (lower G-factor) to reduce cooling needs. A key finding summarized in Table 4 is that with climate changes associated with the 2060 horizon, all NZEBs, even in Stockholm, become positive energy buildings (PEBs). Thus, this shows a key advantages of the NZEB efficiency concept in addressing climate change.

Being less sensitive to weather conditions than baseline buildings, better insulated NZEBs will increase comfort in hot summer conditions in Europe, even in the event of power interruptions. Due to the large impact of internal heat gains on summer overheating, efficient low energy appliances and lighting will be essential to controlling cooling in a climate change scenario.

Simulations established that increased summer night-time temperature with climate change reduces the usefulness of passive cooling strategies. We verified through simulation that night-time ventilation, either natural (by opening windows) or active with mechanical ventilation (to bring in outside air) would provide less relief. This implies that active means of efficient cooling (such as very high efficiency air vapor compression cooling) will become more important in future NZEBs.

Due to lower levels of predicted cloud cover, PV output increases slightly in a climate change scenario (6% more in Milan, 3% in Lisbon, more than 20% in Vienna). In summer, the PV produces more energy than needed in the baseline and nearly three-times in the NZEB building. While the PV output is the same as with standard buildings, NZEBs help in improve self-consumption. With NZEB buildings, energy needs are cut in half and the PV is able to supply about 8% of the required energy on the coldest day of the year in Milan, twice as much as before. Given higher insulation and air tightness, both on winter and summer peak days, the NZEB showed a better match to cover building energy loads using PV. This is particularly evident in the extreme winter peak days when the energy demand covered by renewable energy increases, particularly with daily electrical storage.

Addressing heating loads in NZEB design remains crucial in the climate change scenario because winter season renewable energy production is limited due to low solar angles and duration and heating needs can be high—even in a warmer climate. Summer performance is also important, but largely to control excess solar gains through the building envelope, while not adversely impacting winter performance. Our results emphasize that energy efficiency is an effective hedge against climate change as the better insulated and optimized NZEBs showed more resilence against temperature extremes and adverse weather events.

Finally, we used sensitivity analysis to critically evaluate the RCP 8.5 scenario along with its known uncertainties. In the EU, the implementation of specific climate mitigation policy measures are already in place, aiming to limit greenhouse gas emissions and temperature increase. Thus, future research may profitably revisit different climate change scenarios, comparing results and addressing specific policy initiatives for NZEBs.

Author contribution

Conceptualization: DD, DP, IE, DC; LL. Methodology, Investigation, Simulations, Data elaboration and analysis, Validation, Visualization, Writing: DD, DP. Datasets provider: DC, DP, LL. Statistical analysis, Review & editing: DD, DP, IE.

Data availability

Data are available within an enclosed Data in Brief paper (D'Agostino D, Parker D, Epifani I, Crawley D, Lawrie L, Data on Nearly Zero Energy Buildings (NZEBs) and future climate across Europe, submitted).

Declaration of competing interest

The authors Delia D'Agostino, Danny Parker, Ilenia Epifani, Dru Crawley, and Linda Lawrie declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We appreciate the support of Christian Thiel and Maurizio Bavetta at the Joint Research Centre (European Commission, Ispra, Italy) and James Fenton (University of Central Florida/FSEC Energy Research Center) to encourage this collaborative research.

References

[1] Economidou M, Todeschi V, Bertoldi P, D'Agostino D, Zangheri P, Castellazzi L. Review of 50 years of EU energy efficiency policies for buildings. Energy Build 2020;225:11032. https://doi.org/10.1016/j.enbuild.2020.110322.

[2] EC, A clean Planet for all, COM. 773 final, A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN.

[3] EC A. Union that strives for more – my agenda for Europe, Political guidelines for the next European Commission 2019-2024, by candidate for President of the European Commission Ursula von der Leyen. European Commission; July 2019.

[4] EC, the European Green Deal, COM. 640 final, communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. 2019. https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf.

[5] EC 2013. Green paper, A 2030 framework for climate and energy policies. 169 final. COM; 2013 [FIN:en:PDF], https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0169.

[6] UNFCCC. Adoption of the Paris agreement. Proposal by the president. Paris climate change conference - november 2015. COP 21, 21932(December). 2015. p. 32. FCCC/CP/2015/L.9/Rev.1 WeatherShift 2020, https://www.weathershift.com/.

[7] Regulation. The European parliament and of the council of 11 december 2018 on the governance of the energy union and climate action (EU). 2018/1999 of. ENG&toc=OJ:L:2018:328:FULL, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0001.01.

[8] EC. Commission Staff Working Document, Good practice in energy efficiency, accompanying the document: energy efficiency for a sustainable, safer and more competitive Europe (Communication from the Commission to the. European Parliament and the Council; 2017. 27 April 2017.

[9] D'Agostino D. Assessment of the progress towards the establishment of definitions of nearly zero energy buildings (NZEBs) in European member states. J. Build. Eng. 2015. https://doi.org/10.1016/j.jobe.2015.

[10] D'Agostino D, Mazzarella L. What is a Nearly zero energy building? Overview, implementation and comparison of definitions. Journal of Building Engineering 2019;21:200–12. https://doi.org/10.1016/j.jobe.2018.10.019.

[11] D'Agostino D, Mazzarella L. Data on energy consumption and Nearly zero energy buildings (NZEBs) in Europe, Data in Brief. ISSN 2018:23523409. https://doi.org/10.1016/j.dib.2018.11.094.

[12] Buso T, Becchio C, Corgnati SP. NZEB, cost- and comfort-optimal retrofit solutions for an Italian Reference Hotel. Energy Procedia 2017;140:217–30. https://doi.org/10.1016/J.EGYPRO.2017.11.137.

[13] Cabeza L, Chàfer M. Technological options and strategies towards zero energy buildings contributing to climate change mitigation: a systematic review. Energy Build 2020;219:110009.

[14] Feng W, Zhang Q, Ji H, Wang R, Zhou N, Ye Q, Hao B, Li Y, Luo D, Lau SSY. A review of net zero energy buildings in hot and humid climates: experience learned from 34 case study buildings. Renew Sustain Energy Rev 2019;114:109303. October 2019.

[15] Zacà I, Congedo P, D'Agostino D, Baglivo C. Data of cost-optimality and technical solutions for high energy performance buildings in warm climate. Data in Brief 2015. https://doi.org/10.1016/j.dib.2015.05.015.

[16] Ashrafian T, Yilmaz AZ, Corgnati SP, Moazzen N. Methodology to define cost-optimal level of architectural measures for energy efficient retrofits of existing detached residential buildings in Turkey. Energy Build 2016;120:58–77. https://doi.org/10.1016/J.ENBUILD.2016.03.074.

[17] Becchio C, Ferrando DG, Fregonara E, Milani N, Quercia C, Serra V. The cost optimal methodology for evaluating the energy retrofit of an ex-industrial building in turin. Energy Procedia 2015;78:1039–44. https://doi.org/10.1016/J.EGYPRO.2015.11.057.

[18] Corgnati SP, Fabrizio E, Filippi M, Monetti V. Reference buildings for cost optimal analysis: method of definition and application. Appl Energy 2013;102:983–93. https://doi.org/10.1016/J.APENERGY.2012.06.001.

[19] Baglivo C, Congedo PM, D'Agostino D, Zacà I. Cost-optimal analysis and technical comparison between standard and high efficient mono-residential buildings in a warm climate. Energy 2015;831:560–75.

[20] Corrado V, Ballarini I, Paduos S. Assessment of cost-optimal energy performance requirements for the Italian residential building stock. Energy Procedia 2014;45:443–52. https://doi.org/10.1016/J.EGYPRO.2014.01.048.

[21] D'Agostino, D., Cuniberti, B., Maschio, I., Criteria and structure of a harmonised data collection for NZEBs retrofit buildings in Europe, Energy Procedia140, pp. 170-181. ISSN 18766102, DOI 10.1016/j.egypro.2017.11.133.

[22] D'Agostino D, Tsemekidi Tzeiranaki S, Zangheri P, Bertoldi P, Assessing Nearly Zero Energy Buildings (NZEBs) development in Europe, Energy Strategy Reviews, https://doi.org/10.1016/j.esr.2021.100680.

[23] EC. Guidelines accompanying commission delegated regulation (EU) No 244/2012 of 16 january 2012 supplementing directive 2010/31/EU of the European parliament and of the council. Official Journal of the European Union; 2012.

[24] D'Agostino D, Parker D. A framework for the cost-optimal design of nearly zero energy buildings (NZEBs) in representative climates across Europe. Energy 2018;149:814–29.

[25] D'Agostino D, Parker D. Data on cost-optimal nearly zero energy buildings (NZEBs) across Europe. Data Brief. 2018. https://doi.org/10.1016/j.dib.2018.02.038.

[26] EC A. Renovation Wave for Europe - greening our buildings, creating jobs, improving, COM. 2020. p. 662. final, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662.

[27] Santamouris M. Innovating to zero the building sector in Europe: minimizing the energy consumption, eradication of the energy poverty and mitigating the local climate change. Sol Energy 2016;128:61–94. https://doi.org/10.1016/j.solener.2016.01.021.

[28] EC. Regulation of the European Parliament and of the Council establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law), 2020/0036 (COD). COM; 2020. p. 80 [final].

[29] Robert A, Kummert M. Designing net zero energy buildings for the future climate, not for the past. Build Environ 2012;55:150–8.

[30] Solomon S. Climate change 2007: the physical science basis. Cambridge University Press; 2007.

[31] Guan L. Preparation of future weather data to study the impact of climatechange on buildings. Build Environ 2009;44:793–800.

[32] Gaterell MR, McEvoy ME. The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. Energy Build 2005;37:982–95.

[33] D'Agostino D, Parker D, Melià P. Environmental and economic data on energy efficiency measures for residential buildings. Data in Brief 2020;28(15 October 2020):104905. https://doi.org/10.1016/j.dib.2019.104905.

[34] Conti S, Meli P, Mellini G, Solimini R, Toccaceli V, Vichi M, Beltrano C, Perini L. Epidemiologic study of mortality during the summer 2003 heat wave in Italy. Environ Res 2005;98(3):390–9.

[35] de Dear R. Adapting buildings to a changing climate: but what about the occupants? Build Res Inf 2006;34:78–81.

[36] Bot K, Ramos Nuno MM, Almeida RMSF, Pereira PF, Monteiro C. Energy performance of buildings with on-site energy generation and storage – an integrated assessment using dynamic simulation. J. Build. Eng. 2019;24:100769.

[37] Roberts M, Allen S, Coley D. Life cycle assessment in the building design process – a systematic literature review. Build Environ 2020;185:107274. https://doi.org/10.1016/j.buildenv.2020.107274.

[38] Ferrara M, Fabrizio E, Virgone J, Filippi M. A simulation based optimization method for cost-optimal analysis. Energy Build 2014. https://doi.org/10.1016/j.enbuild.2014.08.031. 2014.

[39] Österbring M, Mata É, Thuvander L, Mangold M, Johnsson F, Wallbaum H. A differentiated description of building-stocks for a georeferenced urban bottom-up building-stock model. Energy Build 2016;120:78–84. https://doi.org/10.1016/j.enbuild.2016.03.060.

[40] Ganesh HS, Seo K, Fritz HE, Edgar TF, Novoselac A, Baldea M. Indoor air quality and energy management in buildings using combined moving horizon estimation and model predictive control. Journal of Building Engineering 2021;33:101552. https://doi.org/10.1016/j.jobe.2020.101552. January 2021.

[41] Jeong J, Hong T, Ji C, Kim J, Lee M, Jeong K, Koo C. Development of a prediction model for the cost saving potentials in implementing the building energy efficiency rating certification. Appl Energy 2007;189:257–70. https://doi.org/10.1016/j.apenergy.2016.12.024.

[42] Nägeli C, Jakob M, Catenazzi G, Ostermeyer Y. Policies to decarbonize the Swiss residential building stock: an agent-based building stock modeling assessment. Energy Pol 2020;146:111814. https://doi.org/10.1016/j.enpol.2020.111814. November 2020.

[43] Moazami A, Nik VM, Carlucci S, Geving S. Impacts of future weather data typology on building energy performance – investigating long-term patterns of climate change and extreme weather conditions. Appl Energy 2019;238:696–720.

[44] Erba S, Causone F, Armani R. The effect of weather datasets on building simulation outputs. Energy Procedia 2017;134:545–54.

[45] Reddy TA. Literature review on calibration of building energy simulation programs: uses, problems, procedures, uncertainty, and tools. Build Eng 2006;112(1):226–40.

[46] Raftery P, Keane M, O'Donnell J. Calibrating whole building energy models: an

evidence-based methodology. Energy Build 2011;43:2356–64.
[47] Firth SK, Lomas KJ, Wright AJ. Targeting household energy-efficiency measures using sensitivity analysis. Build Res Inf 2010;38(1):25–41.
[48] Eames M, Kershaw T, Coley D. The appropriate spatial resolution of future weather files for building simulation. J Building Perform Simulation 2012;5(6):347–58.
[49] de Wilde P. The implications of a changing climate for buildings. Build Environ 2012;55:1–7.
[50] Kapsomenakis J, Kolokotsa D, Nikolaou T, Santamouris M, Zerefos SC. Forty years increase of the air ambient temperature in Greece: the impact on buildings. Energy Convers Manag 2013;74:353–65.
[51] Coley DA. Energy and climate change: creating a sustainable future. Wiley-Blackwell; 2008. p. 331.
[52] Mc Michael AJ, Woodruff RE, Hales S. Climate change and human health: present and future risks. Lancet 2006;367:859–69.
[53] Mazzarella L, Pasini M. On time-alignment of weather data in Building Performance Simulation. In: CLIMA 2016 - proceedings of the 12th REHVA world congress; 2016.
[54] Mazzarella L, Pasini M. Pitfalls in weather data management strategies of Building Performance Simulation tools. BSA 2017. 2017.
[55] Cebecauer T, Suri M. Typical meteorological year data: SolarGIS approach. Energy Procedia 2015;69:1958–69.
[56] Crawley DB. Creating weather file for climate changes and urbanization impacts": proceedings of building simulation 2007. Beijing, China, IBPSA 2007;111:1075–82.
[57] Ferrara M, Fabrizio E. Cost optimal NZEBs in future climate scenarios. Lausanne, Switzerland: CISBAT 2017 International Conference; 2017. p. 6–8. September 2017.
[58] IPCC. In: Pachauri RK, Meyer IA, editors. Climate change 2014: synthesis report, 5th assessment report of the intergovernmental Panel on climate change. Geneva, Switzerland: IPCC; 2014.
[59] Belcher SE, Hacker JN, Powell DS. Constructing design weather data for future climates. Build Serv Eng Technol 2005;26(1):49–61.
[60] Herrera M, Natarajan S, Coley D. A review of current and future weather data for building simulation. University of Exeter; 2017. Journal of Building Services Engineering Research and Technology, 2 May 2017, http://hdl.handle.net/10871/27318.
[61] D'Agostino D, Parker D. "How will climate alter efficiency objectives? Simulated impact of using recent versus historic european weather data for the cost-optimal design of nearly zero energy buildings (nzebs)," CLIMA 2019. 2019. Bucharest, May, 2019, https://publications.energyresearch.ucf.edu/wp-content/uploads/2019/08/FSEC-PF-477-19.pdf.
[62] ASHRAE. International weather for energy calculations (IWEC and IWEC2 weather files) users manual and CD-ROM. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers; 2001.
[63] Build Eng 2006;112(1):226–40.
[64] Huang YJ, Crawley DB. Does it matter which weather data you use in energy simulations? DOE-2 User News 1997;18:2–12.
[65] Crawley DB. Which weather data should you use for energy simulations of commercial buildings? Build Eng 1998;104:498–515. Pt. 2. Atlanta: ASHRAE.
[66] Crawley DB, Lawrie LK. Should I care how old my climate data is? Glasgow, UK: " CIBSE ASHRAE Technical Symposium; 2020. p. 16–7. April 2020.
[67] Huld T, Paietta E, Zangheri P, Pinedo Pascua I. Assembling typical meteorological year data sets for building energy performance using reanalysis and satellite based data. Atmosphere 2018;9:53.
[68] Schwalm CR, Spencer G, Duffy PB. RCP8.5 tracks cumulative CO2 emissions. Proc Natl Acad Sci Unit States Am 2020. https://doi.org/10.1073/pnas.2007117117.
[69] Cai M, Murtazashvili I, Brick Murtazashvili J, Salahodjaev R. Patience and climate change mitigation: global evidence. Environ Res 2020;186:109552.
[70] Boermans T, Hermelink A, Schimschar S, Groezinger J, Offerman M, Thomsen KE, Rose J, Aggerholm S. Principles for nearly zero energy buildings. Brussels: ECOFYS, and the Danish Buildings Research Institute; 2011.
[71] Ballarini I, Cognati SP, Corrado V. Use of reference buildings to assess the energy saving potentials of the residential building stock: the experience of TABULA project. Energy Pol 2014;68:273–84.
[72] EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007.
[73] D'Agostino D, Parker D, Melià P. A multi-criteria decision making approach for the selection of efficient technologies in new residential buildings. Energy strategy reviews 2019. https://doi.org/10.1016/j.esr.2019.100412 [online)].
[74] Burch J, Christensen C. "Towards development of an algorithm to predict mains water temperature," NREL, proceedings of the 2007 American solar energy society. Cleveland, OH: ASES) Annual Conference; 2007.
[75] Bacci P, Maugeri M. The urban heat island of Milan. Il Nuovo Cimento C 1992;15:417–24. https://doi.org/10.1007/BF02511742.
[76] Dacquay C, Holländer HM, Kavgic M, Maghoul P, Liu H, Fujii H. Evaluation of an integrated sewage pipe with ground heat exchanger for long-term efficiency estimation. Geothermics 2020;86:101796. https://doi.org/10.1016/j.geothermics.2019.101796. July 2020.
[77] Christensen C, Horowitz S, Givler T, Barker G, Courney A. BEopt: software for identifying optimal building designs on the path to zero net energy. NREL/CP-550-3733. Golden, CO: National Renewable Energy Laboratory; 2005.
[78] Agudelo-Vera C, Avvedimento S, Boxall J, Creaco E, de Kater H, Di Nardo A, Djukic A, Douterelo I, Fish K, Iglesias Rey P, et al. Drinking water temperature around the globe: understanding, policies, challenges and opportunities. Water 2020;12:1049.
[79] Troup L, Fannon D. "Morphing climate data to simulate building energy consumption," ASHRAE and IBPSA-USA SimBuld 2016 building performance modeling conference. 2016. Salt Lake City, UT, August 8-12, 2016.
[80] Baniasadi A, Habibi D, Al-Saedi W, Masoum MAS, Das Choton K, Mousavi N. Optimal sizing design and operation of electrical and thermal energy storage systems in smart buildings. Journal of Energy Storage 2020;28:101186. https://doi.org/10.1016/j.est.2019.101186.
[81] McCoy DTR, Eastman DL, Hartmann WR. The change in low cloud cover in a warmed climate inferred from AIRS, MODIS, and ERA-interim. J Clim 2017;30:3609–20.
[82] TRNSYS, TRNSYS 18 Reference Manual. Solar energy laboratory. University of Wisconsin-Madison; 2020.
[83] Boeckl B, Kienberger T. Sizing of PV storage systems for different household types. Journal of Energy Storage 2019;24:100763. https://doi.org/10.1016/j.est.2019.100763.
[84] Torcellini P, Houssainy S, Pless S, Livingood W, Polly B. "The future of zero energy buildings: produce, respond, regenerate," proceedings of the 2020 conference of energy efficiency in buildings, American council for an energy efficient economy, NREL/CP-5500-77415. Golden, CO: National Renewable Energy Laboratory; August 2020.
[85] D'Agostino D, Cuniberti B, Bertoldi P. Data on European non-residential buildings. Data in Brief 2017:759–62. https://doi.org/10.1016/j.dib.2017.08.043. 2352-3409.
[86] D'Agostino D, Zacà I, Baglivo C, Congedo PM. Economic and thermal evaluation of different uses of an existing structure in a warm climate. Energies 2017;10(5):658. https://doi.org/10.3390/en10050658.
[87] Congedo PM, Baglivo C, Zacà I, D'Agostino D. Data in Brief 2015;5:502–5. https://doi.org/10.1016/j.dib.2015.09.041.