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Resilience to the climate change of nearly zero energy-building designed according to the EPBD recast: Monitoring, calibrated energy models and perspective simulations of a Mediterranean nZEB living lab

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ABSTRACT

The paper is focused on the evaluation of how the climate changes can influence the performance of buildings designed to be nearly zero energy (nZEB) and on the evaluation of the resilience in term of energy balance. A real case study is used; it is named BNZEB, a single-storey dwelling built in Benevento (South Italy, Mediterranean climate). With five-years monitored meteorological data, both a short-term and medium-term analysis is developed; the first one consists in the evaluation of the energy behavior compared to the first operating year. Then, the energy performance is evaluated considering the medium-term climate projections generated using the CCWorldWeatherGen tool.

This analysis, with reference to the case study, suggests to designers and researchers that, in a typical Mediterranean climate, the reduction of the heating demand could compensate the increment in the cooling request. In the worst climatic scenario, the net primary energy could change from 25.4 kWh/m^2 year (first year of life, 2017) to 19.5 kWh/m^2 year (projection to 2050) with a rate of self-consumption of 85% (80% for 2017).

However, a critical point is the operating period of the cooling system. Indeed, an indoor overheating problem could occur during the spring with operative temperature higher than 30 °C; this indicates that in future, the occupants will require higher number of operating hours with most frequent switch off. This could change the results of the energy balance, reducing, for instance, the imbalance between production and consumption that currently occurs in the intermediate periods.

1. Introduction

Climate change is the key issue of present and future days. Many research report and experts describe climate change as the leading human and environmental problem of the 21st century [1]. Building energy consumptions are greatly vulnerable to climate change due to the dependency from external forcing of heating and cooling energy demands. However, due to the large uncertainties in the assessment of climate changes, it was recognized [2] the importance of assessing the impacts at local scale, and the need for adaptation and mitigation. This topic is addressed under several point of views: the prevision of the evolution of the energy demand for the building stock, the methodologies for simulating the climate changes and the effect of possible refurbishment actions on the existing buildings. About these topics a brief review is proposed.

Considering the regions in southern Chile and two future climatic scenarios, RCP2.6 and RCP8.5, according to the 5th Assessment Report of IPCC [3], Verichev et al. [4] found that the heating energy consumption of a single-family house will decrease by 13% and 27% on average for the RCP2.6 and RCP8.5 scenarios, respectively. Yang et al. [5], for the European residential building stocks, suggested that there will be larger needs for cooling buildings in the future and less heating demand; discomfort hours will increase in cities within cooling-dominated zones. In four Argentinean cities [6], the annual energy uses between the baseline period (1961–1990) and 2080 are predicted to range from −25% to 8% for conventional houses. The energy for the heating and cooling needs will be 23%–59% lower and 360–790% higher. In Italy [7], the results showed a decrease in the heating energy demand up to 30.9% and an increase in the cooling energy demand, up to

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Nomenclature

AP Atmosferic pressure
apr-2017 Distribution of hourly values in April – 2017
apr-RCP4.5-90th Distribution of hourly values in April – RCP4.5–90
apr-RCP8.5-90th Distribution of hourly values in April – RCP8.5–90
BNZEB Nearly zero energy building of Benevento
CDF Cumulative distributionfunctions
δ_k absolute difference between long-term CDF and short-term CDF
DBT Dry bulb temperature
DBT_{avg} Average annual dry bulb temperature
DBTref Hourly values of DBT on the typical day of May – 2017
DBT4.5–90 Hourly values of DBT on the typical day of May – RCP4.5–90
DBT8.5–90 Hourly values of DBT on the typical day of May – RCP4.5–90
$Dev\_DBT_{C,cond}$ Differences in the average DBT calculated in the cooling air conditioning hours (°C)
$Dev\_DBT_{H,cond}$ Differences in the average DBT calculated in the heating air conditioning hours (°C)
Dev_DBT_{ref} Difference in the average monthly dry bulb temperature (°C)
Dev_GHI_{ref} Difference in the average monthly global horizontal radiation (°C)
DHI Diffuse horizontal radiation
DNI Direct normal radiation
$\Delta E_{el,C}$ Percentage difference in energy consumption for cooling [%]
$\Delta E_{el,H}$ Percentage difference in energy consumption for heating [%]
$E_{el,tot}$ Total electricity consumption (kWh_{el}/year)
Eel,C Energy consumption for cooling (kWh_{el})
Eel,H Energy consumption for heating (kWh_{el})
Ep Net primary energy consumption (kWh/m^2 year)
EXP% Percentage of exported electricity respect to the renewable production (%)
FS Finkelstein-Schafer (Sandia method)
GEN Electricity generation from photovoltaic
GHI Global horizontal radiation
I_{ES} Energy supply index
k ranked order number (Sandia method)
m number of days during the month (Sandia method)
may-2017 Distribution of hourly values in May – 2017
may-RCP4.5-90th Distribution of hourly values in May – RCP4.5–90
may-RCP8.5-90th Distribution of hourly values in May – RCP8.5–90
RCP Representative concentration paths
RCP4.5-10th Future projection obtained by Weathershift™ – RCP 4.5 (10 th percentile)
RCP4.5-50th Future projection obtained by Weathershift™ – RCP 4.5 (50 th percentile)
RCP4.5-90th Future projection obtained by Weathershift™ – RCP 4.5 (90 th percentile)
RCP8.5-10th Future projection obtained by Weathershift™ – RCP 4.5 (10 th percentile)
RCP8.5-50th Future projection obtained by Weathershift™ – RCP 4.5 (50 th percentile)
RCP8.5-90th Future projection obtained by Weathershift™ – RCP 4.5 (90 th percentile)
RH Relative Humidity
Self-consumption Electricity self-consumption of building – (kWhel)
S/V Surface to Volume ratio, (m^{-1})
$T_{operative\ ref}$ Zone Operative Temperature in the reference year (2017)
$T_{operative\ RCP4.5\text{-}90}$ Zone Operative Temperature in RCP4.5–90
$T_{operative\ RCP8.5\text{-}90}$ Zone Operative Temperature in RCP8.5–90
TMY Typical meteorological year
W_D Wind direction
Ws Wind speed
WS Weighted sum

255.1% and a significant increase of the overheating risk up to 155%. These data testify that the scientific research is well focused in the evaluation of the energy demand under climate changes with also a discrete knowledge on the possible sensitivity analysis.

Some other papers address the issue of the methodology with which the impact of climate change on building energy performance can be studied. For instance, the comparison between two methods (Morphing and typical meteorological year of future climate) [8] indicated that morphing methods based on different baseline climates, low-grid resolution and/or outdated climate projections lead to simulation average differences of 16%-20%. Zou et al. [9] developed a novel multi-objective framework by using simulation-based surrogate models under the future weather conditions that are determined by morphing the typical meteorological year data. Hosseini et al. [10] studied a hybrid classification-regression model to downscale the bias-corrected general circulation model data to generate future weather data at an hourly resolution for building energy simulation. Bamdad et al. [11] have proposed a new simulation-based optimization method with which they demonstrated that the optimization studies under future climate conditions can lead to different optimal solutions for offices. Yassaghy et al. [12] generated a probabilistic model that captures future building energy performance trends for regions with limited future hourly weather files.

Some other researchers are focused on the impact of refurbishment or restoration solutions under climate changes. It was demonstrated that for each time period and in each geographical area in the Los Ríos region of Chile, the optimal thermal transmittance value of the external walls is different. For instance, for the housing stock, the values pass from 0.49 ± 0.11 W/m^2 K (year 2006) to 0.78 ± 0.14 W/m^2 K for the period 2035–2050 [13]. Results for Hong Kong show that solar protection strategies are still the highly sensitive strategies for building energy performance and the effectiveness of external windows' airtightness is expected to increase up to 329% by the end of this century [14]. For the residential buildings in the south Italy, De Masi et al [15] have found that the most adequate solutions for the refurbishment are the adoption of cool materials and of the external shadings since the cooling demand could be reduced until –33% in some scenarios (e.g. RCP 4.5). For all investigated cities by Nurlybekova [16] a phase change material with a transition temperature between 28 °C and 30 °C allows reducing the thermal cooling demand up to 37% for current and future climate scenarios. Moreover, the mixed mode ventilation strategy has moderate to significant cooling energy saving potentials in different Australian climates, 15% under the future climate conditions [17]. Munoz Gonzalez et al. [18] underlined the fact that the climate change will affect the indoor temperature of historic buildings, impacting the preservation of artworks and the thermal comfort of users, and possibly leading to increased energy consumption. Coelho et al. [19], by means of an hygrothermal model of a historic building, underlined the positive potential of insulation measures on the building's energy consumption (between 13% and 32%).

Otherwise, there is a lack of studies about the impact of future weather data on existing nearly zero energy building (nZEB). Two recent researchers can be cited both based on simulation results. D'agostino et al. [20] showed that for this type of buildings, the heating will decrease by 38%–57%, while cooling will increase by +99%–380% depending on location. For this reason, efficiency measures to reduce cooling needs and overheating will be favored (e.g. roof insulation, window type, solar shading, envelope finishes). Ferrara and Fabrizio [21] found that there are some cost-optimal solutions, with the adoption of heat pump technology, resilient to climate variation.

Starting from this state of fact, the proposed paper, starting from a real case study and monitored data, wants to answer the question: will a nearly zero energy building classified according to the current standards also be resilient to the climate changes?

More in detail, with five-years monitored meteorological data, both a short-term and medium-term analysis is developed for a real nZEB built in the South Italy. The first type of evaluation consists in a sensitivity analysis on the performance of the building respect to the first operating year and respect to the prevision of its behavior with climatic data of the design year. The aim is to evaluate if it is consistent, in the short-term, the variation in the total electricity consumption, in the heating and cooling demands. It is also evaluated the contribution of the renewable energy production in achieving the nZEB target. Moreover, the medium-term analysis is based on the comparison between the energy needs and the energy balance under the climate projections for 2050 and the reference year. This analysis is developed also for the spring season but in term of indoor parameters. Indeed, it is verified if the house could be subjected to overheating phenomenon due to increase of external temperature and the main implications are discussed.

2. Case study

The BNZEB (Fig. 1), selected as case study, is the outcome of an Italian project named "SMARTCASE" (code PON03PE_00093_1), promoted under the umbrella of the European Regional Development Found. The designing phase and the setup of the building – HVAC system were described in detail by Ascione et al. in some previous papers [22,23]. Therefore, only a brief global description is reported in this section, with the aim to help the readers.

It is located in a flat area close to the historic center of the city of Benevento. The site has a typical Mediterranean climate, with warm to hot, dry summers and mild to cool, wet winters. It is inside the "Csa" class according to Koppen classification [24]. Table 1 shows the site characterization according to UNI 10349:2016 [25] and National Decree n○ 412: 1993 [26].

As reported in Fig. 2, the building net conditioned area is about 70 m^2, the window/wall ratio is 22.5% and the shape factor (surface-to-volume ratio) is equal to 1.03 m^{-1}.

The BNZEB is, at the same time, a research laboratory, suitable for testing and measuring energy, and indoor and outdoor conditions, but also a dwelling in which a comfortable life is allowed. In addition, as it has a small size, the BNZEB can be considered representative of a new design method aimed at reducing, as much as possible, the adoption of active systems and covering all of its energy needs entirely with available on-site renewable sources. The size does not influence the type of proposed analysis, which is contextualized to the type of occupation and external conditions.

The layout of the BNZEB is almost a square, with the main entrance close to the living room, that has a large window facing on southwest exposure, appropriately shaded, a kitchen with openings to the north-west and south-west exposures and two bedrooms with openings facing south and south-east. The south-facing windows, along the main section of the house, are fully shaded in the summer by an external porch.

The building envelope is made of cross laminated wood with two layers of fiber-wood insulation with different density; the windows are double-glazed system with argon-filled cavities and low-e coating and PVC frames. The measured thermal transmittance is equal to 0.19 W/m^2 K and 0.22 W/m^2 K, respectively, for the wall and the roof. The thermal transmittance for the window glass is 1.5 W/m^2 K. An aerothermal heat pump can provide heating, cooling, domestic hot water and mechanical ventilation, with an internal filter and an active thermodynamic heat recovery. This compact system has a maximum heat capacity of 3.18 kW and a maximum cooling capacity of 2.14 kW. In order to provide a back-up system, a DX multi-split system is also installed. This technology is composed by one outdoor and two indoor units, with a global heating capacity of 9.6 kW and a cooling capacity of 8.0 kW. Finally, a pre-treatment section of the outdoor ventilation air has been also added to the base configuration. In detail, a water-

Fig. 1. External view of *BNZEB*.

Table 1
Site characterization of Benevento.

Benevento (ITA)		Winter design day		Summer design day	
Latitude	41°7′55″	Outdoor temperature	−2 °C	Outdoor temperature	32 °C
Longitude	14°46′40″				
Elevation	135 m				
Climate zone	C	Outdoor relative humidity	48.8%	Outdoor relative humidity	50%
Heating Degrees-Day (baseline, 20 °C)	1316	Wind speed	4.4 m/s	Daily temperature range	11 °C

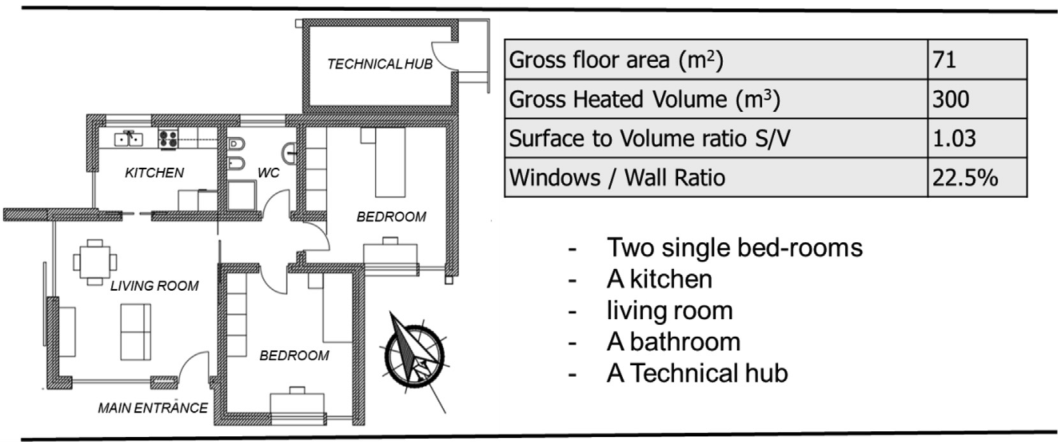

Fig. 2. *BNZEB* plan and features.

to-air heat exchanger linked to geothermal probes (at a depth of 2 m, with a total linear length of 100 m) may pre-cool the ventilation air during the summer period and pre-heat it during the winter, before the aerothermal heat pump. Moreover, there is a solar collector with an area equal to 2.16 m^2; it is connected to a thermal storage tank with a net volumetric capacity of 196 l. A further implemented renewable technology consists in the PV system, with a total capacity of 5.3 kWp. It is installed on the building roof with a title angle of 5° and facing south. For maximizing the on-site use, a lithium battery for the electricity storage with a nominal capacity of 6.5 kWh is also installed.

For this building a numerical simulation model is already available; it is defined according to the monitored data for the building envelope and the plants and it has been described in [22]. The geometrical model has been defined though the DesignBuilder v.6.0 interface [27] and then the heating, ventilation and air-conditioning system has been created with EnergyPlus [28].

The building model was calibrated and validated by means of the comparison of the monitored consumptions and renewable production, and of indoor temperature and relative humidity with the output of simulation for which a proper weather file has been built. In this case, the data measured on the roof of the BNZEB were used for defining a weather file representative of the period of monitoring for which the comparison was developed. As proposed in [22], the values of calibration indicators, according to M&V Guidelines [29] approach, suggest that the energy model can be considered well-representing the real behavior. Indeed, for instance, the mean bias errors (MBE) in case of electricity consumptions is −2.03% and in case of electricity production it is −3.6% with the root mean squared error, CV(RMSE), near 29%. When hourly data are considered, the threshold values are ±30% for CV(RMSE) and ±10% for MBE.

The calibrated model was modified for the following analysis. More in detail, realistic schedules for the occupation and equipment were defined considering that two university students live inside the BNZEB. Thus, it was considered that from Monday to Friday the student leaves the residence at 9:00 am for attending university courses or for studying with their colleagues in other place. They come back for lunch at around 13:00 for one hour and they get back definitively inside their room between 17:00 and 18:00. During the weekend they stay usually at home and they go out to dinner until the night.

3. Method

Fig. 3 summarizes the methodological approach adopted in this paper and a rendering of the numerical model of BNZEB is also shown.

The starting point is the definition of the weather files (EPW format) for Benevento (south Italy) for each year for which the real monitored climate data are available and thus from 2016 to 2020. Considering that EnergyPlus is typically used for simulations with a typical meteorological year in EPW format, the typical meteorological year (TMY) created for Benevento according to the Sandia Method [30] and based on the dataset available from 2016 to 2020 was also created. From this last weather file the future climate projections were generated.

After the definition of the weather files, the operational phase of the nearly zero energy building is evaluated in the short term (2016–2020) and in the medium term (2050 s) scenario. In both cases, 2017 is the real meteorological year taken as reference (RY) since it is the first year of useful life of the case study and for which all data of monitoring are available in term of energy consumptions and indoor variables. Weather data set of 2016 was also considered since this is the real meteorological year used in the design phase (design year - DY) of the BNZEB; indeed, the simulation of potential performance with these data influenced the choices in terms of building envelope and systems. Instead, the availability of future climate files allows to study the behavior of the designed solutions when the external conditions changes compared with the moment during which the design was realized. This analysis can suggest to designers and researchers the aspect to

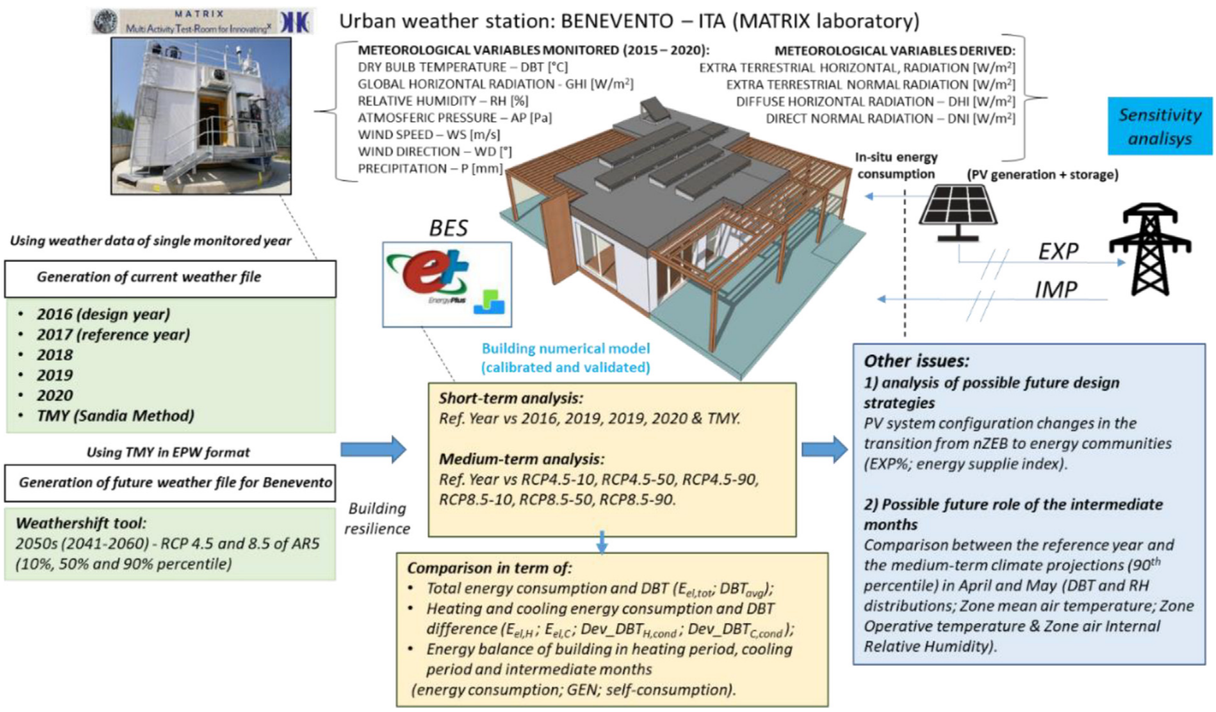

Fig. 3. Methodological approach scheme.

be focused for improving the building resilience in a typical Mediterranean climate.

In the short-term analysis, the differences with respect to the reference year (RY) are first evaluated in terms of average monthly dry bulb temperature (Dev_DBT_{ref}) and average monthly global horizontal radiation (Dev_GHI_{ref}). Then, the differences in the building operational phase, compared to the reference year and to design year, are assessed both in terms of energy consumption and energy balance. In detail, each analysis is divided into three steps. Firstly, the comparison is made for the total electricity consumption ($E_{el,tot}$). Then, the energy consumption for heating ($E_{el,H}$) and cooling ($E_{el,C}$) are separately evaluated. The third step consists in the analysis of the energy balance of the building in order to verify the contribution of the renewable energy production (GEN) in achieving the nearly zero target. In this regard, according to Italian legislation [31] can be assigned when the building reaches the best possible labelling for its energy performance and if simultaneously the energy needs for domestic hot water is covered for at least 50% by in-situ renewable energetic sources and, analogously, renewable sources cover at least the 50% of the sum of the building energy needs. For verifying the energy balance, the primary energy was compared with the consumption of electricity in-situ produced. In the calculation of the primary energy a conversion factor of 0.554 is considered for the electricity [32]. Furthermore, the paper offers interesting insights into the current transition from nearly zero energy buildings to plus energy buildings (PEB) and to the future goal of energy communities or plus energy districts (PEDs). As reported in [33], these scenarios favor the concept of *PROSUMERS* (PRO-ducers and con-SUMERS of energy). In this regard, the choice of whether or not to provide for a storage system can play a fundamental role. This aspect is also discussed by means of the analysis of the percentage change in exported electricity (EXP%) and by introducing the following Energy supply index (I_{ES}):

$$I_{ES} = \frac{N_{imp,h}}{N_{tot,h}} \tag{1}$$

where:

- $N_{imp,h}$ is the number of hours per year in which the building imports electricity from the electric grid;
- $N_{tot,h}$ is the total number of hours per year.

Finally, the comparison between the climate projections for 2050 and the reference year is proposed in term of energy consumption but also in term of indoor parameters. More in detail it is developed an analysis for the spring season and in particular for the months of April and May when the air-conditioning systems are usually turned off but an overheating phenomenon can be experimented in the houses. The effects of global warming could bring to include the aforementioned months in the cooling period in the future. Therefore, in April and May the climate projections were compared with the reference year in terms of DBT, and RH. Then, the trends of the Zone Mean Air Temperature and Zone Mean Air Relative Humidity were evaluated. Finally, a typical day was analyzed for worst-case scenarios in terms of Zone Operative Temperature and relative humidity.

4. Weather file definition

4.1. Current weather data

The construction of the weather file is based on meteorological data monitored in an urban station installed in the city center and in the test-room named MATRIX – Multi Activity Test-Room for Innovating^{X} (41°07′ 54.1″ N, 14°47′ 3.7″ E), owned by the Department of Engineering of the University of Sannio. MATRIX is an experimental laboratory for testing different solutions of building envelope under real weather conditions. The test-room was described in detail by Ascione et al. [34]. The recording of weather data is carried out by the central weather station placed on the roof, at a height of about 7.20 m from the ground level. This apparatus records the most important meteorological variables such as global solar radiation, outdoor air temperature and relative humidity, wind speed and wind direction, in addition to their pressure. For the measurement of amount of rain, it was installed a rain

Table 2
External sensors technical data.

Sensor	Unit	Type	Accuracy
Rain Gauge	mm/h	Cylindrical body of 400 cm^3	±2%
Global solar radiation	W/m^2	II class thermopile pyranometer	<10% day-1
Infrared solar radiation	W/m^2	Pyranometer	−300 ÷ 300 W/m^2 (5.5 ÷ 45 μm)
Wind speed	m/s	Ultrasonic anemometer	±2%
Wind direction	° N	Ultrasonic anemometer	±2° RMSE 1.0 m/s
Air temperature	°C	Pt100	±0.1%
Relative humidity	%	Capacitive transducer	± 1.5% RH at 15 ÷ 35 °C
Atmospheric pressure	hPa	Piezoresistive transducer	±0.5 hPa at 20 °C

gauge with capacity of 400 cm^3. Finally, in order to measure the global solar radiation and infrared solar radiation, five pyranometers and six pyrgeometers have been installed on all exposures, vertical and horizontal. The main characteristics of the sensors are shown in Table 2.

The following meteorological variables on an hourly basis are considered for the definition of the weather files:

- Dry bulb temperature – DBT [°C];
- Dew point temperature – DPT [°C];
- Global horizontal radiation – GHI [W/m^2];
- Relative humidity – RH [%];
- Atmospheric pressure – AP [Pa];
- Wind speed – w_S [m/s];
- Wind direction – w_D [°];
- Precipitation – P [mm].

In addition to the global horizontal radiation (GHI), its diffuse component (DHI) and the direct normal solar radiation (DNI) are needed. As described in previously study, a simplified method for calculating DHI and DNI from GHI is used [15].

4.2. Procedures for developing TMY

TMY methodologies is also considered for the construction of an EPW file for Benevento, starting from the meteorological data monitored from 2016 to 2020. The Sandia method procedure is proposed below:.

Step 1 - For each index and for each month of the calendar year, the long-term cumulative distribution function (CDF) and the short-term CDFs are calculated. The long-term CDF uses one month of the full set of years (2015–2020 in this study), while the short-term CDF uses data from one month of just one year. The CDF for each variable is calculated by:.

$$S_n(x) = \begin{cases} 0, x < x_{(1)} \\ \dfrac{k-0.5}{n}, \quad x_k \le x \le x_{(k+1)} \\ 1, x \ge x_{(n)} \end{cases} \tag{2}$$

where n is the total number of elements and k is the ranked order number (k = 1, 2, 3, …, n-1). Next, for the choice of each typical month, the difference between the short-term CDFs and the long-term CDF is calculated for each index using Finkelstein-Schafer statistics (FS):

$$FS = \frac{1}{m}\sum_{k=1}^{m}\delta_k \tag{3}$$

where m is the number of days during the month and δ_k is the absolute difference between long-term CDF and short-term (month under study) CDF at x_k.

The *FS* obtained for each single year of monitoring are multiplied by the corresponding weights, reported in Table 3, obtaining the weighted statistic (WS):

$$WS = \sum_{j=1}^{N_{index}} W_j(FS)_j \tag{4}$$

where W_j is the weight assigned to the j-th index.

Step 2 – From the lowest WS values, the 5 candidate months are identified for the choice of the typical month and are classified on the basis of their closeness to the long-term mean and median values of the WS.

Step 3 – The persistence of mean dry bulb temperature and daily global horizontal radiation are evaluated by determining the frequency and length of runs of consecutive days with values above and below fixed long-term percentiles. For mean daily dry bulb temperature, runs above the 67th percentile (consecutive warm days) and below the 33rd percentile (consecutive cool days) were determined. For global horizontal radiation, the runs below the 33rd percentile (consecutive low radiation days) were determined. The persistence criterion excludes the month with the longest run, the month with the most runs, and the month with zero runs. The persistence data are used to select from the five candidate months the month to be used in the TMY. The highest-ranked candidate month from Step 2 that meets the persistence criteria is used in the TMY.

Step 4 – The 12 selected months were concatenated to make a complete year and discontinuities at the month interfaces were smoothed for 6 h each side using curve fitting techniques.

4.3. Future weather data

For the definition of future weather data, *Weathershift* [35] tool is used starting from the typical meteorological year (TMY) built for Benevento. The weather generator performs a statistical downscaling based on the so called'morphing' methodology for climate change transformation of weather data, developed by Belcher, Hacker and Powell [36].

Weathershift provides for the application of the morphing method on the offsets of 14 GCM (out of a total of 40 models). In detail, the used models are relative to the phase 5 of the Coupled Model Intercomparison (CMIP5) project. Offsets are available for eight time periods, from the short term (2011–2030) to the long term (2081–2100), relative to the 1976–2005 baseline period and

Table 3
Weighting factors in TMY methods.

INDEX	TMY
Maximum dry bulb temperature	1/24
Minimum dry bulb temperature	1/24
Mean dry bulb temperature	2/24
Maximum dew point temperature	1/24
Minimum dew point temperature	1/24
Mean dew point temperature	2/24
Maximum wind speed	2/24
Mean wind speed	2/24
horizontal solar radiation	12/24

for the representative concentration paths (RCPs) 4.5 and 8.5. In particular, RCP 4.5 is an intermediate scenario (substantial reduction of emissions) while RCP 8.5 is a high emission scenario (business as usual). In general, the RCPs – originally RCP2.6, RCP4.5, RCP6, and RCP8.5 – are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m^2, respectively). The radiative forcing, as defined in is the measure of the influence that a factor has in altering the balance of energy entering and leaving the earth and atmospheric system. This index indicates the importance of the factor as potential climate change mechanism. The values of the radiative forcing refer to 1750, pre-industrial conditions. Moreover, as reported in [37], the four closest grid points of the model are considered for each location and the offsets are calculated by performing a bilinear interpolation. The use of multiple models allows generating a cumulative distribution function (CDF) for each variable using linear interpolation between the model values. Because the offset values for each model is linked with each other, a physically consistent relationship between the values of the variables is maintained. In this study, future climate projections are generated for the time period 2041–2060 (referred as 2050 s), for RCP 4.5 and RCP 8.5, and using the offsets on mean daily temperature change of the 10th, 50th and 90th percentiles. These six future projections within the study are indicated as RCP4.5–10, RCP4.5–50, RCP4.5–90 for the scenario RCP 4.5 and as RCP8.5–10, RCP8.5–50, RCP8.5–90 for RCP 8.5.

5. Weather data analysis

A preliminary analysis for the weather data of the real climatic years is proposed with the aim to underline the peculiarities of the external forcing of the available year. As reported in the methodological approach, 2017 is the reference year for the comparisons since this is the first operational year. In particular, Fig. 4 shows the differences in terms of average monthly dry bulb temperature compared to 2017 (Dev_DBT_{ref}); a positive value means that the temperature is increased. The trend of the differences indicates that also if only 5 years are considered, there are important differences in the monthly average values and thus the climate change is underway and sensible effects could be verified in the short term. Among the winter months, the biggest differences occur in January and it is approximately 4 °C both in 2016 and 2018. It is not possible to establish a trend line even if it can be considered an increase in temperatures in the winter months. However, there are exceptions. March was colder than 2017 with low variations for all considered scenarios. Considering the 2020, only during October the temperature is lower than the reference year.

The summer months have unexpected behavior. Indeed, the reference year is usually hotter than the available years, taking into consideration the average value. The extreme difference (−3.7 °C) occurs in May 2019 otherwise, for the same year, the average temperature in June is higher of around 0.6 °C. July is the month with the lowest differences meanwhile in September the average dry bulb temperatures are always higher than in 2017, with a maximum variation of about +2.3 °C in both 2019 and 2020.

As regard the typical meteorological year, TMY has 3 typical months coincident with 2017 (January, August and December) and in the other ones it is difficult to establish a trend since Dev_DBT_{ref} varies from +1.5 °C in September and −2.7 °C in June.

The same type of comparison is also proposed in terms of global horizontal radiation (Fig. 5). Among the winter months, the variations of the average GHI are never negative in January while the Dev_GHI_{ref} values are always negative in March and November. In March 2018, the maximum decrease of average monthly GHI with respect 2017 was observed, with Dev_GHI_{ref} equal to approximately −131 W/m^2. As with temperature, GHI levels are always lower in June compared to 2017. As regards the design year (2016), the mean GHI levels are always lower than those of 2017 in the months of the cooling season. Thus, it can be concluded that the first operational year was characterized by worst conditions in term of solar radiation and temperature mainly in the summer period than the designed one.

6. Results

6.1. Short term analysis

This study starts from the analysis of the operational phase of the case study in the years after its design and construction.

6.1.1. Energy consumption analysis

Fig. 6 shows the total electricity consumption of the case study and the annual average dry bulb temperature. The design year and the typical meteorological year are also included. In general, the electricity total request increases with the value of the average dry bulb temperature and the magnitude of variation of the energy consumptions has a non-linear correlation with the trend of

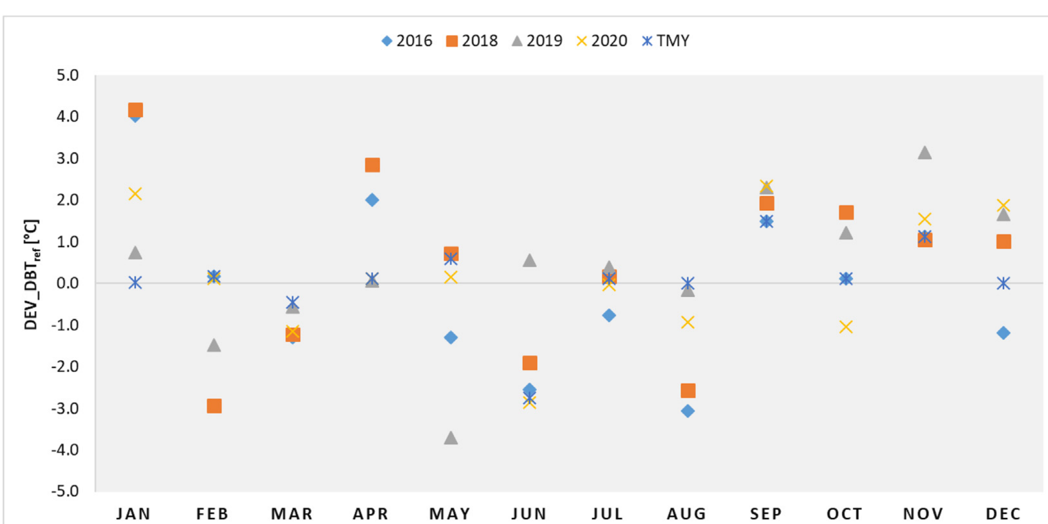

Fig. 4. Changes in monthly average DBT compared to the reference year.

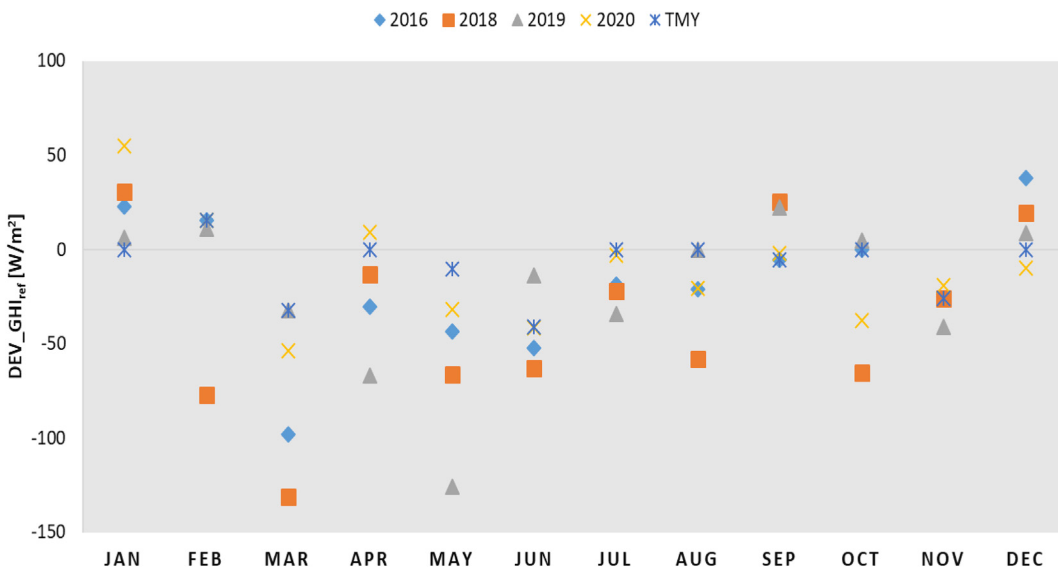

Fig. 5. Changes in monthly average GHI than reference year.

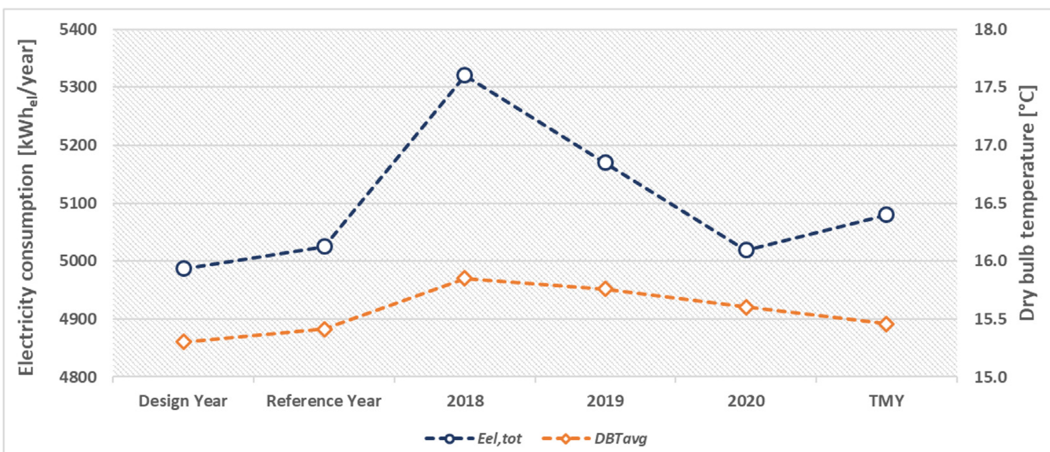

Fig. 6. Comparison of total energy consumptions and annual average DBT – short-term analysis.

DBT_{avg}. However, the annual mean temperature, calculated from hourly monitored values, can indicate what to expect in terms of the building's total energy consumption, for the examined period.

For instance, the values of DBT_{avg} in 2016 and 2017 are comparable and equal to 15.3 °C and 15.4 °C, as well as the $E_{el,tot}$ that differs of around +0.7% (considering as reference the design year). Instead, the increase of DBT_{avg} for 2018 is around 3.6% meanwhile the electricity increases of 6.7% that is the higher recorded variation. Another not predictable situation is the increase of around 2.0% for $E_{el,tot}$ with the lowest increase of temperature (+0.6%) during 2020. At the same time, in 2020 DBT_{avg} is equal to 15.6 °C and it is the year with the total electricity consumption closest to reference year (RY). Finally, the typical meteorological year (TMY) has an average temperature very close to the average value of DBT_{avg} of the reference year with an annual electricity consumption that increase of around 1.9% compared with the DY and of around 1.1% compared with the RY.

For understanding the behavior, the energy consumption for heating ($E_{el,H}$) and for cooling ($E_{el,C}$) are evaluated separately; indeed all other energy uses of the building (hot water, lighting, internal equipment, etc) are not influenced by the external conditions. At the same time, in this phase, the differences in the average dry bulb temperature in the hours in which summer and winter air conditioning is foreseen, $Dev\_DBT_{H,cond}$ and $Dev\_DBT_{C,cond}$ respectively, are taken into account.

In Fig. 7, these variables are reported; herein, $Dev\_DBT_{H,cond}$ and $Dev\_DBT_{C,cond}$, are calculated with respect to the design year. Considering the reference year, $Dev\_DBT_{H,cond}$ is −0.9 °C and $Dev\_DBT_{C,cond}$ is +2.1 °C, thus also if the building has been designed with less extreme summer conditions, the selected technologies assures comparable energy consumption with a variation only of +0.8%. The winter performance improves in the first operating year compared to the design conditions, since weather the mean dry bulb temperature is lower, the heating consumption is reduced of around 10.2%.

Starting from the reference year, also in the short period there is a progressive reduction in the heating demand also when the $Dev\_DBT_{H,cond}$ is positive. Indeed, with reference to 2017, the $Dev\_DBT_{H,cond}$ is −0.9 °C with a variation of the heating request of −9.3%. The higher reduction (−17.4%) is obtained with data of 2020, when $Dev\_DBT_{H,cond}$ was +0.8 °C. The cooling demand is not greatly influenced by the variation of $Dev\_DBT_{C,cond}$ that was always positive with a maximum increment (+2.7 °C) in 2019. During this year, the cooling demand is higher of 3.2%. The values of

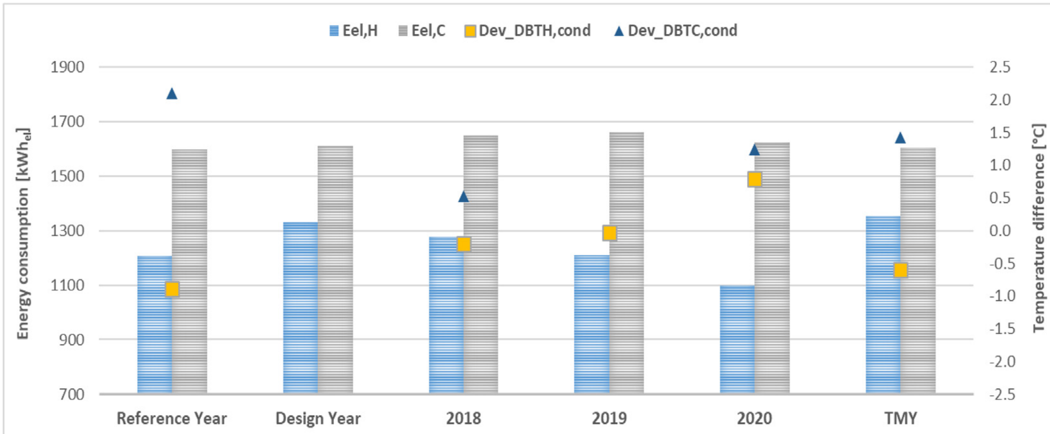

Fig. 7. Comparisons in the heating and cooling periods – Short term analysis.

cooling consumptions remain comparable in all considered years and this trend seems suggest that the design choices are suitable to balance the variation in the short term.

Considering the adoption of TMY, both $E_{el,H}$ and $E_{el,C}$ are comparable with that of the design year and thus it is representative of the operating conditions envisaged in the design phase.

6.1.2. Assessment of the building energy balance

After discussing the differences in the total electricity consumption with a short-term analysis, it is important to verify how the building energy balance varies due to the electricity generation from photovoltaics and whether the building it is always configured as a nearly zero energy. Fig. 8 shows the electricity consumption, the photovoltaic production (GEN) and the building self-consumption during the reference year, thus 2017. The values are divided considering the heating period, the cooling period and the intermediate months; in all cases, it is reported the variation compared to the values obtained for the design year, 2016.

First of all, it can be noted that the renewable production, is lower that the global electricity reduction only during the heating season also if the it is increased (+7%) compared to 2016. The self-consumption also decreases and this means that the major generation is distributed production takes place in hours when it is not necessary for consumption, or when the simultaneity between load and production is reduced. The electricity request during the summer is comparable meanwhile the renewable production increases compared to the design year and this helps to improve the energy balance because the extra-production is verified mainly during the afternoon and thus the self-consumption is higher of +4%. During the intermediate months, the unbalance between production and consumption increases compared with the design reference because there is a slightly reduction of consumptions, due to lower lighting needs meanwhile the PV-production increases and it is about triple of consumption.

Fig. 9 shows the seasonal energy balances for the other climatic years and also in this case the comparison with the design year is reported. The PV-production during the winter is usually lower of electricity request but during the last two years (Fig. 9b and c) these values are really comparable; this is due to a reduction of the electricity request compared to the design year and an increase of the production thanks to most favorable conditions mainly in terms of solar radiation. In both years the self-consumption, also if lower of the design year, is around 65% thus it is higher of the yearly threshold value required by the Italian normative for the nearly zero energy building. If the behavior is compared with the reference year, the consumptions in the wintertime are lower, (−3% for 2019 and −7% for 2020) but the PV-production is reduced (−6% for 2019 and −3% for 2020); instead the self-consumption is increased (+6%) thanks to the higher contemporaneity.

Considering the summer, the whole renewable production is always higher than the required electricity, also when this contribute is reduced compared to 2016 (Fig. 9a). When the building was simulated in the design phase (with weather data of monitored), it was obtained that around 89% of in-situ production could be used during the summer; this data is confirmed considering the operational phase since the incidence of self-production is around

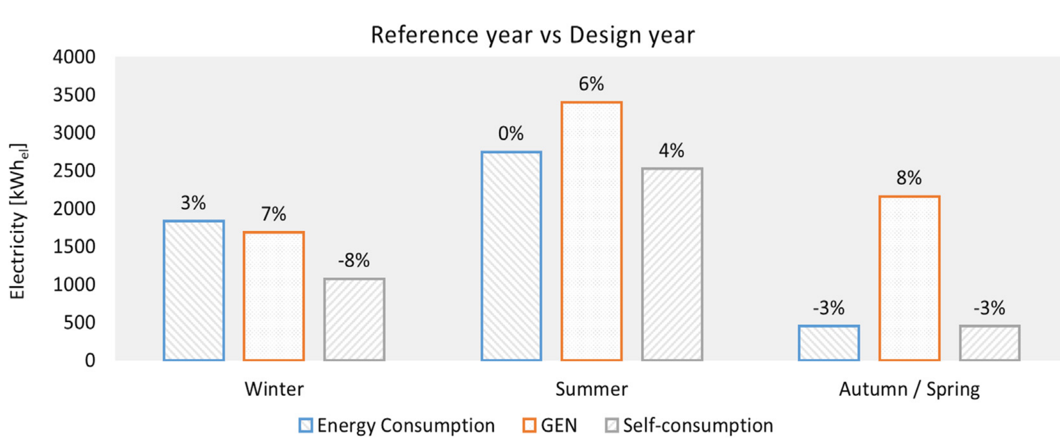

Fig. 8. 2017 vs 2016 – total energy consumption, PV generation and self-consumption.

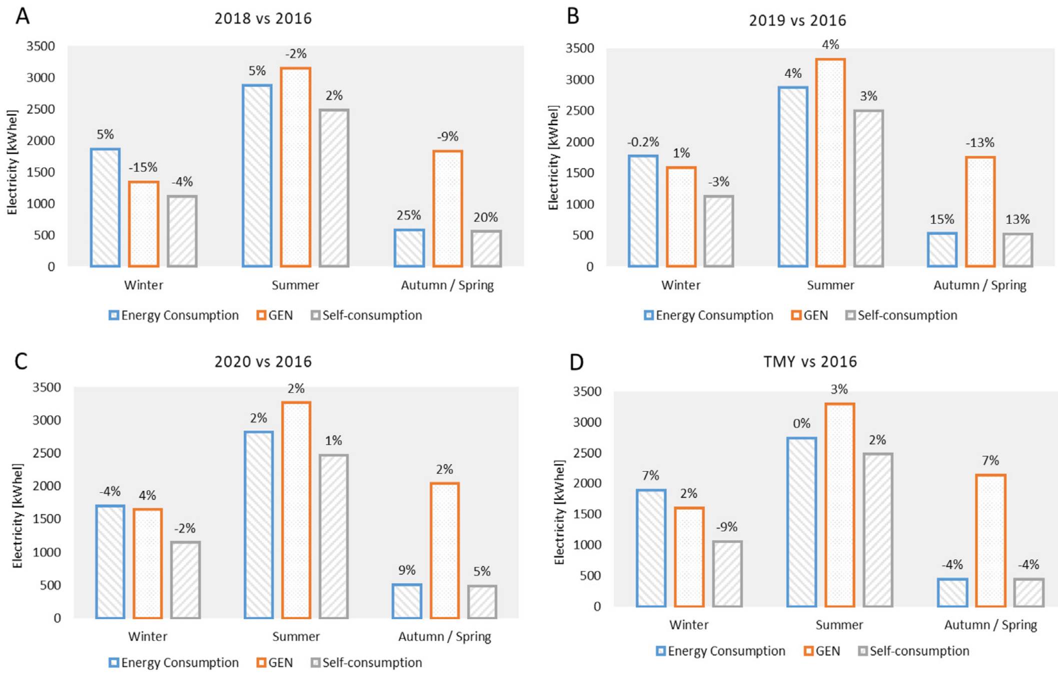

Fig. 9. Building energy balance assessment: a) 2018 vs DY; b) 2019 vs DY; c) 2020 vs DY; d) TMY vs DY.

87% in all three years. This result is important and confirms that the behavior in the short-term analysis is comparable with the design prevision and the in-situ energy consumption is enough simultaneous, during the summer with the occupants' request. A particular condition was verified during the first year of monitoring (RY), see Fig. 8, when all electricity consumptions was covered by in-situ production. Considering RY, for the evaluation of the yearly performance, during 2019 and 2020, the summer electricity request increases, respectively of 5% and 2%, and the in-situ production decreases respectively of −2% and −4%; this explains the different data obtained for the self-consumption.

In general, despite the negative percentage variations during 2018 (Fig. 9a) and 2019 (Fig. 9b), the PV production is always higher than the required electricity and thus there is an important contribute for the exported electricity. This result allows underlining an important aspect of operating behavior of nZEB. With the objective to satisfy the requirement for the renewable coverage, the installed power usually is overestimated and thus, mainly during the intermediate seasons, the feed-in of electricity by many nZEBs could cause imbalances on the national grids. This suggests that planners and designers need to work on the diffusion of communities and energy clusters to convey the swap of surplus energy, or on the optimization of batteries' size. For the case study, it can be also underlined that the self-consumption in these months is nearly 98% for all years.

Finally, it must be underlined that the adoption of TMY methodology is enough adequate to represent the behavior both of design and reference years. Indeed, considering Fig. 9d, the winter consumptions are overestimated meanwhile in the other months the values are enough comparable. The renewable production is always higher but only for the intermediate months this variation reaches an important value (+7%) meanwhile the self-consumption is 56% for the wintertime, 90% and 99% respectively for summer and other months. If the 2017 is considered for the comparison, the renewable production is always lower (between −1% to −5%) instead the consumptions are comparable with a maximum difference (+3%) during the winter.

Basing on the discussed energy balances, the annual results are reported in terms of percentage of self-consumption respect to the total building energy demand and the primary energy consumption per m^2 (Fig. 10).

In general, in the reference year and in the other examined years, the design choices assure that the energy balance is nearly zero in the Mediterranean climate. Indeed, the net primary energy is globally lower of 30 kWh/m^2 year with a percentage coverage of 80% from in-situ production. Yearly, low variations can be obtained for the renewable production and this indicates that the variation of irradiation and efficiency of PV-panels give equilibrate results in a short term analysis. Instead, the net annual primary request can vary greatly; indeed, it passes form 24 kWh/m^2 year for the DY to 25.4 kWh/m^2 year in the reference yea. More in general, considering the years 2018 and 2020 this variation is around 20% and this suggests that the monitoring and the definition of the smart readiness indicator is important for give confidence to occupants about the potential savings of those new enhanced-functionalities. Also in this case, the adoption of the TMY seems adequate to provide a prevision of the building energy behavior on the short term.

6.2. Medium-term analysis

The comparisons based on the results of the numerical simulations carried out with the climate projections are shown in this section. The first year of useful life of the case study (2017) is considered as reference for the comparison because it is representative of the real behavior. However, some comparisons with the design previsions are also introduced.

6.2.1. Energy consumption analysis

Fig. 11 shows the total energy consumption and the average annual dry bulb temperatures for the climate projections and for the reference year. The effects of climate change cause the linear increase of the DBT_{avg} with the most critical conditions for the scenarios RCP 8.5; in detail the increment goes from 9.6% to 21.4% passing from 10th to 90th percentile. Instead the result for the $E_{el,tot}$ is not uniform because it depends by the weight that the increase in summer period has on the reduction of winter energy requirements. Indeed, compared to the reference year, the total demand slightly increases when the 10th percentile is used:

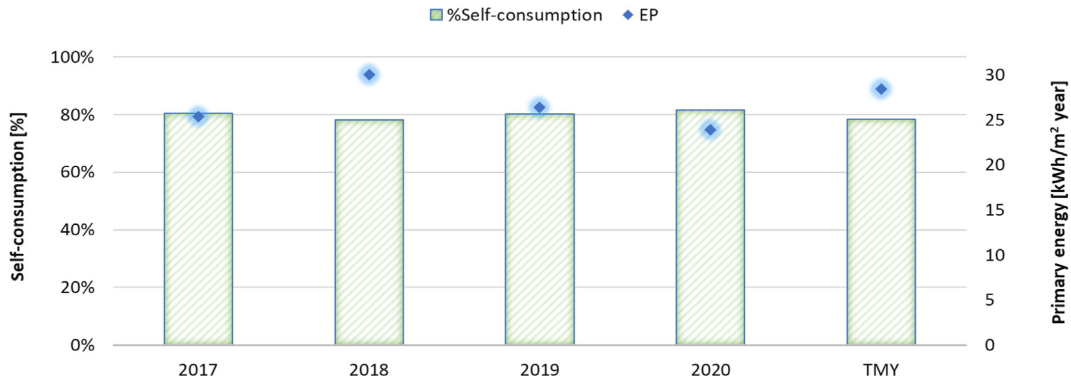

Fig. 10. Percentage of in-situ energy consumption and primary energy demand – Short-term analysis.

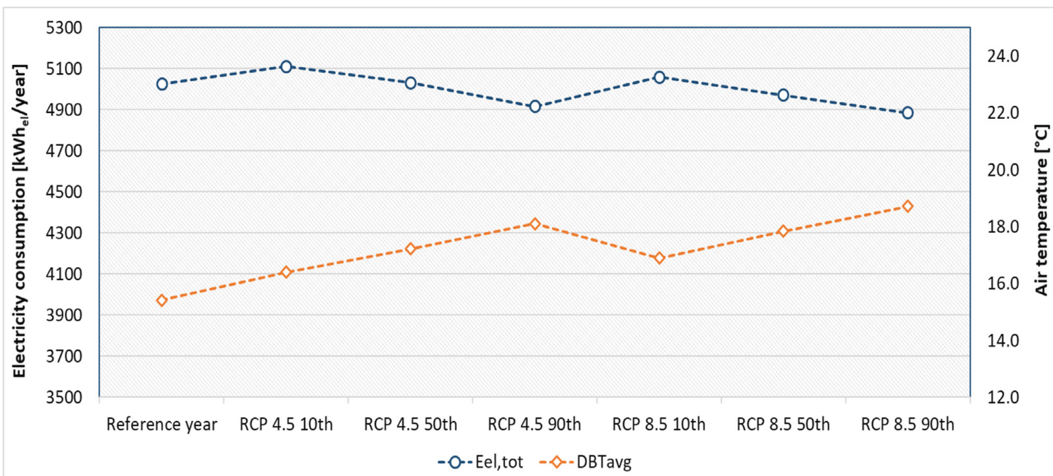

Fig. 11. Comparison of total energy consumptions and annual average DBT – Medium-term analysis.

+1.7% with RCP 4.5 and +0.7% with RCP 8.5. Moving to 90th percentile, the increment of the average temperature in the wintertime seems most important that the increment during the summer months. This implies that the total demand is reduced of around −2.2% with RCP 4.5 and −2.8% with RCP 8.5. The 50th percentile brings to different results; indeed, in the scenario RCP 4.5, the total demand is qute equal (+0.1%) to the RY, otherwise it decreases (−1.1%) in the scenario RCP 8.5. Thus, compared to the first operating year, the solutions for the building- HVAC system are resilient to the incoming climate changes.

The result does not change if the comparison is done with the data obtained for the design year. In this case, when the 10th percentile is considered, the expected increment of the total energy request is +2.5% in the scenario RCP 4.5 and +1.4% in the RCP 8.5 scenario. In the 90th percentile, the total demand decreases of around −1.4% with RCP 4.5 scenario and −2.1% with RCP 8.5 scenario.

In conclusion, the available projections indicate that for this type of building, the compensation between the increment of cooling demand and the reduction of the heating one, does not affect, substantially, the building energy balance. For verifying this conclusion, Fig. 12 shows the heating and cooling energy consumptions deriving from the numerical simulations and the differences in the average dry bulb temperatures during winter and summer air conditioning hours considering, as reference, the first year of life of the building.

The effect of global warming is very evident in this case since considering the air-conditioned hours, the average dry bulb temperature can increase also of more than 3.0 °C (RCP 8.5 90th). Consequently, in the medium-term analysis, the energy consumptions for cooling always increases. However, also if $Dev\_DBT_{H,cond}$ is lower, the reduction of the heating demand prevails on the increment of the air-condition request. For instance, in the "business as usual" scenarios 90th (RCP 8.5) $Dev\_DBT_{H,cond}$ is 2.8 °C and $E_{el,H}$ decreases of −34%; with the same climate projection, $Dev\_DBT_{C,cond}$ is 3.6 °C and $E_{el,C}$ increases of +7.6% compared to 2017.

The choices in term of insulation level and efficiency of the heating system allow the building to be resilient. Indeed, considering the case of RCP 4.5 50th, $Dev\_DBT_{H,cond}$ and $Dev\_DBT_{C,cond}$ are respectively 1.5 °C and 1.6 °C, but in terms of energy consumption, $E_{el,H}$ decreases of −28% and $E_{el,C}$ increases of 5.6%.

In detail, during the design the thickness of insulations and the type of materials were selected to be better of the constructive standard established by the Italian law for new buildings that should not be nZEB until 2021. More in detail, Benevento is within the Italian climatic zone C, and the values of thermal transmittance should be not higher than 0.34 W/m^2 K for the external walls, 0.33 W/m^2 K for the roofing slab, 0.38 W/m^2 K for the floor slab. For the windows, the cited law prescribes a total thermal transmittance equal to 2.2 W/m^2 K. Finally, regarding the technical systems, the same decree establishes the energy efficiency ratio of cooling system (i.e., SEER – Seasonal Energy Efficiency Ratio, at least equal to 2.5) and of energy systems from renewables [31]. The characteristics selected for the BNZEB are higher for all elements and thus for all projections the changes it is possible to meet the efficiency objective with performance comparable to the moment in which

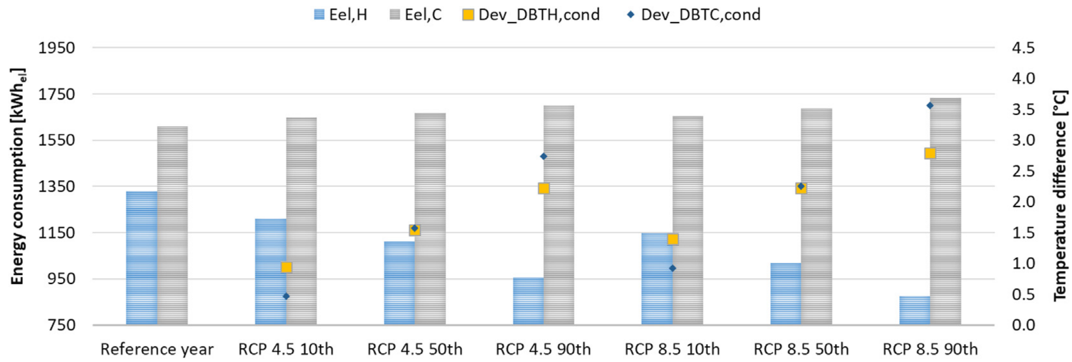

Fig. 12. Comparisons in the heating and cooling periods – medium-term analysis.

the building was designed. However, looking at the single terms of Fig. 12, it cannot fail to highlight that while now in a Mediterranean climate the requests for winter and summer air conditioning are balanced, in the future there will be a strong difference between the two rates.

6.2.2. Assessment of the building energy balance

Based on the previous considerations, it is important to understand what happens in terms of building energy balance; the simulation results carried out with the climate projections are reported in Fig. 13. With regard to the 10th percentile models (Fig. 13a and b), in the heating period the generation of electricity decreases of −5.4% and −6.2% with RCP 4.5 and RCP 8.5, respectively. Therefore, in the winter months, the simultaneous reduction of total electricity consumption and PV production lead to a reduction in self-consumption. However, the coverage from in-situ renewable source, slightly increases compared to 2017 and it becomes around 62% in both scenarios. Even in the cooling period, climate projections always show a lower generation of electricity compared to 2017 but the contemporaneity between demand and production increases, the self-consumption, slightly increases and it becomes 90% in both cases. Moving from the 10th percentile to the 50th percentile, low differences are observed in terms of renewable energy production in the heating period, compared to 2017.

However, as observed in the previous analysis, electricity consumption is reduced and consequently, there is a low self-consumption (Fig. 13c and 13d). In both cases, the coverage with renewable sources is near 62%. In the cooling season, photovoltaic production shows an increase of +2.2% with RCP4.5–50 and of +4.4% with RCP8.5–50. This effect, combined with the increase in total energy consumption, causes an increase in self-consumption compared to 2017 and globally it is 91%. The simulations carried out with the climate projections of the 90th percentile show an overall increase in electricity generation both in winter and in summer, compared to 2017 (Fig. 13e and f). The most interesting result is observed in the cooling period. Indeed, it is more evident that PV production allows the building to better balance

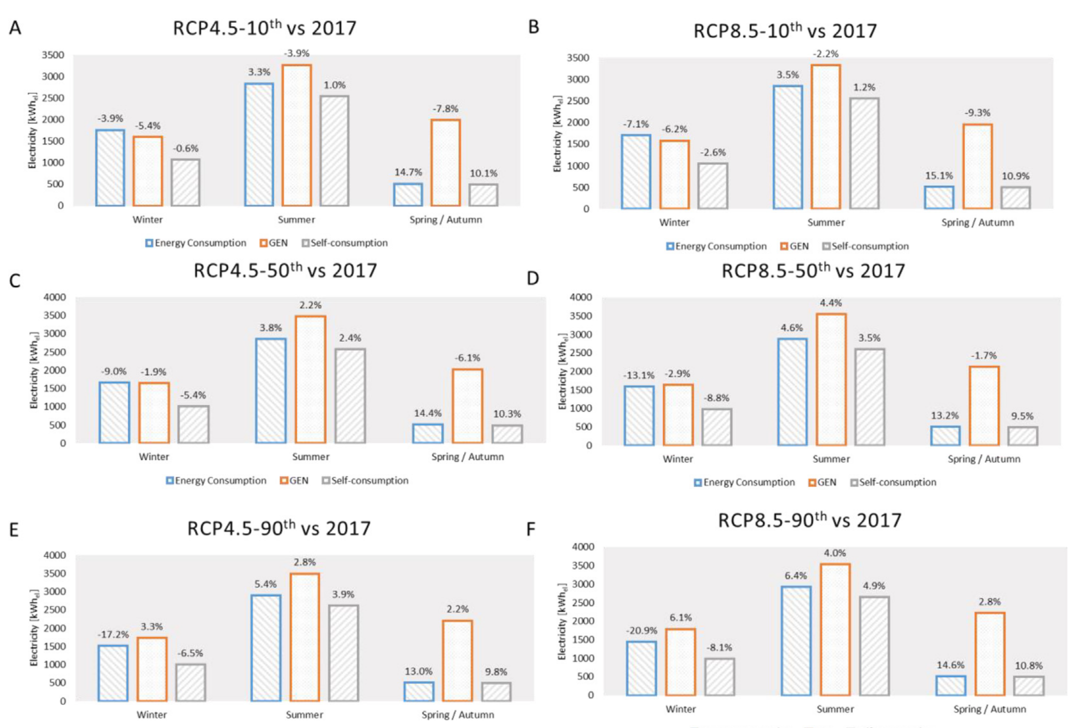

Fig. 13. Building energy balance assessment: a) RCP4.5–10; b) RCP4.5–50; c) RCP4.5–90; d) RCP8.5–10; e) RCP8.5–50; f) RCP8.5–90.

the increase in the energy consumption for cooling but the overall self-consumption does not change compared to the other scenarios and it is 91%.

In the intermediate months, once again, a strong imbalance between production and consumption is observed, but substantially there is an increase in self-consumption also due, for the 10th and 50th percentiles, to a reduction in production compared to 2017.

Finally, Fig. 14 shows the yearly balance in term of primary energy. The building balance indicates that the designed configuration can be resilient to climate change induced by global warming. Indeed, the reduction of the heating demand and the adoption of air-conditioning systems with high efficiency causes a reduction of the required primary energy in all scenarios except RCP 4.5-10th, meanwhile the consumption of in-situ production increases form the value recorded in 2017 (80%). The most extreme case is represented by the RCP8.5-90th. Indeed, despite this climate projection represents the worst climatic scenario in the medium term, the maximum percentage of annual self-consumption becomes 85%, and there is the lowest primary energy consumption, –23% compared to 2017.

6.3. Discussion about the role of renewable energy system

The term Prosumers indicates the buildings that not only use the renewable energy produced in-situ, but that also share the excess of energy produced with their neighbors through the connection to a smart grid. The aim of transforming buildings into Prosumers causes an important uncertainty on the optimal configuration of the renewable energy source systems during the design of nZEBs. Indeed, designers could optimize self-consumption or renewable electricity exported to the grid. In this study, the present and future levels of self-consumption of the building have already been discussed on the basis of the numerical simulations. From the same results it is possible to make some considerations regarding the interaction of the building with the utility during its operational phase, both in the short- and medium-term scenarios. In particular, Fig. 15 shows the results obtained in terms of energy supply index (I_{ES}) and percentage of electricity exported to the grid compared to that generated by photovoltaics (EXP%).The observed exported values are comparable and these vary form 34% during 2018 to 45% with 90th percentiles of both projections. The resilience of the design causes a variation of the energy demand; however it is always possible to find the balance created during the design phase thanks to the variation of the renewable production and to the work of electric storage.

On average, in the years of the short-term analysis I_{ES} is extremely variable and the maximum value (0.36) occurs in 2018. In the same year, the lowest value of EXP% also occurs. There were no significant variations in the results with the climate projections for the same percentile. However, on average, the operational phase of the building will be in future characterized by lower interaction with the electric grid, with a minimum I_{ES} value of 0.25 in the scenario RCP 8.5-90th.

The results drastically vary if the storage system is not considered. This could be the situation in which it is considered most profitable to deliver the produced electricity in the grid for instance for the energetic independency of an energy community. Fig. 16 shows the values of I_{ES} and EXP% without considering the presence of the storage system in the energy simulation results. For the proposed case study, there is only slightly difference from the short-term and medium-term performance. In this case the value of I_{ES} increases and it is very often equal to 0.65. Therefore, the number of hours per year in which the building draws electricity from the utility increases. The same consideration can be done for the exported electricity usually higher than 60%. The increase in EXP% can negatively impact the energy balance in term of nearly zero objective. However, it should be noted that with the future advent of Prosumers the emission factor of the electricity grid could undergo a significant reduction since most of the energy imported from the grid would be produced locally by the other buildings. At the same time, the more frequent hourly power absorption and the greater electricity exported require important insights into the impact of buildings on voltage levels and the robustness of local electric grid.

Presently, the best solution for the designers seems to be the maximization of the size of the photovoltaic system but providing the electrical energy storage system.

6.4. Discussion on the future role of the intermediate months

The last analysis is developed for the spring months because the increment of outdoor temperature could cause overheating phenomena that could bring to the need of turned-on the cooling sys-

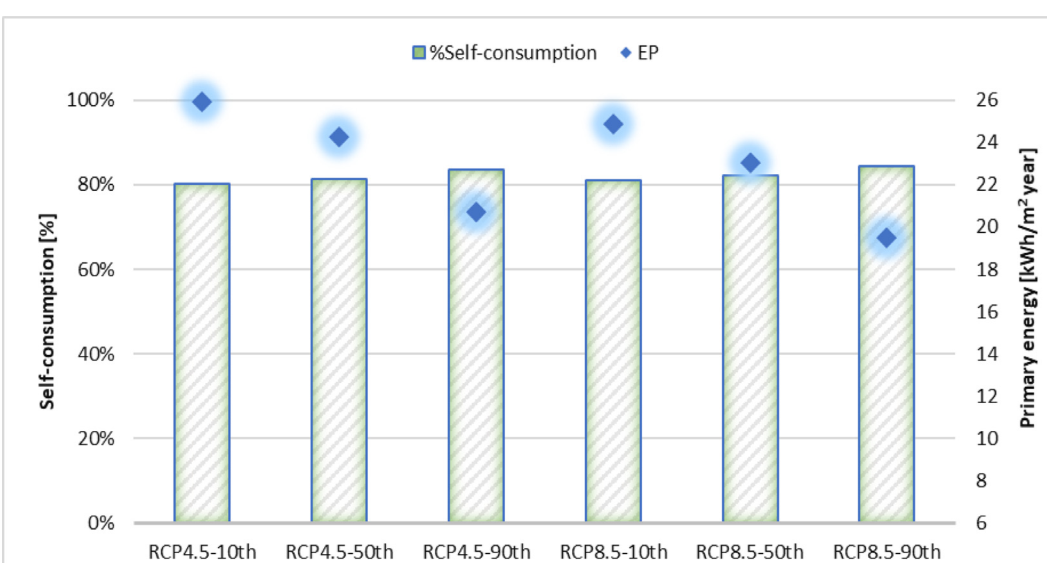

Fig. 14. Percentage of in-situ energy consumption and primary energy demand – medium-term analysis.

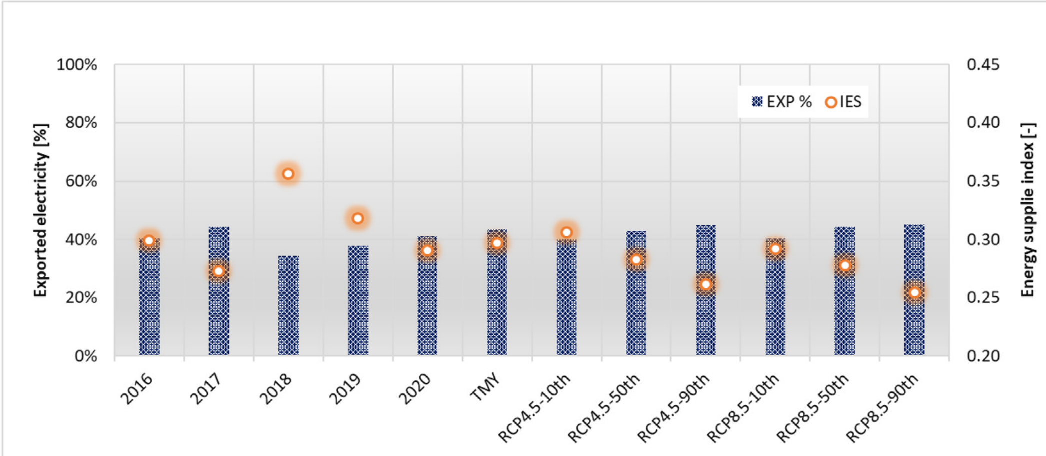

Fig. 15. Evaluation of exported electricity (EXP%) and energy supply index (I_{ES}) – PV system + storage.

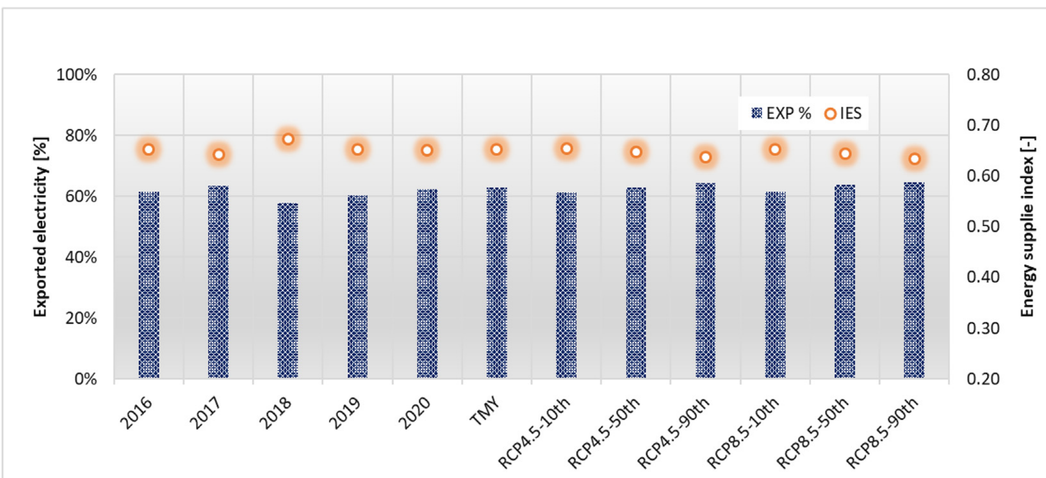

Fig. 16. Evaluation of exported electricity (EXP%) and energy supply index (I_{ES}) – PV system without storage.

tems also during periods not considered in the present analysis and common building management. In Fig. 17 the box plots relating to the DBT and RH distributions in the intermediate months of April and May are shown. With respect to the baseline year, the worst case (90th percentile) was assessed for each RCP. In general, the box plots of RCP4.5–90 and RCP8.5–90 show increasing levels of DBT compared to 2017, both in April and May (Fig. 17a). The opposite happens in terms of RH (Fig. 17b). In April, the mean value of DBT is 13.1 °C meanwhile it should become 15.2 °C and 15.9 °C in RCP4.5-90th and RCP8.5-90th scenarios, respectively. Compared to April, the box plot shows higher levels of DBT in May. For example, the value of the first quartile in May 2017 is 13.6 °C and therefore exceeds the mean DBT value of the April 2017 of +0.5 °C. Furthermore, compared to April, the differences observed between the reference year and the projections to 2050 are higher. The mean dry bulb temperature value of May 2017 is 18.2 °C. Instead, in the case of the climate projections the mean DBT is 21.2 °C and 21.7 °C, respectively with RCP 4.5 and RCP 8.5.

Considering the reference year, the mean RH value is around 68% in April and 65% in May. In the case of RCP4.5-90th and tRCP8.5–9 h 0, the relative humidity is on average equal to 66% and 65%, respectively in April. Instead, in May, the mean RH value is around 61% both with RCP 4.5 and RCP 8.5, for the 90th percentile. The effect in term of indoor air temperature and relative humidity is shown in Fig. 18 and Fig. 19 considering the average daily value of all thermal zones of the building. During these simulations, the heating and cooling systems were considered turned

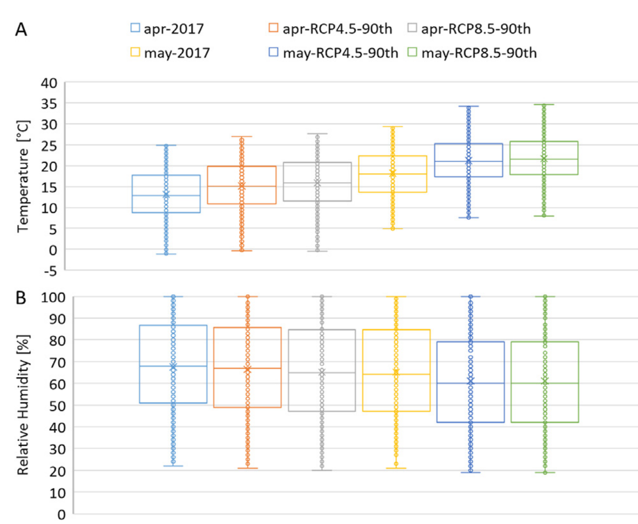

Fig. 17. Weather data distributions in the intermediate months – 2017 vs RCP4.5–90 and RCP8.5–90. a) DBT; b) RH.

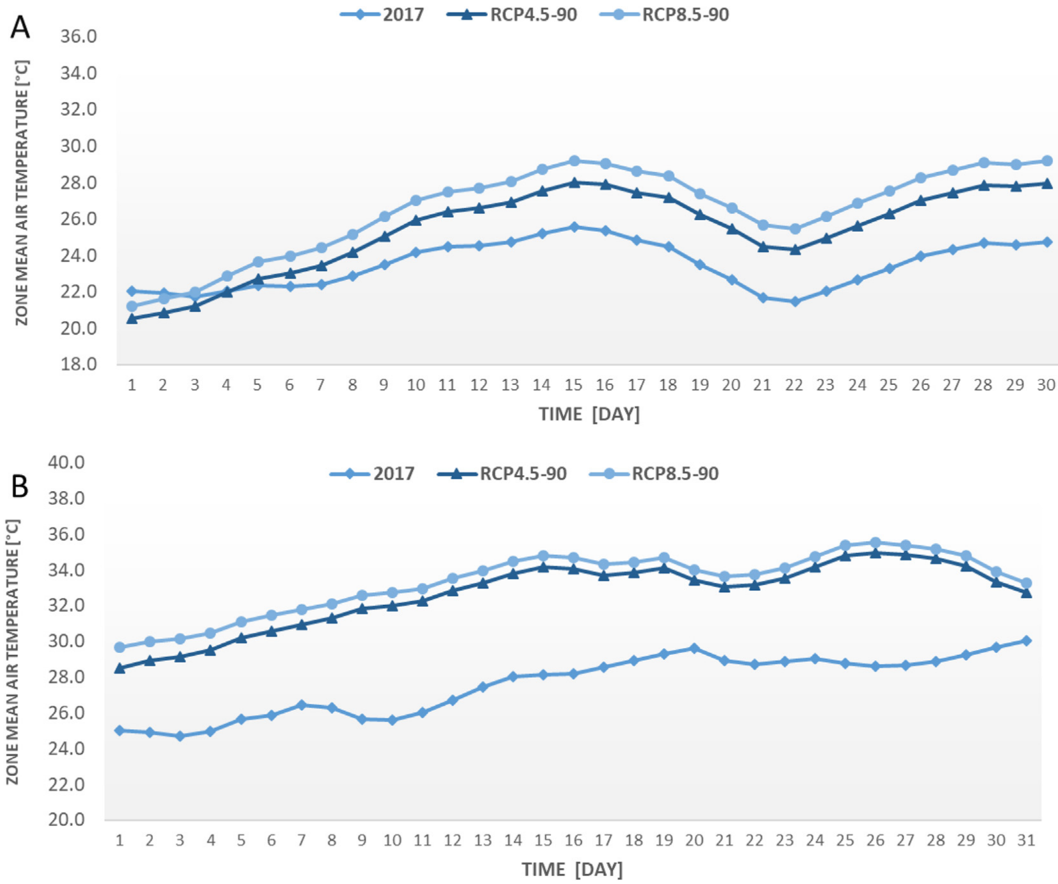

Fig. 18. Trend of Zone mean air temperature: a) April; b) May.

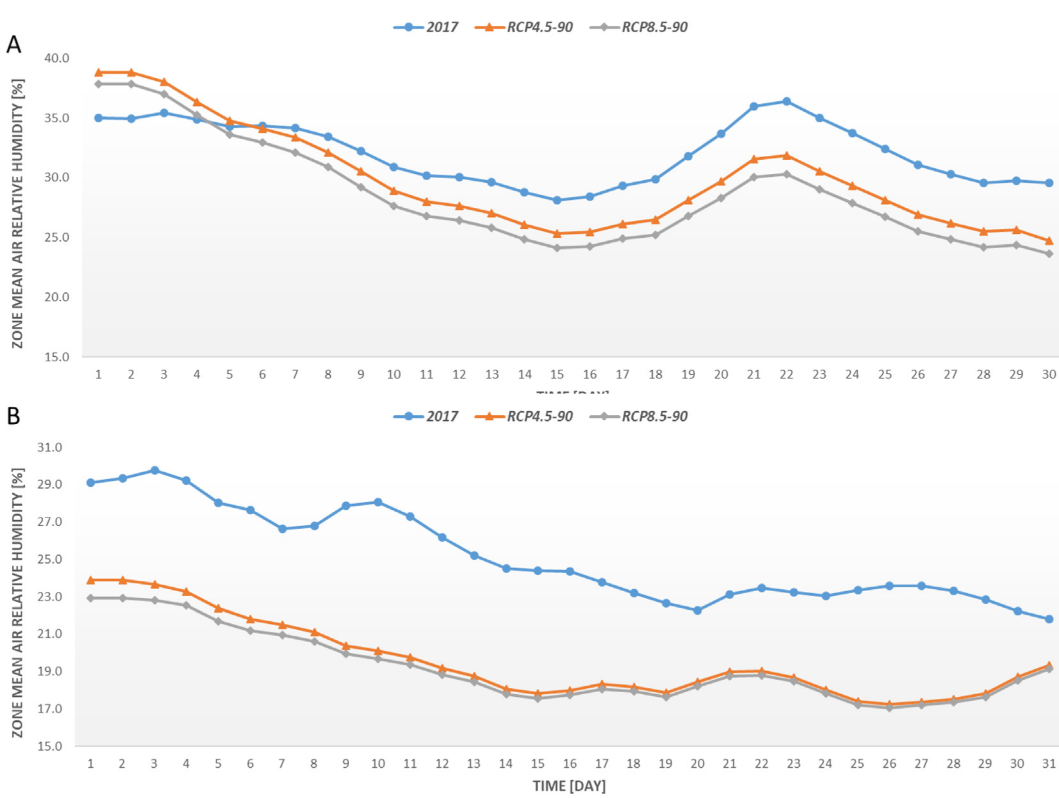

Fig. 19. Trend of Zone mean air relative humidity: a) April; b) May.

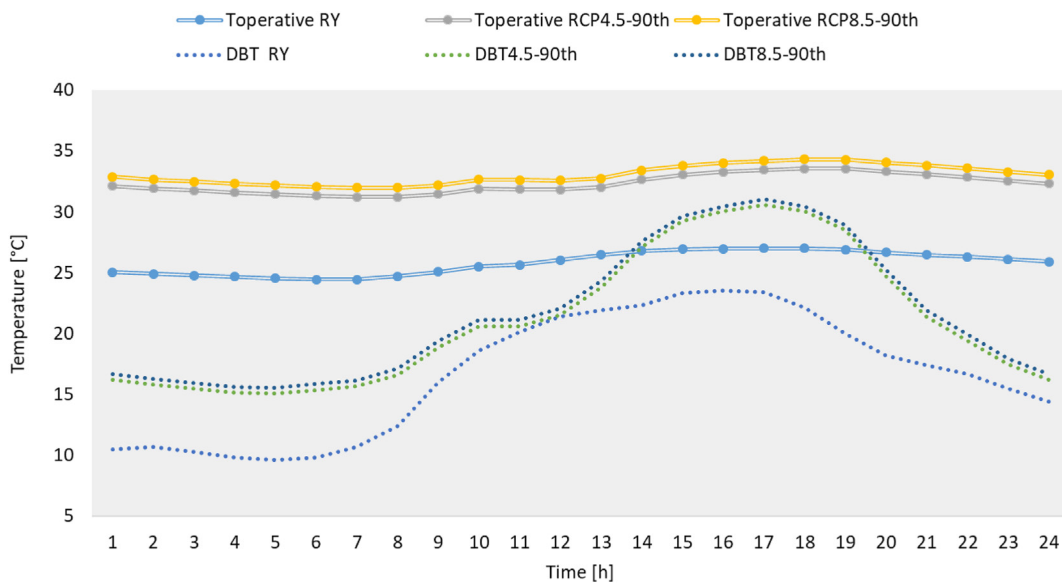

Fig. 20. Analysis of operative temperature and DBT on a representative day in May.

off. The trends of the zone mean air temperature (Fig. 18) confirm what has been observed in the previous analysis. Climate change causes an increase in the zone mean air temperature, compared to the reference year. In the medium term, higher differences in zone mean air temperatures are observed in May. In particular, the average difference between the daily values in April is equal to 1.9 °C between RCP4.5-90th and 2017 and 3 °C between RCP8.5-90thand 2017.The maximum difference with respect to the trend of reference year occurs in both cases for April 30th and is equal to 3.2 °C and 4.5 °C, respectively with RCP 4.5 and RCP 8.5. In May, the average difference with the trend of the reference year is approximately 5 °C for RCP4.5-90th scenario and 5.7 °C with RCP8.5-90th scenario. The maximum differences compared to 2017 occur during May 10th in both cases and these are equal to 6.4 °C and 7.1 °C with RCP 4.5 and RCP 8.5, respectively. In Fig. 19 the same type of comparison is shown in terms of zone mean air relative humidity. Again, the effects of climate change are most evident in May meanwhile the difference is quite negligible in April.

Finally, Fig. 20 shows a comparison between the hourly operative temperature and DBT values considering May 10th that is the day with the greatest differences between the reference year and the future climate projections. The operative temperature is reported for the living room. In terms of DBT, in the reference year an average daily value of 17 °C and a maximum value of 24 °C occur. With both climate projections, the average DBT is around 22 °C while the maximum value is 31 °C. Regarding the internal conditions, in 2017, the operative temperature varies between 24 °C and 27 °C and this suggests these conditions are acceptable for the present comfort normative also without the service of the cooling system. Instead, in the case of the climate projections the operative temperature is between 31 °C and 34 °C without significant differences between the scenarios RCP4.5-90th and RCP8.5-90th. The overall thermal sensation and the degree of discomfort of people exposed to moderate thermal environments can be determined under the conditions specified by the international standard EN ISO 7730 [38]. It specifies that during the summertime the operative temperature must be included between 23 °C and 26 °C. Thus, in future, without the active system, overheating phenomenon would occur in the living room, resulting in discomfort for the occupants.

This result indicates that for a correct evaluation, when the building energy balance is analyzed for the climate projections, it could be useful to consider different timing for the heating and cooling system. Indeed, the discussed increment of the cooling demand could be higher because the number of hours with the system turned on will increase. This aspect will be further investigated.

7. Conclusion

In the context of building energy simulation, there is an increasing need to assess the impact of strong climate changes on the building energy performance.

About this topic, the paper proposes the evaluation of the resilience of the design choices made for the BNZEB, a nearly zero energy building built in Benevento, a city of South Italy.

Several general findings can be remarked that could help designers and researchers. First of all, in the short-term, slightly variations in the external weather data and in the building energy balance were found with a reduction of the heating energy request and the increase of the cooling one. For the case study, designed basing on data monitored during 2016, after 5 years, with an increase of the average dry bulb temperature during the heating hours of +0.8 °C, it was obtained a reduction of the heating demand of −17.4%; otherwise the cooling demand is stable (+0.8%) with an increase of the average dry bulb temperature during the cooling hours of 1.2 °C.

The annual energy balance indicates that the net primary energy, equal to 24.0 kWh/m^2 year with weather data of design year (2016) can vary between 23.9 kWh/m^2 year (2020) and 30.1 kWh/m^2 year (2018). Instead the self-consumption of in-situ renewable production does not vary, also if the production is varied, and it is always near 80%.

In the medium-term analysis, in the most extreme scenario (2050), RCP 8.5-90th, the average dry bulb temperature calculated on the heating hours is 2.8 °C and the heating energy request decreases of −34%; instead the average dry bulb temperature during the cooling hours is 3.6 °C and the increase of the cooling energy demand is +7.6%. Considering the yearly balance, the annual self-consumption of in-situ renewable production becomes 85%, and there is the lowest primary energy consumption, –23% compared to 2017.

These results allow concluding that the choice to design the building with the thickness of insulations and the type of materials and plants better of the constructive standard, assures the resilience to the climate change. However, it must be underlined that the selected passive solutions for a building classified as nZEB with the current weather file, could be not able to reduce the overheating problem during the spring. For instance, in a typical day of May, with the weather data of the first operating year, the operative temperature, in the living-room, can vary between 24 °C and 27 °C without the cooling service. Instead, in the case of the climate projections the operative temperature is between 31 °C and 34 °C without significant differences between the scenarios RCP4.5-90th and RCP8.5-90th. This result suggests that designers and researchers should always consider the analysis of indoor conditions when the active systems are turned off. The effect of climate changes, in a typical Mediterranean climate, could bring to turn ton he cooling system also in the months classified as spring seasons, meanwhile the activation could be delayed in what is now considered the typical heating season.

CRediT authorship contribution statement

Fabrizio Ascione: Conceptualization, Methodology, Supervision, Writing – original draft. **Rosa Francesca De Masi:** Conceptualization, Formal analysis, Investigation, Supervision, Writing – original draft. **Antonio Gigante:** Data curation, Formal analysis, Investigation. **Giuseppe Peter Vanoli:** Conceptualization, Methodology, Supervision, Writing – original draft.

Declaration of Competing Interest

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

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References

[1] F. Atsu, S. Adams, Energy consumption, finance, and climate change: Does policy uncertainty matter?, Econ Anal. Policy 70 (2021) 490–501.
[2] J. Huang, K.R. Gurney, The variation of climate change impact on building energy consumption to building type and spatiotemporal scale, Energy 111 (2016) 137–153.
[3] IPCC, Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel On Climate Change. Cambridge University Press, Cambridge, United KingdomNew York, NY, USA (2013).
[4] K. Verichev, M. Zamorano, M. Carpio, Effects of climate change on variations in climatic zones and heating energy consumption of residential buildings in the southern Chile, Energy Build. 215 (2020).
[5] Y. Yang, K. Javanroodi, V.M. Nik, Climate change and energy performance of European residential building stocks – A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment, Appl. Energy 298 (2021).
[6] S. Flores-Larsen, C. Filippín, G. Barea, Impact of climate change on energy use and bioclimatic design of residential buildings in the 21st century in Argentina, Energy Build. 184 (2019) 216–229.
[7] M.P. Tootkaboni, I. Ballarini, V. Corrado, Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: A study of climate change impacts, Energy Rep. 7 (2021) 8548–8560.
[8] J. Bravo Dias, G. Carrilho da Graça, P.M.M. Soares, Comparison of methodologies for generation of future weather data for building thermal energy simulation, Energy Build. 206 (2020).
[9] Y. Zou, S. Lou, D. Xia, I.Y.F. Lun, J. Yin, Multi-objective building design optimization considering the effects of long-term climate change, J. Build. Eng. 44 (2021) 102904.
[10] M. Hosseini, A. Bigtashi, B. Lee, Generating future weather files under climate change scenarios to support building energy simulation – A machine learning approach, Energy Build. 230 (2021).
[11] K. Bamdad, M.E. Cholette, S. Omrani, J. Bell, Future energy-optimised buildings — Addressing the impact of climate change on buildings, Energy Build. 231 (2021).
[12] H. Yassaghi, P.L. Gurian, S. Hoque, Propagating downscaled future weather file uncertainties into building energy use, Appl. Energy 278 (2020).
[13] K. Verichev, M. Zamorano, A. Fuentes-Sepúlveda, N. Cárdenas, M. Carpio, Adaptation and mitigation to climate change of envelope wall thermal insulation of residential buildings in a temperate oceanic climate, Energy Build. 235 (2021) 110719.
[14] S. Liu, Y.T. Kwok, K.-L. Lau, W. Ouyang, E. Ng, Effectiveness of passive design strategies in responding to future climate change for residential buildings in hot and humid Hong Kong, Energy Build. 228 (2020) 110469.
[15] R.F. De Masi, A. Gigante, S. Ruggiero, G.P. Vanoli, Impact of weather data and climate change projections in the refurbishment design of residential buildings in cooling dominated climate, Appl. Energy 303 (2021).
[16] G. Nurlybekova, S.A. Memon, I. Adilkhanova, Quantitative evaluation of the thermal and energy performance of the PCM integrated building in the subtropical climate zone for current and future climate scenario, Energy 219 (2021).
[17] K. Bamdad, S. Matour, N. Izadyar, S. Omrani, Impact of climate change on energy saving potentials of natural ventilation and ceiling fans in mixed-mode buildings, Build. Environ. 209 (2022).
[18] C.M. Muñoz González, A.L. León Rodríguez, R. Suárez Medina, J. Ruiz Jaramillo, Effects of future climate change on the preservation of artworks, thermal comfort and energy consumption in historic buildings, Appl. Energy 276 (2020) 115483.
[19] G.B.A. Coelho, H. Entradas Silva, F.M.A. Henriques, Impact of climate change in cultural heritage: from energy consumption to artefacts' conservation and building rehabilitation, Energy Build. 224 (2020).
[20] D. D'Agostino, D. Parker, I. Epifani, D. Crawley, L. Lawrie, How will future climate impact the design and performance of nearly zero energy buildings (NZEBs)?, Energy 240 (2022) 122479
[21] M. Ferrara, E. Fabrizio, Cost optimal nZEBs in future climate scenarios, Energy Proc. 122 (2017) 877–882.
[22] F. Ascione, M. Borrelli, R.F. De Masi, F. de Rossi, G.P. Vanoli, A framework for NZEB design in Mediterranean climate: design, building and set-up monitoring of a lab- small villa, Sol. Energy 184 (2019) 11–29.
[23] F. Ascione, N. Bianco, R.F. De Masi, F. de Rossi, G.P. Vanoli, Concept, design and energy performance of a net zero energy building in Mediterranean climate, Proc. Eng. 169 (2016) 26–37.
[24] M.C. Peel, B.L. Finlayson, T.A. McMahon, Updated world map of the Koppen-Geiger climate classification, Hydrol. Earth Syst. Sci. 4 (2) (2007) 1633–1644.
[25] Italian Organisation for Stardardisation (UNI). UNI 10349-1:2016, Heating and cooling of buildings -Climatic data -Part 1: Monthly means for evaluation of energy need for space heating and cooling and methods for splitting global solar irradiance into the direct and diffuse parts and for calculate the solar irradiance on tilted planes.
[26] President of the Republic. Regulation containing prescriptions for the design, installation, operation and maintenance of heating systems in buildings in order to limit energy consumption, implementing art. 4, par. 4 of Low 9 January 1991, n. 10. Decree 26.08.1993 no. 412; 1993 (in Italian).
[27] DesignBuilder, 2018, v. 6.0. https://doi.org/10.1016/j.renene.2020.03.180. Last access 25 June 2021.
[28] U.S. Department of Energy, Energy Plus Simulation software, version 8.9. Last access 25 June 2021.
[29] U.S. Department of Energy Federal Energy Management Program, M&G Guidelines: Measurement and Verification of Performance-Based Contacts, 2015. Version 4.0.
[30] I.J. Hall, R.R. Prairie, H.E. Anderson, E.C. Boes, Generation of a typical meteorological year, Proceedings of the 1978 annual meeting of the American Section of the International, Solar Energy Soc. (1978) 669–671.
[31] DM 26/06/2015, Italian Ministerial Decree, "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici", (In Italian), 2015.
[32] Atmospheric emission factors of greenhouse gases in the national electricity sector and in the main European countries, ISPRA 2020 [in Italian]: Rapporto317_2020. pdf (isprambiente.gov.it).
[33] A. Magrini, G. Lentini, S. Cuman, A. Bodrato, L. Marenco, From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge - The most recent European trends with some notes on the energy analysis of a forerunner PEB example, Develop. Built Environ. 3 (2020).

[34] F. Ascione, R.F. De Masi, F. de Rossi, S. Ruggiero, G.P. Vanoli, MATRIX, a multi activity test-room for evaluating the energy performances of 'building/HVAC' systems in Mediterranean climate: Experimental set-up and CFD/BPS numerical modeling, Energy Build. 126 (2016) 424–446.
[35] www.weathershift.com.
[36] S.E. Belcher, J.N. Hacker, D.S. Powell, Constructing design weather data for future climates, Build. Serv. Eng. Res. Technol. 26 (1) (2005) 49–61.
[37] R. Dickinson, B. Brannon, Generating future weather files for resilience. Plea 2016 Los Angeles – 36th International Conference on Passive and Low Energy Architecture. Cities, Buildings, People: Towards Regenerative Environments.
[38] International Standardization Organization, ISO 7730 - Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort, Geneva (2005).