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Analyzing the climate-driven energy demand and carbon emission for a prototype residential nZEB in central Sweden

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ABSTRACT

The changes in climate and the expected extreme climate conditions in the future, given the long life span of the buildings have pushed the design limits. In this study, the changes in primary energy use (PE_{PET}), total energy use and CO_2 emission were investigated for a prototype residential building. The building fulfils nearly zero energy building (NZEB) characteristics, imposed by the Swedish building regulations. Different cooling technologies and various typical meteorological year (TMY) climate files assembled for different periods, as well as automatic shading were investigated. The assembled TMY files advocated for the present (2001–2020) and mid-future (2041–2060) period using the CORDEX data. Different cooling methods and set-points (24–28 °C) were defined to evaluate the cooling energy demand changes.

It was discovered that the freely available typical climate file fails to cover the induced changes in climate and its extreme implications on the building. The required cooling energy use increased from 1.7 to 5.8 times the freely available climate file, when using the projected TMY and the extreme climate files.

Addition of automatic shading system reduced cooling energy up to 75% within the studied cooling methods and set-points. Moreover PE_{PET} and CO_2 emission also decreased for the studied cooling methods, climate and weather files.

1. Introduction

Buildings are a major source of GHG emissions, and use large amounts of energy and natural resources. One third of the world's total energy use corresponds to the building sector [1]. With increase in population and more time spent indoors, the energy use of the building stock also increases. This increase in building energy use leads to increase in carbon emission [2]. Building construction and operation account for 36% of global final energy use and of 39% of energy related GHG emissions [3]. Awareness of the threat of a climate crisis and its recognition in global Sustainable Development Goals, and in European and national political targets, has increased the pressure to take necessary measures to reduce anthropogenic GHG emissions. Due to the impacts associated with the greenhouse gas (GHG) emission from energy sector and consequently the climate changes, they are now regarded as environmental problems rather than environmental issues [4]. To overcome these problems, the European (EU) commissions has introduced the European Green Deal to make Europe's economy secure and sustainable [5,6]. The European Green Deal consists of number of climate actions to cut the GHG emissions and preserve Europe's natural environment. One of the climate actions to reach the European Green Deal is the European Climate Law [7]. Based on this action, the European Union is trying to reduce the net greenhouse gas emissions by 55%, compared to 1990′s level by 2030, and further become a climate neutral continent by 2050. Alongside this, the European Union aims for a climate resilient society by 2050 as well [7]. To achieve improvement in the energy performance of the buildings as well as promoting policies that help obtaining stable conditions for investment decisions and the climate goals, the EU Commission has implemented the Energy Performance of Buildings directives and Energy Efficiency Directives as a legislative framework [8]. Within the mentioned framework, policies and measures have been developed to improve the buildings' energy performance. In addition to legislation, taxation and different benefit packages, environmental assessment methods can be regarded as a voluntary way to work with environmental governance and reduce GHG emission, which may also influence legislation [9]. For example, the Swedish environmental assessment method Miljöbyggnad has inspired a new legislation regarding climate declaration for all new buildings in Sweden, which is mandatory from January 2022

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1.1. Nearly zero energy buildings and primary energy number

Commission Recommendation (EU) 2016/1318 established in 2016 introduced guidelines for the promotion of NZEB, referring to a building with high energy performance that uses low amount of energy which is covered mostly by renewable sources [10]. Article 2 of the Energy Performance of Buildings Directive 2010/31/EU, defines energy performance as the amount of energy in the form of heating, cooling, ventilation, hot water, lighting and inter alia that is required by the building to meet its demands [11]. The European Commission within the Official Journal of European Union [12,13] provide guidelines on calculating the energy performance of buildings. The calculation starts with quantification of the building's final energy needs to assess the net primary energy use [10].

In order to improve the energy performance of the buildings, Directive 2010/31/EU emphasized the importance of Nearly-Zero Energy Buildings [11,14]. Therefore the EU member states were obliged to comply with the implications by providing their national or regional reflections in the definition of NZEB as well as presenting the numerical indicator of Primary Energy (PE) [14,15].

Primary energy is the energy that has not undergone any conversion and transformation and is used to anticipate the end-use energy [16]; it is a measure of how natural resources are used. In order to be able to evaluate energy use in terms of primary energy, delivered energy is used to estimate the primary energy. This can be done through a set of constants called Primary Energy Factors (PEF) and these are regarded as the ratio between the total used primary energy and total end use delivered energy [17]. Studies were conducted to calculate the PEF, for example in the USA [17], European Union member states [14] and Sweden [18]. A study was conducted by Duh Čož et al. [19] to calculate the PEF of district cooling system in Slovenia.

The PE number is a numerical indicator that is included in NZEB definition and it is expressed in kWh/(m^2•year). The majority of the EU members have been developing a PE numerical indicator to provide a comprehensive definition and a criteria of NZEBs on national levels [20]. The Swedish National Board of Housing, Building and Planning (Boverket) proposed a definition for NZEB in 2017 that set several building energy use-related limitations. This step was taken to reduce energy use in buildings. Building regulations also makes use of the term Primary Energy Number that is depicted as PE_{PET} and it is based on weighting factors of energy carriers present in the building (see more details in section 2.5). The method to calculate the PE number for Sweden is expressed in Swedish Building Codes [21] and later will be explained in section 2.5 of this study. Bounding the PE_{PET} below 75 kWh/ m$^{2\cdot}$ year, for residential buildings [21] is among the proposed regulation requirements which is the main focus in this research project.

1.2. Future climate

Building Performance Simulation (BPS) helps predicting/estimating the energy performance and indoor thermal condition of a prototype building during the design stage. To describe the dynamic energy behavior of a building, hourly weather data is required as it is considered as the external boundary condition for building simulation [22,23].

Future weather files are built based on multiyear observation data. The Typical Meteorological Year (TMY) files are a representative dataset, containing 8760 h, derived from multiyear recorded observational data to represent statistical trends over the recorded period [1,24]. A number of researches have tried generating TMY files over the years for regions including Greece [25], Italy [26], Malaysia [27], Nigeria [28], Argentina [29] and Sweden [30,31].

These single year weather datasets, as mentioned previously, are representatives of 2–3 decades of historic observational data and with the ongoing climate changes, these weather files generally fail to represent future climate conditions. The third assessment report of the Inter-Governmental Panel on Climate Change (IPCC) has contributed to climate change models and provided a collective picture of weather changes [32]. A number of researchers have tried to represent future conditions and extreme weather, using these historic datasets, however, they have reported that the weather datasets were not adequate [1,23,33]. Therefore to study the resilience of the building and its performance in the future, several methods have been developed to create future weather files [24].

The IPCC introduced the first set of scenarios to project future climate changes in the IPCC Special report on Emission Scenarios (SRES) in 1996 [34] and later in 2014, the Representative Concentration Pathways (RCP) was introduced [35]. These emission scenarios help in analyzing climate changes and its modeling, as well as the influence of the driving forces (socio-economic development, technological changes, etc.) on future emission outcomes by providing initial conditions for Global Climate Models (GCM) [22,34]. The GCMs are the numerical representatives of the global climate system's physical processes and their outputs cover the entire globe and these are used to assess the impact of climate changes, however, their resolution is too coarse (100–300 km^2) to be used for BPS purposes [36]. In order to be able to use the GCM data, these should be downscaled to the appropriate resolution of less than 100 km^2. Two downscaling methods have been introduced, statistical and dynamical downscaling methods [24,37].

Several researchers have studied the effect of future climate on the energy performance of the buildings. They have depicted an increase in cooling requirements and reduction in heating requirements of the buildings in different regions such as the USA [38], Iberian Peninsula [4], Hong Kong [39], Tokyo [40], Denmark [23], Sweden [41] and Finland [42].

Present buildings may not withstand the future heatwaves and extreme climate conditions considering the ongoing climate changes. Therefore, the resilience of the building has to be accounted during the design stage. Given that, current Swedish residential buildings and other buildings, such as kindergartens, are not equipped with cooling units. A number of resilient cooling strategies has been reviewed by Zhang et al. [43] based on categories created in IEA EBC Annex 80, to cool people or the indoor environment. Regulations and the typical climate files used for simulating purposes, especially to prove fulfillment of building regulation energy requirements, have to be updated to increase the accuracy of the simulated result for the buildings that are to be built or have to undergo deep renovations. The use of future climate files is not considered in updating the building regulations in Sweden and has to be considered to match the requirements of EU Commissions. This is a research gap that has to be accounted for.

This study aims to explore the impact of several factors on the energy performance, PE_{PET} and carbon emission of a residential building. Climate files representing different periods from past to future to cover the research gap mentioned earlier as well as different cooling strategies and technologies were investigated to meet the aim of the research project.

This study has raised two research questions: Is it possible to use currently available typical meteorological year (TMY) climate files to evaluate the future energy need of buildings?

And, how to improve the indoor thermal conditions and reduce CO_2 emission from building operation, and evaluate the effects on primary energy use?

The cooling demand assessment and heat load reduction as well as implementing solar shading are among the Key Performance

Indices (KPIs) proposed by IEA EBC Annex 80: *Resilient cooling of buildings*. Therefore the characteristics of the model building are aligned with these KPIs [44].

2. Methods

An overview of the considered case studies and the results to have a proactive design strategy is presented in Fig. 1. Furthermore, each of the case studies accounted in the study are explained in sections 2.1 to 2.6. Procedures to assemble future climate files are presented in section 2.1. In section 2.2, the building characteristics and construction details based on Swedish proposal for NZEB are presented. Different cooling methods are explained in section 2.3 and the CO_2 impact and emission calculation is depicted in section 2.4. The method to calculate the PE_{PET} is depicted in section 2.5. Finally, in section 2.6 the comfort model is described. Limitations of the study are presented in section 2.7.

2.1. Assembling future climate

In order to study the effect of climate change and its implications on the energy performance of the building, a TMY file was produced for the Mid-term future (2041–2060). To assemble the Mid-future climate file, the methodology proposed by Machard et al. [45] was implemented. The climate file was assembled from the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) which can be accessed through the Earth System Grid Federation (ESGF) [46]. CORDEX strives to provide an internationally coordinated framework that delivers high resolution climate scenarios to standardize and improve regional climate downscaling methods [47]. As previously mentioned, two downscaling methods have been introduced, empirical-statistic and dynamical approach, which CORDEX takes into account [47].

After selecting EU-11 as the domain for Europe with 1-hour time frequency, REMO 2015 was selected as the downscaling method. The required climate variables to assemble the climate files were dry bulb temperature, relative humidity, atmospheric pressure, wind speed, total cloud cover and surface downwelling shortwave radiation. Representative Concentration Pathway (RCP) 8.5 was chosen as the socio-economic scenario for this study.

In the next step, the downloaded data were extracted for the city Gävle, Sweden (60.67°N, 17.14°E) using CORDEX-DATA Extractor.

The extracted data are not bias-adjusted, therefore these were post-processed using the multivariate bias correction algorithm (MBCn) method, proposed by Cannon [48,49]. The method is used for projection/ prediction of multiple climate variables. Bias-adjustment methods compare the distribution curve of the extracted data with observational data and help correcting climate variables distribution function [45]. The method helps linking the climate simulated by Regional climate model (RCM) with rural observation data at the gauging station. In this study, the extracted data were calibrated against 20 years of hourly historical observation data Finally, the TMY files were built using the EN-ISO 15927–4 method [26] for the Average (2001–2020) and Mid-future period (2041–2060). The TMY files are used to assess the long-term mean energy use. The same processes were carried out to produce a climate file for the period 2001–2020. This assembled climate file was used in this study to ensure the authenticity of the Mid-future climate file, as the observational data are available for 2001–2020 for comparison purposes.

2.2. Nearly-zero energy buildings

A prototype multifamily building in central-Sweden was modelled adopting the latest available features of constructed buildings from newest districts in Gävle. The construction material and specifications were developed based on the latest available materials in the market to achieve NZEB qualities. The studied future district in this research is a part of a construction project that comprises 6000 new residential buildings [50]. Buildings such as the one introduced in this study are common in new city districts [51]. The

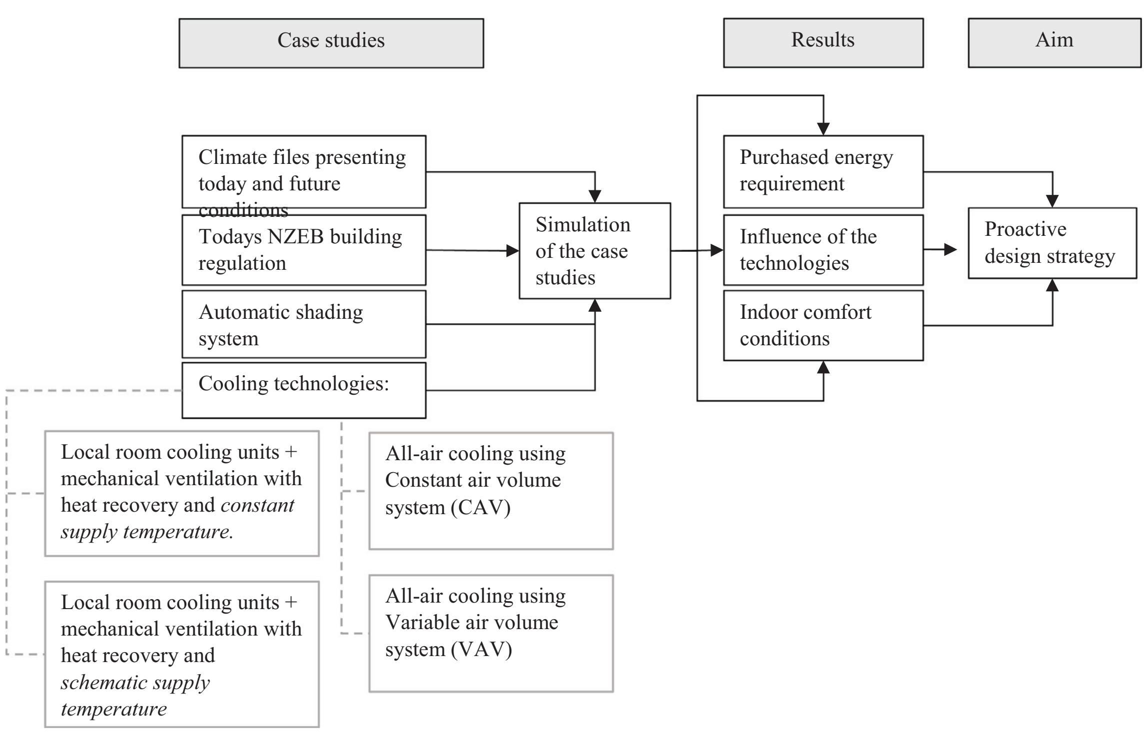

Fig. 1. Overview of the research process.

Table 1
Input parameters for the prototype modelled building.

Parameter	Values	Parameter	Values
U_{value} Glazing	0.8 W/m^2·K	Heating set-point [52]	21 °C
U_{value} Total Window	0.92 W/m^2·K	Heat exchanger efficiency	0.8
U_{value} External walls	0.1 W/m^2·K	Window to floor ratio	10%
U_{value} Roof	0.06 W/m^2·K	AHU specific fan power	0.75 kW/m^{3}s^{-1}
Number of occupants per zone	1.63	Total floor area	75 m^2 1414 m^2

internal gains (lighting, appliance and occupant gain) and building properties were defined based on the energy requirements defined in Swedish building regulations, as well as building simulation standards [21,52]. More information is provided regarding energy requirements in section 2.5. The building is shown in Fig. 2 and the building specifications are depicted in Table 1.

The building was modelled in IDA-Indoor Climate and Energy (IDA-ICE) [53]. The software has been validated using BESTEST Test procedure in ASHRAE Standard 140 [54]. Also the simulation result of the software have been validated against measured data in number of studies [55–58]. A number of researchers have used IDA-ICE in their researches and validated the simulated result against measured data [59–62].

Each apartment is considered as one large zone with calculated 1927 kWh/ year of total emitted sensible heat which corresponds to household electricity [63]. This study was carried out on 3000 newly built apartments, and the reported values are 30% lower than the values suggested by Sveby-standard.

The energy carriers are district heating and cooling for conditioning spaces and electricity for empowering facility and household equipment and lighting. The household electricity was assumed constant throughout all simulations including the future time.

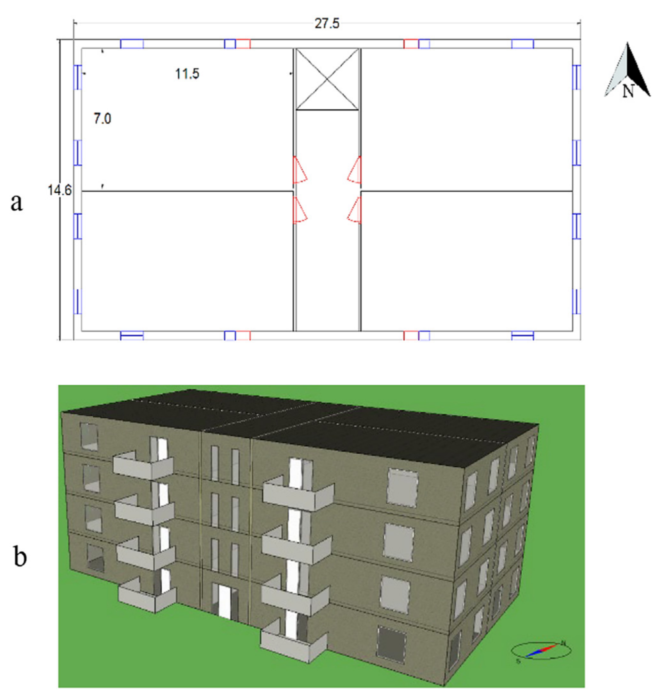

Fig. 2. Scheme of the model's geometry. (a) The plan of the building (dimensions are in meters); each apartment is modelled as a zone (b) Modelled building in IDA-Indoor Climate and Energy (IDA-ICE).

2.3. Simulations

In order to evaluate and improve the building's energy performance, different strategies were considered. Section 2.3.1 investigates the different cooling technologies and section 2.3.2 investigated the effect of automatic external shading on the energy performance of the building.

2.3.1. Investigation of different cooling technologies

Given the geographic location of the building, one strategy is to use the ambient air as cooling carrier; this in view that building regulations formulate to have mechanical ventilation system with heat recovery as a solution to fulfill both ventilation and energy requirements. The supply temperature was first considered constant (16 °C). Correspondingly, the supply temperature of the AHU also is 16 °C as long as the ambient temperature is below 16 °C. From this temperature and higher, the supply temperature will be the same as the ambient temperature.

The second investigated supply temperature strategy was a piecewise proportional controller. Fig. 3 depicts the applied strategy for this scheme. Correspondingly, when the ambient temperature is below 8 °C, the supply temperature would be 16 °C. It was noticed that from this ambient temperature onwards, the indoor temperature rises above the defined set-point with the defined ventilation strategy. By increase in the ambient temperature, the supply temperature gradually decreases. Similar to the previous strategy, the supply temperature would be the same as ambient temperature from 16 °C onwards. This is due to the absence of cooling coil in the ventilation system to compensate; ideal coolers were anticipated in the zones. Ideal coolers/ heaters are standalone units that are not connected to the plant [64], although their energy source is considered to be from district sources in this

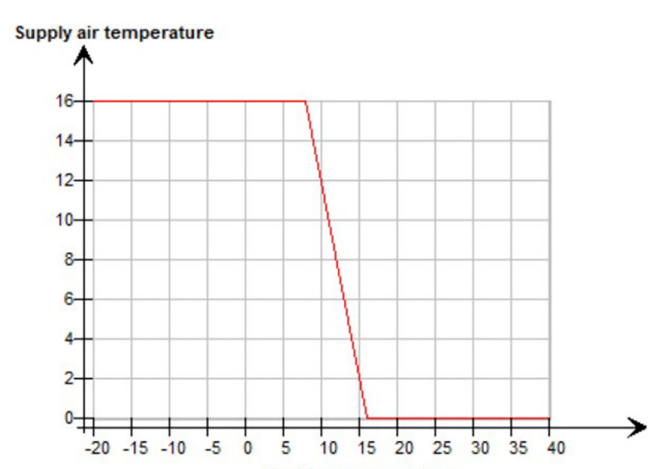

Fig. 3. Piecewise controller scheme depicting supply air temperature versus ambient temperature.

study. The depicted cooling strategy was chosen after analyzing different combinations of supply temperature to find the scheme that helps reducing the exhaust air temperature, which consequently reduces the cooling load.

In addition, two all-air cooling technologies, constant air volume (CAV) and variable air volume (VAV) ventilation systems were studied to assess their performance. In this case, the ideal coolers were removed. This was done to provide more realistic indoor conditions. Since ideal coolers have the ability to maintain a constant indoor temperature within the defined indoor conditions. Based on the return temperature, a minimum air supply temperature of 16 °C was considered. For the CAV system, to keep the indoor temperature within the defined range, a two-speed fan was defined. The fan supplies a maximum constant supply air flow 1 L/(s·m^2) and maximum exhaust air flow 1.1 L/(s·m^2) from May-July. The fan works half load, during the rest of the year with constant supply and exhaust of 0.35 and 0.37 L/ (s·m^2) for the rest of the year.

For the VAV system the minimum air flow rates for the supply and exhaust were 0.35 and 0.37 L/(s·m^2) and maximum 1 L/(s·m^2) and 1.1 L/(s·m^2), respectively. The amount of supplied air to the zone automatically varies within the defined minimum and maximum values in order to keep the zones at the defined set-points.

Based on Swedish guidelines for indoor climate specifications [65], two thermal classes Thermal quality 1 (TQ1) and Thermal quality 2 (TQ2) are defined. These describe the requirement for different thermal indoor climates. TQ1 and TQ2 accept indoor room temperatures above 26 and 28 °C respectively, for a short period during summer. Therefore five different cooling set-points 24–28 °C were selected to compare the energy performance of the building for three periods; Historic (1981–2010), Average (2001–2020) and Mid-future (2041–2060), as well as the hot summer weather of 2018. The Historic climate is the typical climate file that is used for building simulation purposes either for academic research or consultant and design purposes. In this research, it is referred to as Historic climate instead of Typical climate to maintain consistency in the names assigned to the climate files. This climate data file was created by Swedish Meteorological and Hydrological Institute (SMHI) after order from SVEBY [66], an organization that standardizes energy simulation in junction with building regulations. The file has been generated based on models and interpolation of data from the 30-year series 1981–2010 for energy calculation programs. The resolution is 11x11 km around the resort. It is aimed to analyze if it is appropriate to keep using this climate file for simulation purposes, especially, analyzing the future cooling demand of the buildings or if it should be updated for proactive design purposes.

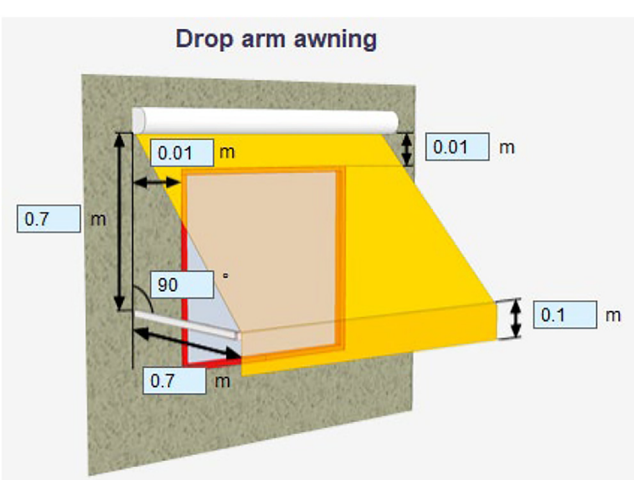

Fig. 4. Drop-arm awning configuration details. Figure from IDA to ICE software.

2.3.2. Addition of external automatic shading system

Automatic shades were added on the façade, above the windows. The shades are of the Drop arm awning type. Fig. 4 depicts the details of the awnings. These are utilized during warm period of May-August and the sensors are set to drop the awning to cover the windows when the solar radiation reaches 100 W/m^2 (1500 lx). Simulations were carried out for all the mentioned cooling technologies and for all mentioned periods.

2.4. Evaluation of changes in CO_2 emissions

Changes in CO_2 emissions were evaluated in this study. A framework was introduced by Levihn [67] which provides guidelines on the performance of different allocation methods to evaluate Carbon emission. This study considered the impact assessment for a future prototype building, therefore excluding the consequential analysis since no measurements or investment impacts were considered. Several studies have evaluated the emission changes in Sweden [6,68], Finland [69], etc., when different energy conservation methods (ECMs) are utilized.

Since the Swedish electricity grid is connected with Norway, Finland, Denmark, Germany, and Poland, considering a single national value for Swedish CO_2 emission is not relevant [70]. To evaluate the carbon emission changes, and analyze the impact assessment, the mean electricity composition mix for Nordic countries have been considered which corresponds to 90.4 gCO_2e/kWh [71].

The heat delivered to the buildings is considered to be from a District Heating System (DHS) with the following production mix for 2020 for the studied region: 60% residual heat from industry, 25% heat from combined heat and power plants that are fired with biofuels in the form of bark, 7% flue gas condenser, 7% wood from demolished buildings and other waste wood product and bio-oil and 1 % electricity [68,72]. The emission factor for DH for year 2020 was measured to be 3.66 g CO_2 equivalents/kWh [72]. District Cooling (DC) was considered as the cooling carrier for the building (cooling coil in the air handling unit as well as the local room cooling units). The Coefficient of Performance (COP) of the central chillers for the studied city were found to be four. Since the chillers use electricity as their energy carrier, the impact assessment for the cooling system was carried out using the mean electricity composition mix for Nordic countries. It is noteworthy that the Swedish electricity generation mix has a different value, however, the grid is highly interconnected and cannot be individualized [73]. This value was used to assess the carbon emission for Historic, Average and Extreme conditions. However, for the Mid-Future condition, based on the European Climate Law, mean electricity composition mix for Nordic countries was considered zero, since the Mid-Future climate is a presentative of 2050 s.

2.5. Primary energy number (PE_{PET})

As mentioned in the introduction section, primary energy is the energy in its natural state and it has not undergone any transformation. Therefore obtaining primary energy use can help calculating the environmental impact, since lower delivered energy cannot be concluded as lower primary energy use [16]. To calculate the building regulation PE_{PET}, weighting and geographical adjustment factors are required which are based on the National Board of Housing, Building and Planning building regulations [21]. The weighting factors are not the same as PEF, since the regulations has ambitions to navigate towards sustainable building solution, such as have a higher weight factor (high value is unfavorable) than the actual PEF. Based on Swedish building regulations, Eq. (1) is used to express the PE_{PET}. In order to meet the NZEB requirements, PE < 75 kWh/ (m^2·year).

$$PE_{PET} = \frac{\sum_{i=1}^{6}\left(\frac{E_{heating,i}}{F_{geo}} + E_{cooling,i} + E_{DHW,i} + E_{f,i}\right) \times WF_i}{A_{temp}} \quad (1)$$

where:

PE_{PET} Primary energy number, kWh/ (m^2 ·year)
$E_{heating}$ Energy for heating, kWh/year
F_{geo} Geographical adjustment factor
$E_{cooling}$ Energy for cooling, kWh/year
E_{DWH} Energy for domestic hot water, kWh/year
E_f Building operational electricity use, kWh/year
WF Weighting factor
i Index denoting energy carrier type

The operational electricity is related to the building's energy need, such as the electricity for pumps, fans, monitoring equipment, elevators, etc [9,21]. It should be pointed that tenant electricity is not considered in calculating the PE_{PET}. The value for F_{geo} and WF could be found in the building regulations [21]. The geographical factor is implemented to compensate for different climates in different regions [6] and is in this study F_{geo} = 1.1. The WF was chosen based on the energy carriers (district heating and cooling) with WF = 0.7 and 0.6 respectively.

2.6. Indoor comfort model

After finding the PE_{PET}, total energy use and CO_2 emission, a thermal comfort model was taken into account to explore the indoor conditions for each of the case studies. This is to evaluate the building performance from comfort point of view, also to ensure acceptable indoor conditions as lack of thermal comfort could lead to respiratory disorders [74]. In order to evaluate the thermal comfort conditions for all the cases considered, Predicted Percentage of Dissatisfied (PPD) was investigated. Based on the Swedish standard for indoor thermal comfort [75], different levels are considered for the indoor environment. If PPD is less than 6%, it is denoted as "Best". "Good" when PPD is less than 10% and "Acceptable" when PPD is less than 15%. However, PPD larger than 15% is considered "Unacceptable" [76]. To measure the thermal comfort in this study, an occupant was considered to be in the center of the zone, 0.6 m from the floor. The chosen metabolic value was 1.2 met, for the seated or relaxed condition. The clothing value ranges between 0.85 ± 0.25 clo. The PPD results were obtained by means of IDA-ICE simulation.

2.7. Limitations

Limitations associated with the generation of future climate files include the method and combination of GCM-RCM used, as well as the availability of observational data for the bias-correction process. Observational data may not be available on hourly basis or at all for all the climate variables. To overcome this issue, data has to be interpolated. Each apartment was considered as a zone. Also the building type and its geometrical configurations were limited in this study, although, it is within the scope of the project to evaluate more building geometries, and energy use, including commercial buildings, within larger scales in the future works.

3. Results and discussion

The results of the simulations are depicted in the following sections. Section 3.1 presents the result of the bias-corrected climate files to check if the process was well performed. In addition, figures are presented to show the evolution of the climate over time. Section 3.2 presents the result for energy performance of the different cooling technologies, for all five cooling set-points (24–28 °C), the mentioned climate files and the effect of shading on building energy use. Section 3.3 and 3.4 present the results for PE_{PET} and CO_2 emission for all the cases respectively. The comfort conditions for all the studied cooling technologies and climate files are investigated in Section 3.5.

3.1. Projection of future climate files

This section presents the result of the extracted and calibrated climate files. The calibration process was carried out by training a multivariate bias correction (MBC) method. The MBC model was used to predict bias corrected RCM data over the studied periods. Table 2 represents the statistical distribution of two climate variables. The data presented in the table include minimum and maximum as well as the quartiles (Qu), median and mean values for the observational, extracted and bias-corrected values. The bias-correction process has adjusted the simulated data to the observational data since the statistical distribution is the same as the observational datasets.

The frequency of the distributed representative variables of Table 2, for the observational and bias-corrected simulated data for the correction period (1986–2005) is shown in Fig. 5. Based on the result of the distribution frequency of the variables; the bias-correction process has calibrated the simulated data against the observational period.

Fig. 6 shows the regression evaluation for temperature and solar radiation for all the studied climates. The slope of the regression curve remains relatively the same regardless of the climate file used; however, the regression line is pushed upward when moving forward in time, representing the increase in ambient temperature while receiving relatively the same solar radiation. It could be concluded from the figure that cooling requirement of the buildings is dependent on the ambient temperature. Therefore, the type of cooling technology and the supply strategies are the key to keep indoor temperature within the defined range.

There exists a reduction in solar radiation for the Mid-future climate file. Global dimming has been studied in a number of studies [77–79]. GCM indicates a reduction in cloud cover over Europe therefore increase in surface solar radiation. On the other hand, RCMs do not show any significant changes in cloud cover, although the atmospheric absorption increases which leads to surface solar reduction [79]. Since the overall changes in solar radiation are relatively the same, as depicted in Fig. 6, it could also be inferred that the effect of shading systems, in terms of reduction in cooling requirement (kWh/m^2) remains quite unchanged over time.

Average and Mid-future climate files have been assembled based on CORDEX data, therefore uncertainties are inevitable. As can be seen from Fig. 6, there exists a line of data at 0 °C for these climate files which could be due to these uncertainties. The same figure was plotted for Average climate, though using an assembled TMY file from observational data for the same period (2001–2020). The "line" slightly above 0 °C was depicted, although not as clear as the line seen in the projected data. It is noteworthy that the latter mentioned figure is not presented in this study, as it was not within the scope and aims.

The curve of solar radiation against temperature is shown in Fig. 7 for monthly mean values in the studied city for all the four periods. Based on the results, the average monthly temperature increases over time. The changes in temperature are more perceptible during the summer period (May- August). The total average temperature of the Historic climate file is 5.8 °C while the average temperature for the present and mid-future TMY climate files are 6.9 and 8.8 °C. This implies the increased need in cooling demand of the building overtime to keep the indoor temperature within the comfort range.

Table 2
Statistical distribution dry bulb temperature and global solar irradiation for the historical period 1986–2005.

	Dry bulb temperature (°C)			Global solar irradiation (kJ/m^2)		
YEAR	Observation	Extracted	Bias-corrected	Observation	Extracted	Bias-corrected
Min. :1986	−27.4	−38.5	−27.4	0.0	0.0	0.0
1st Qu.:1991	−0.1	−0.8	−0.1	0.0	0.0	0.1
Median :1996	5.4	5.0	5.4	4.0	0.5	4.0
Mean :1996	6.0	4.9	6.0	108.4	88.7	108.5
3rd Qu.:2000	12.7	11.5	12.7	157.0	78.6	157.0
Max. :2006	33.9	33.4	33.9	803.0	801.3	803.0

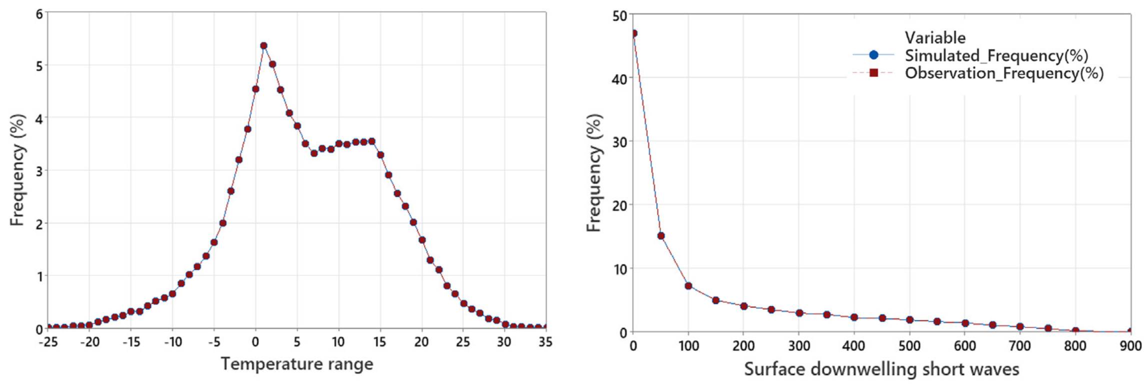

Fig. 5. Distribution frequency of two of the variables for observational and bias-corrected simulated data for the correction period (1986–2005).

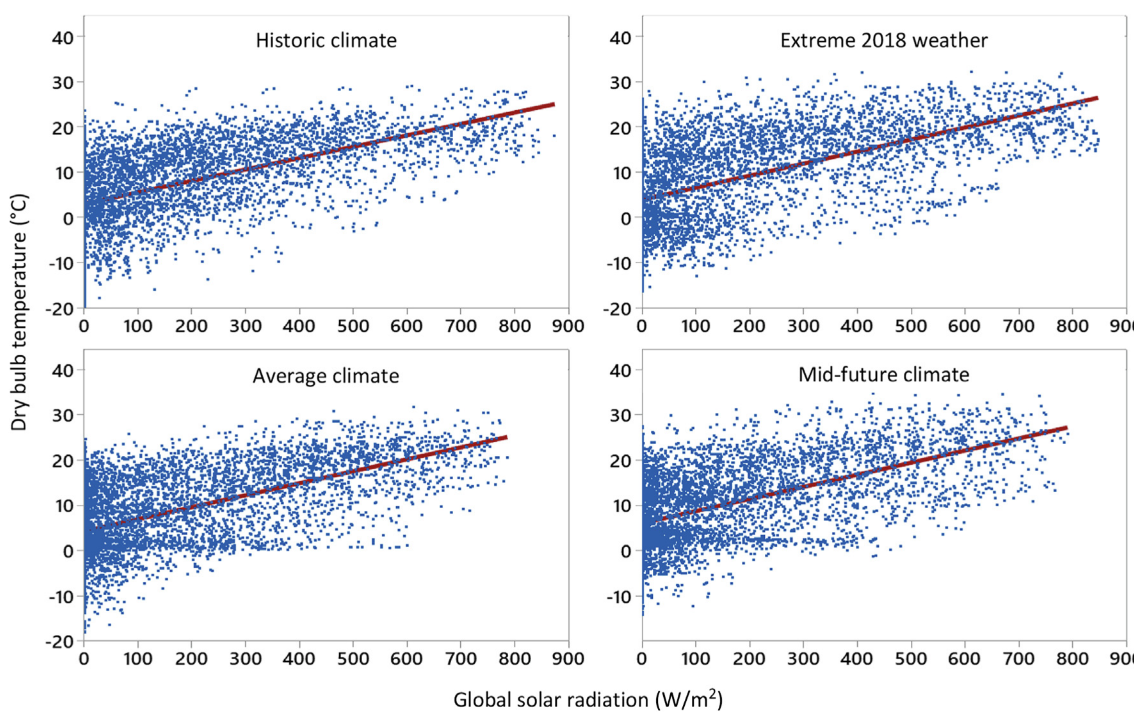

Fig. 6. Regression evaluation for the studied climates and the extreme weather 2018.

Depending on the models used, +0.8 °C to 3.5 °C increase in average temperature was depicted in [45]. Nik et al. [22] followed a different method based on [80] to generate weather files representing future climate. In their study, they also concluded increase in annual average temperature for the studied future climate files in relation to a baseline period 1960–1991.

3.2. Energy performance of the building

The result of the simulations (delivered energy) for the prototype building when employing the constant and schematic supply temperature strategies, for all cooling set-points and climate conditions are depicted in Fig. 8. Fig. 8a represents the case where

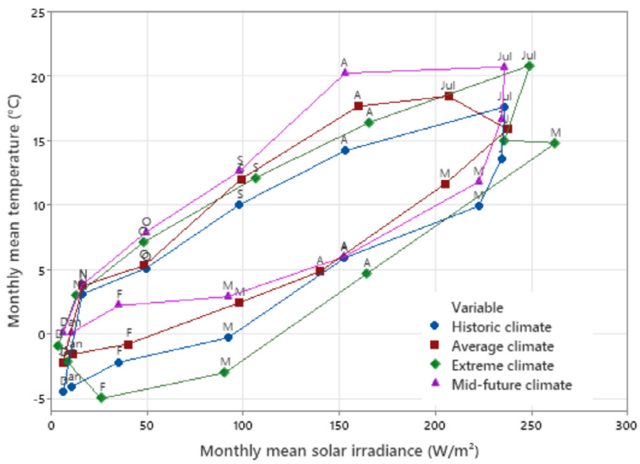

Fig. 7. Curve of average monthly solar radiation against temperature for all the climate files and the extreme weather 2018.

automatic shading system *was not* implemented and Fig. 8b represents the case where automatic shading system was implemented. The solid filled bars represent the case with constant supply temperature (16 °C) and the hatch filled bars represent the case with schematic supply scheme (Fig. 3). District heating includes both domestic hot water and zone heating, and tenant electricity is represented as *electricity*; aux is the annual energy used by facility equipment such as fans and pumps, 4.6 kWh/m^2. As it could be seen from Fig. 8, the required heating is lower when employing the Average and Mid-future climate files compared to the Historic climate file. On the other hand, the cooling demands, especially for the Extreme weather file, are higher.

From the breakdown of energy performance aspects in Fig. 8a, district heating increases 3% and district cooling decreases 16% for almost all the studied cooling set-points and climate files when using the schematic supply temperature compared to constant supply temperature. By examining the monthly energy use of the building, it was discovered that schematic supply strategy increases the heating requirement during September and October. The heating energy for the two implemented supply strategies was analyzed. It was found that during September and October, the ambient temperature distribution varies from 0 to 20 °C with mostly above 8 °C and below 16° C, which based on the scheme depicted in Fig. 3, within this range the heating coil is set to initiate reduction in the supply air temperature. Therefore, within this range, the supply air temperature for the AHU executing schematic supply strategy is below 16 °C, consequently the ideal heaters have to compensate for the deficiency of heat in the zones. Thus employing the schematic supply strategy increases the heat load in the zones compared to the constant supply strategy. On the other hand, when utilizing the schematic supply, the cooling load reduces due to the reduction in AHU's ambient supply temperature.

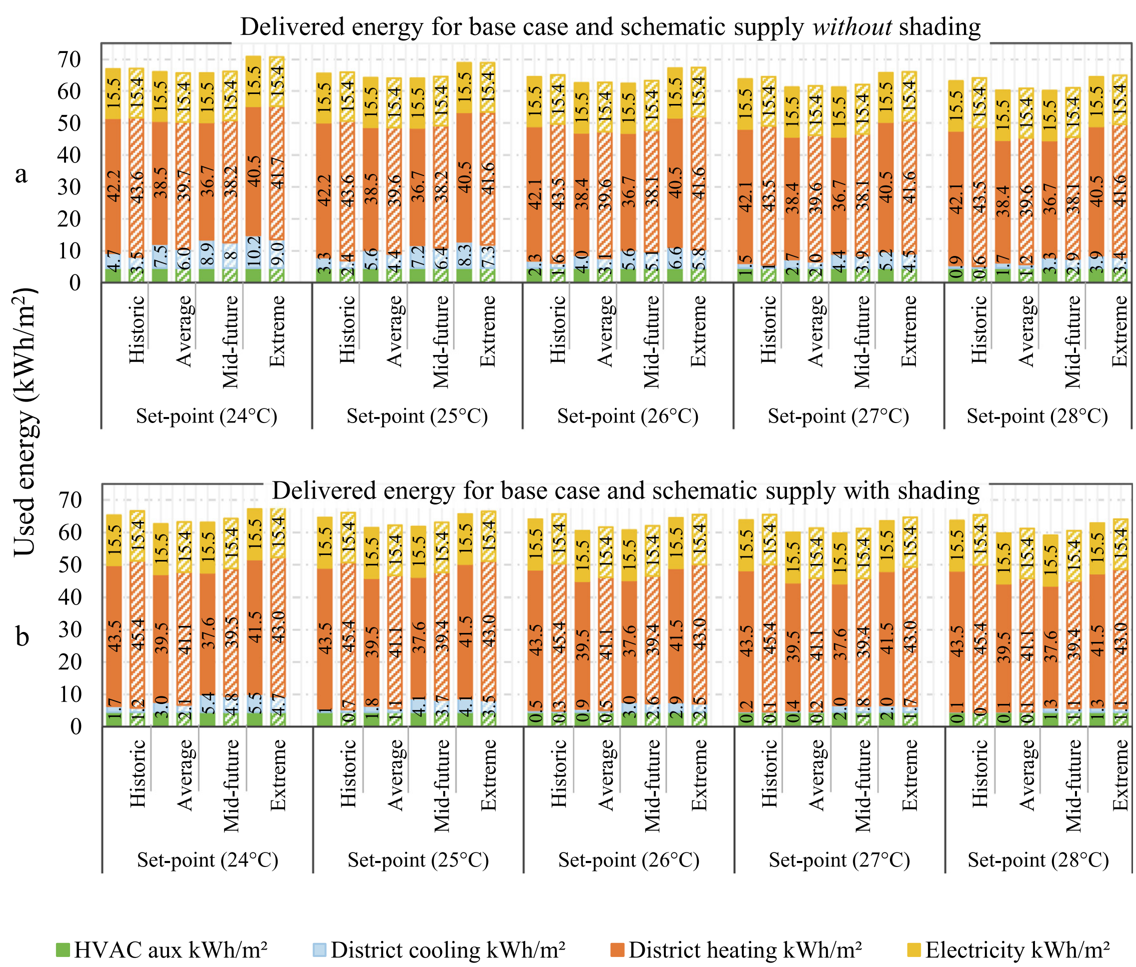

Fig. 8. Energy performance of the prototype nearly-Zero Energy Building (NZEB), a) constant and schematic supply strategy *without* shade. b). constant and schematic supply strategy with shade. *Solid filled bars* represent constant supply temperature. *Hatched bars* represent schematic supply temperature.

The increase in the heating demand and the GHG emission associated with it is not substantial from primary energy use point of view as the energy carrier for the heating system in district heating and renewable sources of energy are employed in the DHS. As mentioned in section 2.4, the carbon emission of the district heating system is 3.66 g CO_2 equivalents/kWh. However, the reduction of cooling demand on the other hand could be prioritized.

By comparing the heating and cooling energy use in Fig. 8b (where automatic shading was added) to Fig. 8a, it was discovered that on average, the heating energy use increased by 3%, cooling energy use decreased by 70%, for all the cooling set-points and climate files. The heating energy of the two supply strategies was analyzed to investigate these changes in heating energy use. Additional heating requirement (other than September and October) by the end of April and whole May was discovered. The shading system is scheduled to be activated during summer time (May-August). Since apart from cooling energy requirement, there is still some heating energy required during May, the shading system prevents the solar irradiation from entering the space, which blocks solar gain that helps reducing heating requirement during heating season.

Fig. 9 depicts the result of the simulations (delivered energy) when employing the CAV and VAV all-air cooling systems. Solid filled bars represent CAV and hatched bars represent VAV system. HVAC aux for CAV and VAV systems is almost 7 and 3.5 kWh/m^2 respectively. From the breakdown of energy performance aspects in Fig. 9a, district heating decreases 12% and district cooling increases 26% for almost all the studied cooling set-points and climate files when using the VAV system compared to CAV system.

By comparing Fig. 9a and b, heating demand has slightly increased on average 1%; cooling demand on the other hand has reduced, on average 45% for all the set-points when adding automatic shading. However, employing automatic shading appears more effective for VAV system compared to CAV system by comparing Fig. 9a and b. The changes in delivered energy is dominated by the reduction in cooling demand when adding shade for VAV system.

To analyze the effect of each cooling set-point on building's energy for all the climate files, Fig. 10 is plotted. Fig. 10a depicts the total energy use changes between Fig. 8a and b. Fig. 10b depicts the total energy use changes between Fig. 9a and b. The circle markers depict the constant supply strategy and the triangle markers depict the schematic supply strategy. From Fig. 10, it could be concluded that for every climate file by employing a lower cooling set-point, addition of shade helps in saving more cooling energy compared to higher set-points, regardless of the supply temperature or the ventilation strategies studied. The negative values represent reduction in energy use when automatic shades were added, compared to the case without shading system. It should be noted that total energy use i.e., district heating and cooling, electricity and HVAC aux were considered to plot Fig. 10.

When simulating using the lower cooling set-points (24, 25 and 26 °C), the cooling demand increases to keep the indoor temperature at the desired set-point. On the other hand, choosing higher cooling set-points (27 and 28 °C), reduces the cooling load required to maintain the indoor temperature. The Historic climate file shows the least amount of changes in total energy use, since during this period (1986–2010), the average annual temperature was 1.5 °C and 3 °C lower compared to Average and Mid-future climate files, respectively.

The slope of the presented results in Fig. 10a and b follow the same trend. Historic and Average climate, as shown in Fig. 7, have lower average monthly temperatures, therefore increase in heating load is more substantial compared to reduction of cooling load when adding the shading system. Therefore, this leads to a higher delivered energy than expected, as it was previously discussed in case of Figs. 8 and 9. On the contrary, in case of Mid-future and Extreme climate files, due to higher ambient temperatures, especially during summer, as presented in Fig. 7, changes in total delivered energy is dominated by the reduction in cooling load. The reduction in cooling load is more significant than increase in heating load, especially when using lower cooling set-points. Overall, both Extreme and Mid-future show the same energy change level as per Fig. 10. Based on Fig. 7, during summer, Extreme weather depicts higher solar radiation; though lower outdoor temperature. On the other hand, Mid-future climate shows lower solar radiation and higher outdoor temperature. The increase in the cooling demand corresponds to 1.7–5.8 times the Historic climate when employing the extreme and the assembled climate files.

These results are consistent with several earlier studies. Jylhä et al. [42] evaluated the heating and cooling demand for typical detached houses in Finland, reported 20–40% decrease in heating and 40–80% increase in the cooling requirements when employing projected climate file. A study carried out by Machard et al. [45] for a residential building in France also depicted increase in cooling requirement, by a factor 3 to 4 for future typical weather.

Thalfeldt et al. [81] studied the effect of automated external Venetian blind on the energy performance of NZEB in Estonia. The control schedule and the blinds were adopted from [82]. The shades were scheduled to be raised during winter. Beck et al. [82] reported a slight increase in heating and lighting demand and reduction in cooling demand especially for south orientations (over 70% reduction) in Stockholm. Similar result was depicted in this study, though with different external shade. On the other hand, Thalfeldt et al. [81] concluded that the shades were not economic due to high investment cost. Also for smaller windows, due to lower initial space cooling need, the reduction in cooling energy could not compensate the increase in heating and lighting, consequently it increased the primary energy use. However, these effectively reduced cooling need for large double or triple glazing windows.

3.3. The PE_{PET} evaluation for the studied prototype building

Fig. 11 presents PE_{PET} for all the cooling set-points, climate files and ventilation strategies. The values representing the CAV system and constant supply strategy are presented with circle markers. The values presenting the VAV system and schematic supply strategy are presented with triangle markers.

The extreme climate 2018 shows the highest PE_{PET} for each of the set-points, regardless of the ventilation or supply strategy in all the plots in Fig. 11. An average 3.3 K increase in temperature during year 2018, compared to 1961–1990 climatological mean was recorded [83,84]. The anomalies in the weather condition were caused due to high-pressure dominated weather and increased solar radiation due to clear skies as shown in Fig. 7. Therefore cooling demand was almost doubled compared to Average climate (the TMY assembled from 2001 to 2020). The second high PE_{PET} is associated with the Historic climate file. This is due to the relatively lower average monthly temperature, specifically for the heating season (September-May). The TMY file was based on the 30-year series data (1981–2010) from SMHI. Mid-future climate file has the third high PE_{PET}.

From the figure, when adding the automatic shading system, overall PE_{PET} decreases in all the studied climate and weather files. Cooling set-points 27 and 28 °C show the least reduction in PE_{PET} since addition of shades affect the cooling energy of the system, and as these two set-points do not require a high cooling energy, shading did not appear as effective when using lower cooling set-points.

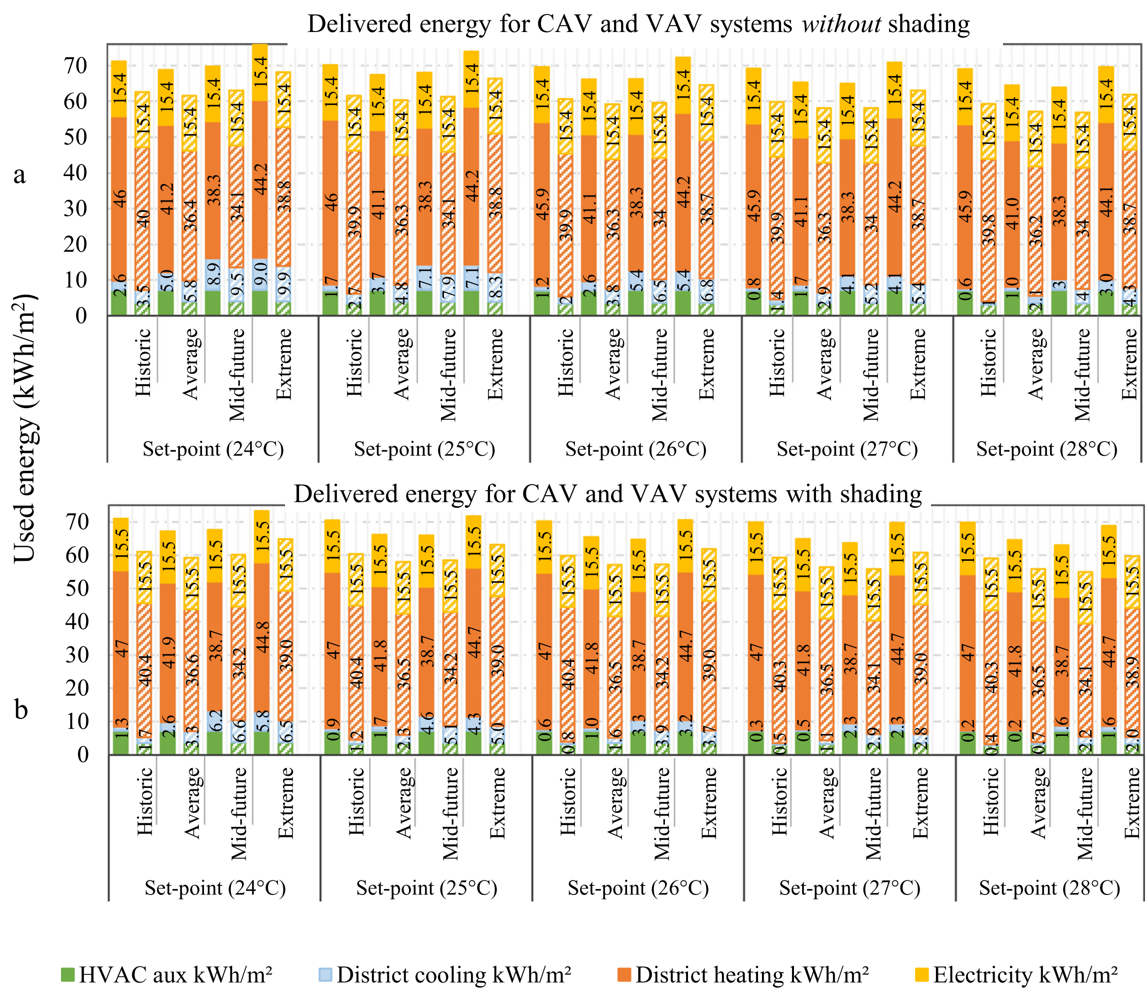

Fig. 9. Energy performance of the prototype nearly-Zero Energy Building (NZEB), a) CAV and VAV systems *without* shade. b). CAV and VAV system with shade. *Solid filled bars* represent CAV system. *Hatched bars* represent VAV system.

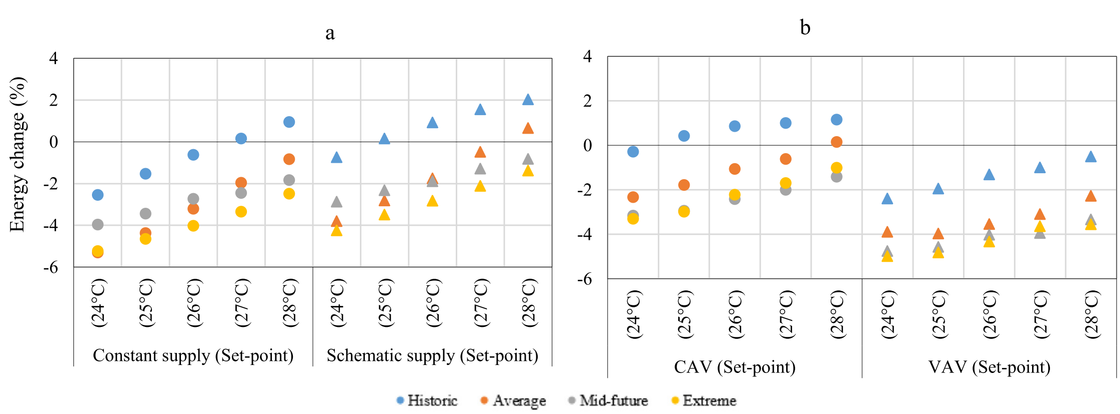

Fig. 10. a) Changes in total energy between Fig. 8a and b. b) Changes in total energy between Fig. 9a and b. The constant supply strategy and CAV system are represented with *Circle markers*. The schematic supply strategy and VAV system are represented with *triangle markers*.

In case of Historic and Average climate, the trend of result when adding the shades, is not as steep as the other studied climate files which is mainly due to the lower cooling demands, especially when operating with higher cooling set-points. PE_{PET} remains relatively the same when adding the shading systems for the mentioned climate files.

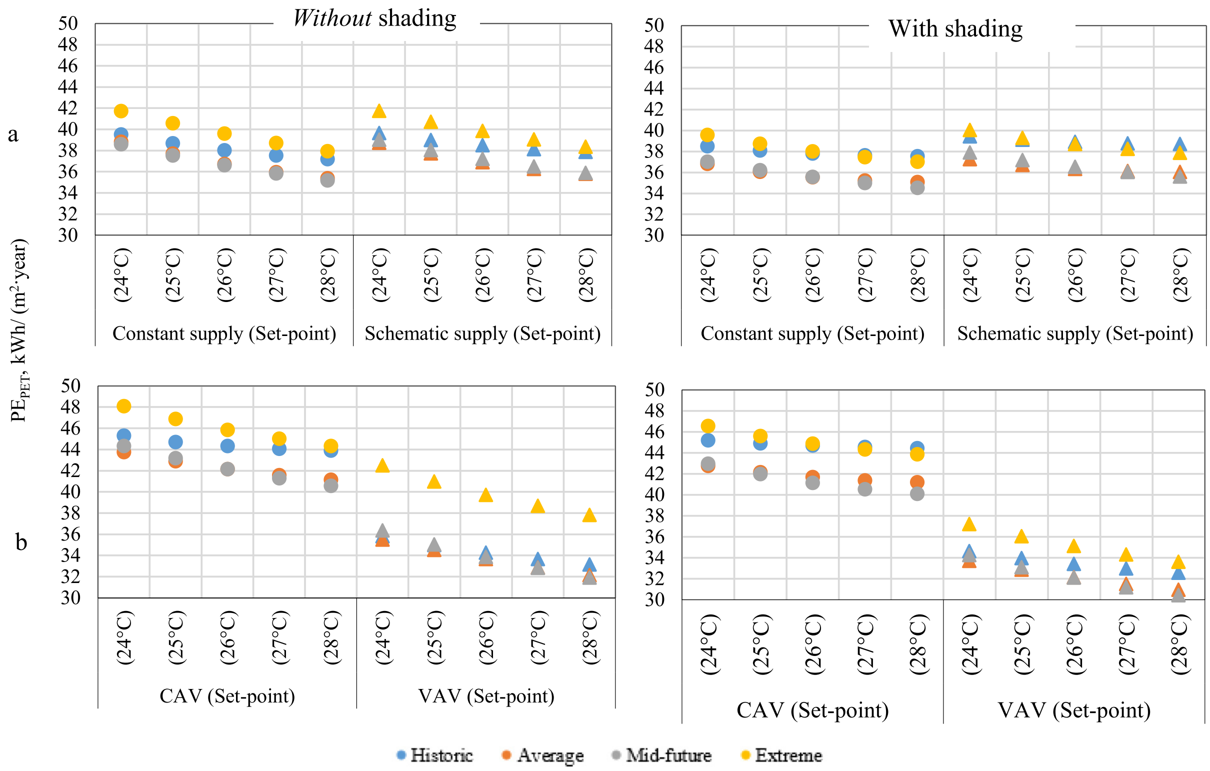

Fig. 11. *a*) PE_{PET} for the investigated prototype building for constant and schematic supply strategies. b) PE_{PET} for CAV and VAV systems. The constant supply strategy and CAV system are represented with *circle markers*. The schematic supply strategy and VAV system are represented with *triangle markers*.

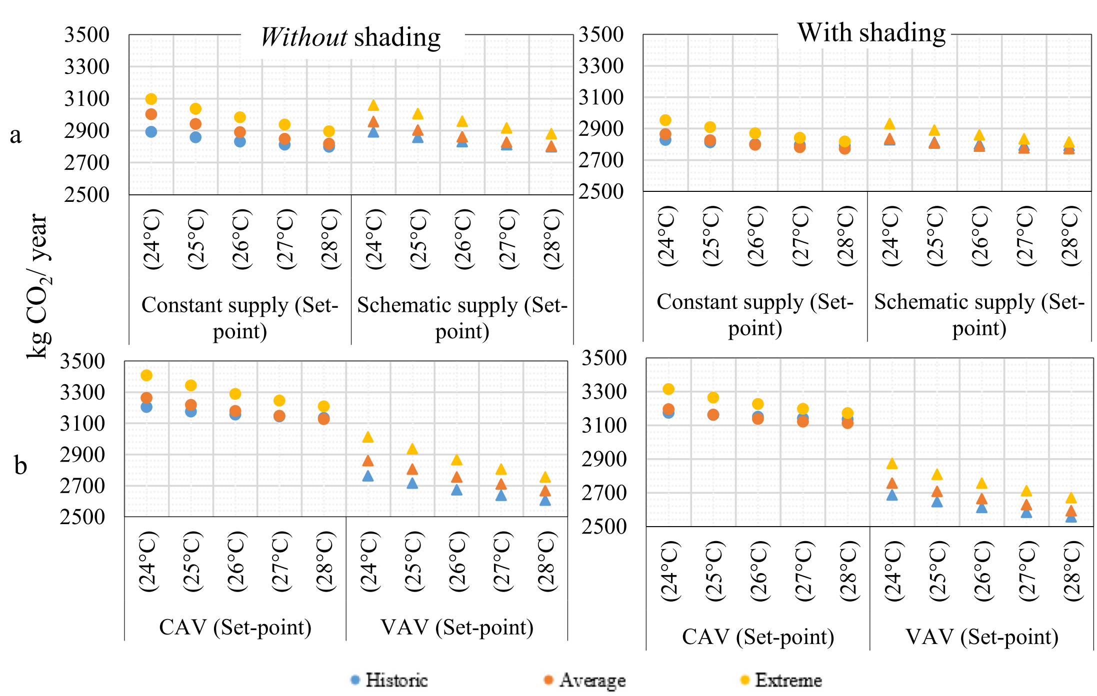

Fig. 12. The carbon emission for the Historic, Average and Extreme climate files and all cooling set-points. a) Depicts the CO_2 emission for constant and schematic supply strategy. b) Depicts the CO_2 emission for CAV and VAV system.

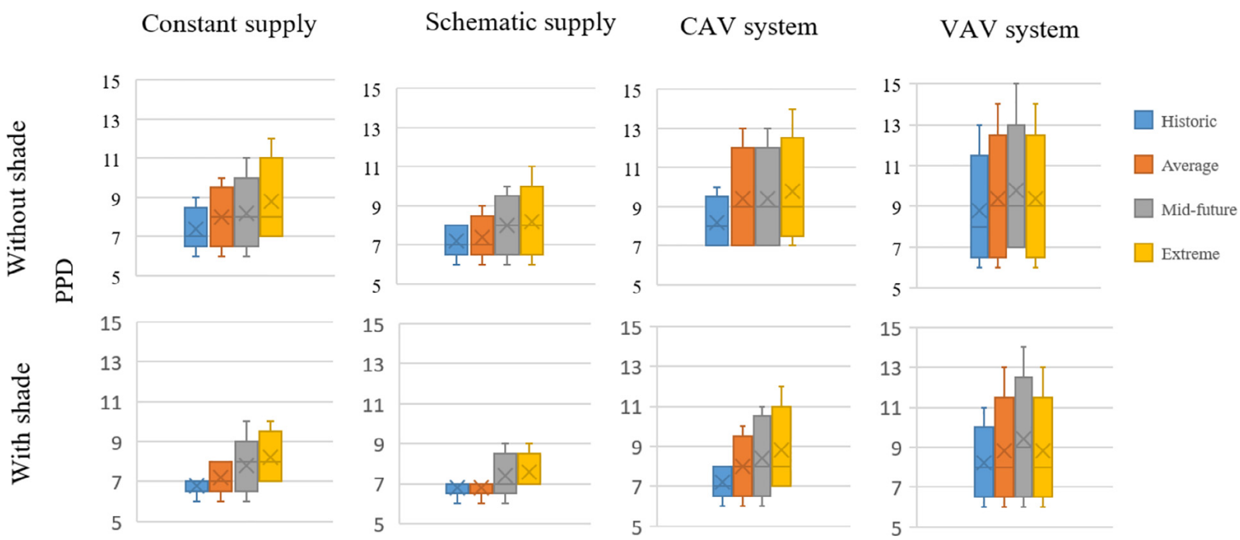

Fig. 13. Predicted Percentage of Dissatisfied (PPD) associated with all the cooling strategies.

3.4. CO_2 emission evaluation for the studied prototype building

The carbon emission from the building exposed to all the studied climate files and set-points have been plotted in Fig. 12. However as mentioned in the introduction part, based on the European Climate Law, the EU aims to become a climate neutral continent by 2050. Therefore, the emission factor for the Mid-future period was excluded from the calculations in order to match the European Climate Law.

Addition of shade reduces the carbon emission as it could be concluded from Fig. 12. Based on the results from Fig. 12a, the reduction in the CO_2 emission ranges from 0.3% to 4.7% for the studied climate files. The least amount of changes belong to the Historic climate with cooling set-point 28 °C and the highest value belongs to the cooling set-point 24 °C when employing the Extreme weather file. Overall addition of shades appear more advantageous when adopting the constant supply strategy and the reduction in the CO_2 emission is more evident when Extreme and Average climate files were employed. The mean electricity mix for the Nordic countries of today was employed as the allocating method to measure the CO_2 emission which corresponds to 90.4 g CO_2e/kWh [71]. The chillers in the DCS use electricity to match the cooling demand of the district. The COP for the system was found to be four. Historic climate was recognized as the climate file with the least cooling demand. Therefore, the carbon emission also is the least when using this climate file. On the other hand, the building shows higher cooling demand when employing the Extreme and Average climate files, therefore changes in cooling demand and consequently the CO_2 emission is more substantial. It must be noted that district cooling and heating use mostly free cooling and renewable sources of energy, as mentioned in section 2.4.

Much the same as the result from Fig. 12a, for Fig. 12b also addition of automatic shades helped in reducing the CO_2 emission for the two utilized all-air cooling systems. The least amount of changes belong to the Historic climate for CAV system, specifically when higher cooling set-points were employed for the ventilation system. On the other hand, VAV system shows further decrease in the CO_2 emission level after utilizing the automatic shading system. These reductions in the CO_2 emission range from 0% to 4.6% for the studied climate files.

3.5. Investigation of the comfort conditions

The predicted percentage of dissatisfied (PPD) associated with the studied ventilation strategies is depicted in Fig. 13. Boxplot was chosen to show the distribution of PPD over all the set-points for each climate. Each box represents the range of PPD for all the chosen set-points. Combination of schematic supply strategy and the automatic shading system depicts the least PPD, which overall lies within level "Good". However, employing the VAV system depicts the highest PPD within the studied cooling technologies that is placed in "Acceptable" level.

Fig. 14 depicts the exhaust air temperature for the studied cooling technologies during one year. The depicted results belong to the Historic and Mid-future climates, cooling set-point temperature 24 °C as a representative. The schematic supply strategy helps reducing the exhaust air temperature compared to the constant supply temperature. The reported exhaust temperature is the mean regulated value of the sum of exhaust airs from the zones. Decrease in exhaust air temperature, implies lower indoor temperature, therefore reduction in the cooling load when utilizing the schematic supply strategy. By evaluating the thermal indoor conditions, percentage of total occupant hours with thermal dissatisfaction associated with schematic supply strategy, indicated better indoor conditions compared to constant supply strategy. By comparing the variations of PPD ranges for CAV and VAV with the two supply strategies, it could be concluded that ideal local coolers maintained the temperature within the defined set-point, which is an ideal case. However, CAV and VAV adopt a more practical practice as the variations in PPD is larger, depicting the delay within the system to adjust to the set-points. By checking the maximum operative temperature for different zones, it was discovered that in the top floor zones, the operative temperature exceeds the cooling set-point for up to 3 °C. However, that is not the case for the constant and schematic supply strategy as an ideal local cooler is employed in each zone. It is usually acceptable for the room temperature to rise above

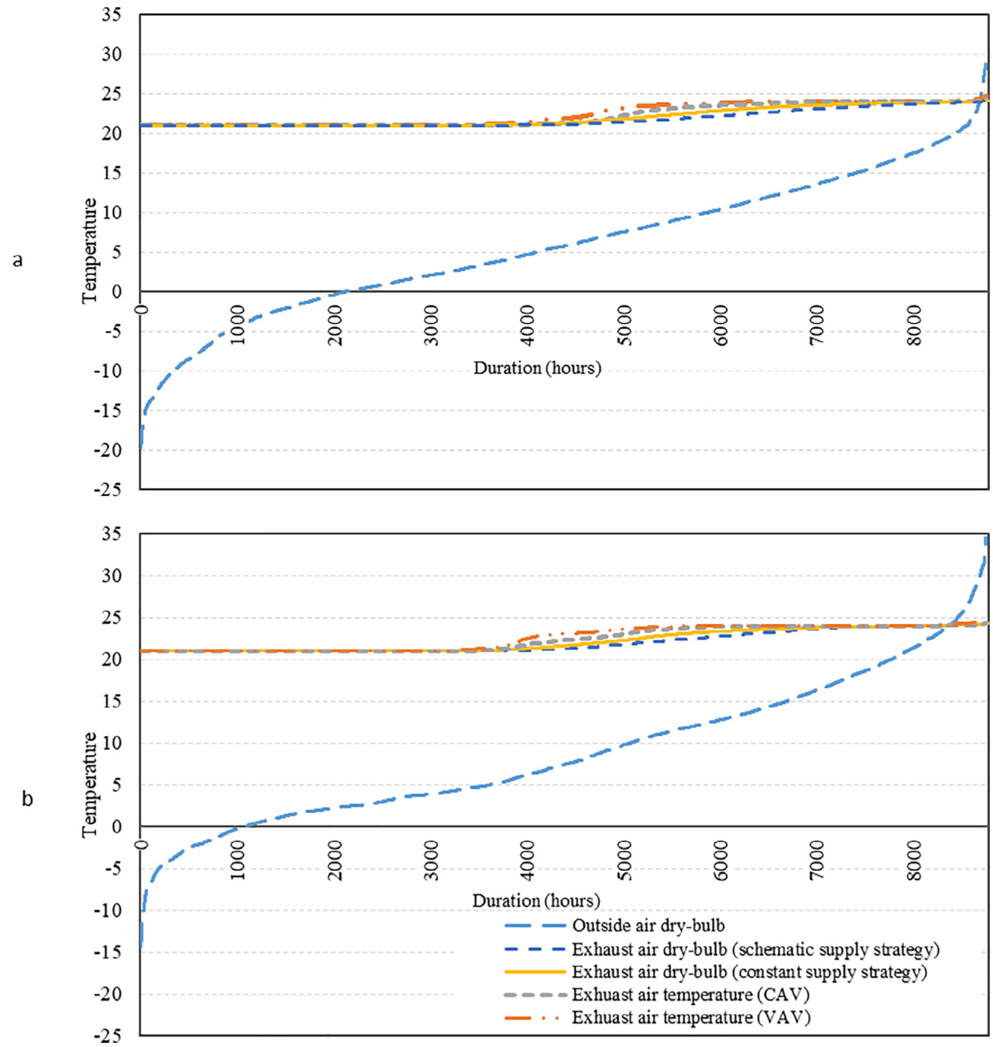

Fig. 14. Exhaust air temperatures for the studied cooling technologies for cooling set-point temperature 24 °C. a) Representing variables for *Historic climate*. b) Representing variables for *Mid-future climate.*

the defined set-point for short intervals as it requires an advanced HVAC system to keep a constant indoor temperature [85].

4. Conclusion

This study aimed to answer two research questions: Is it possible to use currently available typical meteorological year (TMY) climate files to evaluate the future energy need of buildings?

Moreover, how to improve the indoor thermal conditions and reduce CO_2 emission from building operation, and evaluate the effects on primary energy use?

The energy criteria to fulfil the Swedish building regulations are based on a typical meteorological year to estimate the energy use of the building, which in this study the climate was referred to as Historical climate. PE_{PET} also, is based on weighted values depending on the sources of energy the building uses. Historical, Average, Mid-future TMY files as well as an extreme weather file of year 2018 were used to evaluate the climate-driven energy demand. The Historical climate file, which is the typical weather file used for assigning regulation, underpredicetd the cooling demand for the residential prototype building. The required cooling energy use increased from 1.7 to 5.8 times the Historic climate file when employing the Average, Mid-future and extreme climate files, respectively.

This implied the need to update the climate files that are used for building simulations. Cooling systems should be designed and operated to be resilient under extreme conditions to protect occupants from potentially dangerous indoor thermal conditions.

Four different cooling methods were introduced. Two all-air cooling systems, constant air volume (CAV) and variable air volume (VAV) as well as two different supply strategies for air temperature, constant and schematic supply, for a mechanical ventilation system with room units were defined.

Increasing the cooling set-point reduced PE_{PET} up to 5.5%. The effectiveness of the schematic supply strategy was more perceptible compared to the constant supply strategy as it effectively reduced the cooling energy need of the building (up to 28%) by reducing the indoor air temperature. Therefore, more number of hours were found to be below the required set-points. However, addition of shade increased the heating energy need especially for schematic supply strategy due to the additional heating energy required during May. Therefore, combination of automatic shading and schematic supply strategy does not appear as effective as the same ventilation *without* shade from PE_{PET} and energy use perspective. However, PPD is higher for the latter case.

For the studied all-air cooling systems, VAV depicted a lower delivered energy compared to the CAV system. Addition of shades reduced the cooling and consequently reduced the PE_{PET}. The changes in energy were dominated by the cooling demand, which depicted 45% reduction on average.

From the studied cooling methods for the four climate files, combination of all-air cooling system, VAV, with automatic shading system, showed the least total energy use. The total annual energy use for the other cooling systems was 4–17% more compared to the mentioned technology. Constant supply strategy with automatic shading system could be considered, after the former mentioned combination. These two mentioned technologies, combined with the introduced shading system, showed to be more resilient towards the induced climate changes.

Apart from the thermal comfort improvement when combining shading system with the studied cooling methods, the CO_2 emission also reduced. The emission abatement is more substantial for cooling set-points 24–26 °C when adding the shading system, due to the larger cooling load.

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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] Y. Cui, D. Yan, T. Hong, C. Xiao, X. Luo, Q. Zhang, Comparison of typical year and multiyear building simulations using a 55-year actual weather data set from China, Appl. Energy. 195 (2017) 890–904, https://doi.org/10.1016/j.apenergy.2017.03.113.

[2] Y.H. Yau, S. Hasbi, A review of climate change impacts on commercial buildings and their technical services in the tropics, Renew. Sustain. Energy Rev. 18 (2013) 430–441, https://doi.org/10.1016/J.RSER.2012.10.035.

[3] T. W. T. Abergel, B. Dean, J. Dulac, I. Hamilton, Global Status Report Towards a zero-emission, efficient and resilient buildings and construction sector, 2018. www.iea.org (accessed November 6, 2021).

[4] H. Campaniço, P.M.M. Soares, R.M. Cardoso, P. Hollmuller, Impact of climate change on building cooling potential of direct ventilation and evaporative cooling: a high resolution view for the Iberian Peninsula, Energy Build. 192 (2019) 31–44, https://doi.org/10.1016/j.enbuild.2019.03.017.

[5] European Commission, A European Green Deal | European Commission, (n.d.). https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en (accessed May 27, 2021).

[6] M. Gustafsson, R. Thygesen, B. Karlsson, L. Ödlund, Rev-changes in primary energy use and CO2 emissions - An impact assessment for a building with focus on the Swedish proposal for nearly zero energy buildings, Energies. 10 (7) (2017) 978, https://doi.org/10.3390/en10070978.

[7] European Commission, European Climate Law | Climate Action, (n.d.). https://ec.europa.eu/clima/policies/eu-climate-action/law_en (accessed May 27, 2021).

[8] European Commission, European Union. Energy efficient buildings, (n.d.). https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings_en (accessed May 27, 2021).

[9] M. Wallhagen, J. Akander, A. Hayati, M. Cehlin, B. Karlsson, Viewpoints on environmental assessment of building certification method - Miljöbyggnad, IntechOpen (2021), https://doi.org/10.5772/INTECHOPEN.100699.

[10] European Commission, Official Journal of the European Union L208, (2016) 2. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L:2016:208:TOC (accessed May 28, 2021).

[11] European Commission, Official Journal of the European Union L 153, (2010). doi:10.3000/17252555.L_2010.153.eng.

[12] European Commission, Official Journal of the European Union L 81, (2012). doi:10.3000/19770677.L_2012.081.eng.

[13] European Commission, Official Journal of the European Union C 115, (2012). doi:10.3000/1977091X.C_2012.115.eng.

[14] E. Latõšov, A. Volkova, A. Siirde, J. Kurnitski, M. Thalfeldt, Primary energy factor for district heating networks in European Union member states, in: Energy Procedia, Elsevier Ltd, 2017, pp. 69–77, https://doi.org/10.1016/j.egypro.2017.05.056.

[15] D. D'Agostino, Assessment of the progress towards the establishment of definitions of Nearly Zero Energy Buildings (nZEBs) in European Member States, J. Build. Eng. 1 (2015) 20–32, https://doi.org/10.1016/j.jobe.2015.01.002.

[16] M. Swing Gustafsson, M. Gustafsson, J.A. Myhren, E. Dotzauer, Primary energy use in buildings in a Swedish perspective, Energy Build. 130 (2016) 202–209, https://doi.org/10.1016/j.enbuild.2016.08.026.

[17] M.K. Dixit, C.H. Culp, J.L. Fernandez-Solis, Calculating primary energy and carbon emission factors for the United States energy sectors, RSC Adv. 4 (97) (2014) 54200–54216.

[18] J. Gode, F. Martinsson, L. Hagberg, A. Öman, J. Höglund, D. Palm, Miljöfaktaboken 2011 Uppskattade emissionsfaktorer för bränslen, el, värme och transporter, Stockholm, Sweden, 2011.

[19] T. Duh Čož, A. Kitanovski, A. Poredoš, Primary energy factor of a district cooling system, Stroj. Vestnik/J. Mech. Eng. 62 (12) (2016) 717–729, https://doi.org/10.5545/sv-jme.2016.3777.

[20] BPIE, Nearly Zero Energy Buildings Definitions across Europe, (2015) 8. https://www.bpie.eu/ (accessed May 28, 2021).

[21] Boverket, Konsekvensutredning BFS 2020:4 Boverkets föreskrifter om ändring i verkets byggregler (2011:6) – föreskrifter och allmänna råd, BBR, avsnitt 5 och 9, BBR 29, 2020.

[22] A. Moazami, V.M. Nik, S. Carlucci, S. Geving, Impacts of future weather data typology on building energy performance – Investigating long-term patterns of climate change and extreme weather conditions, Appl. Energy. 238 (2019) 696–720. doi:10.1016/j.apenergy.2019.01.085.

[23] S. Petersen, The Effect of Local Climate Data and Climate Change Scenarios on the Thermal Design of Office Buildings in Denmark, in: IBPSA-Nordic, 13th-14th Oct. 2020, Oslo, 2020: pp. 179–186.

[24] M. Herrera, S. Natarajan, D.A. Coley, T. Kershaw, A.P. Ramallo-González, M. Eames, D. Fosas, M. Wood, A review of current and future weather data for building simulation, Build. Serv. Eng. Res. Technol. 38 (5) (2017) 602–627, https://doi.org/10.1177/0143624417705937.

[25] A. Argiriou, S. Lykoudis, S. Kontoyiannidis, C.A. Balaras, D. Asimakopoulos, M. Petrakis, P. Kassomenos, Comparison of methodologies for TMY generation using 20 years data for Athens, Greece, Sol. Energy. 66 (1) (1999) 33–45, https://doi.org/10.1016/S0038-092X(99)00012-2.

[26] G. Pernigotto, A. Prada, A. Gasparella, J.L.M. Hensen, Analysis and improvement of the representativeness of EN ISO 15927–4 reference years for building energy simulation, J. Build. Perform. Simul. 7 (6) (2014) 391–410, https://doi.org/10.1080/19401493.2013.853840.

[27] I.A. Rahman, J. Dewsbury, Selection of typical weather data (test reference years) for Subang, Malaysia, Build. Environ. 42 (10) (2007) 3636–3641, https://doi.org/10.1016/j.buildenv.2006.10.004.

[28] O.S. Ohunakin, M.S. Adaramola, O.M. Oyewola, R.O. Fagbenle, Generation of a typical meteorological year for north-east, Nigeria 112 (2013) 152–159, https://doi.org/10.1016/j.apenergy.2013.05.072.

[29] F. Bre, V.D. Fachinotti, Generation of typical meteorological years for the Argentine Littoral Region, Energy Build. 129 (2016) 432–444, https://doi.org/10.1016/j.enbuild.2016.08.006.

[30] A. Dodoo, L. Gustavsson, F. Bonakdar, Effects of future climate change scenarios on overheating risk and primary energy use for Swedish Residential Buildings, Energy Procedia. 61 (2014) 1179–1182, https://doi.org/10.1016/J.EGYPRO.2014.11.1048.

[31] A. Eklund, J.A. Mårtensson, S. Bergström, E. Björck, J. Dahné, L. Lindström, D. Nordborg, J. Olsson, L. Simonsson, E. Sjökvist, Sveriges framtida klimat Underlag till Dricksvattenutredningen, Sweden, 2015.

[32] D.J. Griggs, M. Noguer, Climate change The scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change, Weather 57 (2002) (2001) 267–269, https://doi.org/10.1256/004316502320517344.

[33] S. Erba, F. Causone, R. Armani, The effect of weather datasets on building energy simulation outputs, in: Energy Procedia, Elsevier Ltd, 2017, pp. 545–554, https://doi.org/10.1016/j.egypro.2017.09.561.

[34] N. Nakicenovic, J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Grubler, T.Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, D. Zhou, IPCC SPECIAL REPORT: EMISSIONS SCENARIOS, 2000. https://escholarship.org/uc/item/9sz5p22f (accessed June 11, 2021).

[35] R.K. Pachauri, L. Meyer, S. Hallegatte France, W. Bank, G. Hegerl, S. Brinkman, L. van Kesteren, N. Leprince-Ringuet, F. van Boxmeer, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth

Assessment Report of the Intergovernmental Panel on Climate Change, Gian-Kasper Plattner, Geneva, Switzerland, 2014. http://www.ipcc.ch. (accessed May 31, 2021).
[36] F. Kreienkamp, H. Huebener, C. Linke, A. Spekat, Good practice for the usage of climate model simulation results - a discussion paper, Environ. Syst. Res. 1 (1) (2012) 9, https://doi.org/10.1186/2193-2697-1-9.
[37] D. Ramon, K. Allacker, N.P.M. van Lipzig, F. De Troyer, H. Wouters, Future Weather Data for Dynamic Building Energy Simulations: Overview of Available Data and Presentation of Newly Derived Data for Belgium BT - Energy Sustainability in Built and Urban Environments, Springer Singapore, Singapore, 2019, pp. 111–138, https://doi.org/10.1007/978-981-13-3284-5_6.
[38] J.A. Dirks, W.J. Gorrissen, J.H. Hathaway, D.C. Skorski, M.J. Scott, T.C. Pulsipher, M. Huang, Y. Liu, J.S. Rice, Impacts of climate change on energy consumption and peak demand in buildings: a detailed regional approach, Energy. 79 (2015) 20–32, https://doi.org/10.1016/j.energy.2014.08.081.
[39] A.L.S. Chan, Developing future hourly weather files for studying the impact of climate change on building energy performance in Hong Kong, Energy Build. 43 (10) (2011) 2860–2868, https://doi.org/10.1016/j.enbuild.2011.07.003.
[40] Y. Arima, R. Ooka, H. Kikumoto, T. Yamanaka, Effect of climate change on building cooling loads in Tokyo in the summers of the 2030s using dynamically downscaled GCM data, Energy Build. 114 (2016) 123–129, https://doi.org/10.1016/j.enbuild.2015.08.019.
[41] V.M. Nik, A. Sasic Kalagasidis, Impact study of the climate change on the energy performance of the building stock in Stockholm considering four climate uncertainties, Build. Environ. 60 (2013) 291–304, https://doi.org/10.1016/j.buildenv.2012.11.005.
[42] K. Jylhä, J. Jokisalo, K. Ruosteenoja, K. Pilli-Sihvola, T. Kalamees, T. Seitola, H.M. Mäkelä, R. Hyvönen, M. Laapas, A. Drebs, Energy demand for the heating and cooling of residential houses in Finland in a changing climate, Energy Build. 99 (2015) 104–116, https://doi.org/10.1016/j.enbuild.2015.04.001.
[43] C. Zhang, O.B. Kazanci, R. Levinson, P. Heiselberg, B.W. Olesen, G. Chiesa, B. Sodagar, Z. Ai, S. Selkowitz, M. Zinzi, A. Mahdavi, H. Teufl, M. Kolokotroni, A. Salvati, E. Bozonnet, F. Chtioui, P. Salagnac, R. Rahif, S. Attia, V. Lemort, E. Elnagar, H. Breesch, A. Sengupta, L.L. Wang, D. Qi, P. Stern, N. Yoon, D.-I. Bogatu, R.F. Rupp, T. Arghand, S. Javed, J. Akander, A. Hayati, M. Cehlin, S. Sayadi, S. Forghani, H. Zhang, E. Arens, G. Zhang, Resilient cooling strategies – a critical review and qualitative assessment, Energy Build. 251 (2021) 111312.
[44] IEA EBC, The International Energy Agency's Energy in Buildings and Communities Programme, (2021). https://www.iea-ebc.org/ (accessed June 18, 2021).
[45] A. Machard, C. Inard, J.M. Alessandrini, C. Pelé, J. Ribéron, A methodology for assembling futureweather files including heatwaves for building thermal simulations from the European coordinated regional downscaling experiment (EURO-CORDEX) climate data, Energies. 13 (2020) 3424, https://doi.org/10.3390/en13133424.
[46] ESGF, ESGF-LLNL - Home | ESGF-CoG, (n.d.). https://esgf-node.llnl.gov/projects/esgf-llnl/ (accessed June 10, 2021).
[47] S. Kotlarski, K. Keuler, O.B. Christensen, A. Colette, M. Déqué, A. Gobiet, K. Goergen, D. Jacob, D. Lüthi, E. Van Meijgaard, G. Nikulin, C. Schär, C. Teichmann, R. Vautard, K. Warrach-Sagi, V. Wulfmeyer, Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble, Geosci. Model Dev. 7 (2014) 1297–1333, https://doi.org/10.5194/gmd-7-1297-2014.
[48] A.J. Cannon, Multivariate bias correction of climate model output: matching marginal distributions and intervariable dependence structure, J. Clim. 29 (2016) 7045–7064, https://doi.org/10.1175/JCLI-D-15-0679.1.
[49] A.J. Cannon, Multivariate quantile mapping bias correction: an N-dimensional probability density function transform for climate model simulations of multiple variables, Clim. Dyn. 50 (1-2) (2018) 31–49, https://doi.org/10.1007/s00382-017-3580-6.
[50] Gävle kommun, The industry - one of Europe's most sustainable districts - Gävle municipality, (2021). https://www.gavle.se/kommunens-service/bygga-trafik-och-miljo/planer-och-samhallsbyggnadsprojekt-i-gavle/pagaende-byggprojekt-i-gavle/naringen/ (accessed January 7, 2022).
[51] SCB, Statistikmyndigheten SCB, (n.d.). https://www.scb.se/ (accessed January 17, 2022).
[52] Sveby, Brukarindata bostäder, Branschstandard För Energi i Byggnader, Stock. Version 1. (2012) PP.28. http://www.sveby.org/wp-content/uploads/2012/10/Sveby_Brukarindata_bostader_version_1.0.pdf (accessed December 14, 2020).
[53] Equa Simulation, Building Performance - Simulation Software | EQUA, (n.d.). https://www.equa.se/en/ (accessed August 19, 2020).
[54] ANSI/ASHRAE, Standard 140-2017: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs, Ashrae. (2017).
[55] H.-L. Achermann Matthias, Hochschule Technik+Architektur Luzern HLK Engineering VALIDATION OF IDA ICE, Version 2.11.06 With IEA Task 12-Envelope BESTEST, 2000. http://www.equaonline.com/iceuser/validation/old_stuff/BESTEST_Report.pdf (accessed February 16, 2021).
[56] S. Kropf, G. Zweifel, Validation of the Building Simulation Program IDA-ICE According to CEN 13791 "Thermal Performance of Buildings-Calculation of Internal Temperatures of a Room in Summer Without Mechanical Cooling-General Criteria and Validation Procedures," 2001. http://www.equaonline.com/iceuser/validation/ice_vs_pren13791.pdf (accessed February 16, 2021).
[57] P. Sahlin, L. Eriksson, P. Grozman, H. Johnsson, A. Shapovalov, M. Vuolle, Whole-building simulation with symbolic DAE equations and general purpose solvers, in: Build. Environ., Elsevier BV, 2004, pp. 949–958, https://doi.org/10.1016/j.buildenv.2004.01.019.
[58] S. Moosberger, IDA ICE CIBSE-Validation Test of IDA Indoor Climate and Energy version 4.0 according to CIBSE TM33, issue 3 Report 2007-12-17, 2007. http://www.equaonline.com/iceuser/validation/ICE-Validation-CIBSE_TM33.pdf (accessed February 16, 2021).
[59] H. Bakhtiari, J. Akander, M. Cehlin, A. Hayati, On the performance of night ventilation in a historic office building in Nordic climate, Energies. 13 (2020) 4159, https://doi.org/10.3390/en13164159.
[60] J.S. Englund, M. Cehlin, J. Akander, B. Moshfegh, Measured and Simulated Energy Use in a Secondary School Building in Sweden—A Case Study of Validation, Airing, and Occupancy Behaviour, Energies 2020, Vol. 13, Page 2325. 13 (2020) 2325. doi:10.3390/EN13092325.
[61] A. Hayati, Measurements and modeling of airing through porches of a historical church, Sci. Technol. Built Environ. 24 (3) (2018) 270–280, https://doi.org/10.1080/23744731.2017.1388132.
[62] L. Liu, B. Moshfegh, J. Akander, M. Cehlin, Comprehensive investigation on energy retrofits in eleven multi-family buildings in Sweden, Energy Build. 84 (2014) 704–715, https://doi.org/10.1016/J.ENBUILD.2014.08.044.
[63] R. Westin, HUSHÅLLSEL I NYBYGGDA FLERBOSTADSHUS, Hudiksvall, Sweden, 2019.
[64] EQUA, IDA-Indoor Climate and Energy Support, (n.d.). http://www.equaonline.com/iceuser/new_documentation.html (accessed February 7, 2021).
[65] L.E. Ekberg, R1 - riktlinjer för specifikation av inneklimatkrav., [4., rev., EMTF förlag, 2013. https://search.ebscohost.com/login.aspx?direct=true&AuthType=shib&db=cat02894a&AN=hig.14971981&lang=sv&site=eds-live&custid=s3912055.
[66] SVEBY, Sveby | Branchstandard för energi i byggnader, (n.d.). http://www.sveby.org/ (accessed June 21, 2021).
[67] F. Levihn, CO2 emissions accounting: whether, how, and when different allocation methods should be used, Energy. 68 (2014) 811–818, https://doi.org/10.1016/j.energy.2014.01.098.
[68] M. Gustafsson, M. Rönnelid, L. Trygg, B. Karlsson, CO2 emission evaluation of energy conserving measures in buildings connected to a district heating system - case study of a multi-dwelling building in Sweden, Energy. 111 (2016) 341–350, https://doi.org/10.1016/j.energy.2016.05.002.
[69] S. Rinne, S. Syri, Heat pumps versus combined heat and power production as CO2 reduction measures in Finland, Energy. 57 (2013) 308–318, https://doi.org/10.1016/j.energy.2013.05.033.
[70] J. Orgen, S. Odin, S.G. Onkvist, Emissions accounting for use and supply of electricity in the Nordic market, Energy Policy. 32 (2004) 1555–1564, https://doi.org/10.1016/S0301-4215(03)00129-0.
[71] A. Sandgren, J. Nilsson, Emissionsfaktor för nordisk elmix med hänsyn till import och export, IVL Swedish Environmental Research Institute, Forskningsinstitut, Executive, 2021. http://naturvardsverket.diva-portal.org/smash/get/diva2:1540012/FULLTEXT01.pdf.
[72] Gävle Energi, Gävle Energi AB, (n.d.). https://www.gavleenergi.se/ (accessed June 4, 2021).
[73] E. Dotzauer, Greenhouse gas emissions from power generation and consumption in a Nordic perspective, (2009). doi:10.1016/j.enpol.2009.10.066.
[74] C. Sun, G. Cai, W. Liu, Z. Zou, C. Huang, Thermal comfort in residences related to respiratory diseases among preschool children in Shanghai, Energy Build. 236 (2021) 110729.
[75] EN 15251:2007, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, (2007). https://ci.nii.ac.jp/naid/20001266485/en/.
[76] L. Liu, P. Rohdin, B. Moshfegh, Evaluating indoor environment of a retrofitted multi-family building with improved energy performance in Sweden, Energy Build. 102 (2015) 32–44, https://doi.org/10.1016/j.enbuild.2015.05.021.
[77] J.A. Crook, L.A. Jones, P.M. Forster, R. Crook, Climate change impacts on future photovoltaic and concentrated solar power energy output, Energy Environ. Sci. 4 (2011) 3101–3109, https://doi.org/10.1039/C1EE01495A.
[78] G. Stanhill, S. Cohen, Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences, Agric. For. Meteorol. 107 (4) (2001) 255–278, https://doi.org/10.1016/S0168-1923(00)00241-0.
[79] B. Bartók, M. Wild, D. Folini, D. Lüthi, S. Kotlarski, C. Schär, R. Vautard, S. Jerez, Z. Imecs, Projected changes in surface solar radiation in CMIP5 global climate models and in EURO-CORDEX regional climate models for Europe, Clim. Dyn. 49 (2017) 2665–2683, https://doi.org/10.1007/S00382-016-3471-2/FIGURES/7.
[80] V.M. Nik, Making energy simulation easier for future climate – synthesizing typical and extreme weather data sets out of regional climate models (RCMs), Appl. Energy. 177 (2016) 204–226, https://doi.org/10.1016/j.apenergy.2016.05.107.
[81] M. Thalfeldt, E. Pikas, J. Kurnitski, H. Voll, Facade design principles for nearly zero energy buildings in a cold climate, Energy Build. 67 (2013) 309–321, https://doi.org/10.1016/j.enbuild.2013.08.027.

[82] W. Beck, D. Dick, G. Dutoo, A. Hall, O. Seppänen, Solar shading, Finland, 2010. https://scholar.google.com/scholar_lookup?title=Solar shading&author=W. Beck&publication_year=2010.
[83] SMHI, Väder Väderprognoser Klimat- & Vädertjänster i Sverige | SMHI, (n.d.). https://www.smhi.se/q/Myrbacken/Götene/2690682 (accessed December 1, 2020).
[84] R. Wilcke, E. Kjellström, C. Lin, D. Matei, A. Moberg, The extremely warm summer in Sweden – set in a historical context, Earth Syst. Dyn. Discuss. 11 (2020) (2018) 1107–1121, https://doi.org/10.5194/esd-2020-25.
[85] P.E. Nilsson, Achieving the Desired Indoor Climate –Energy Efficiency Aspects of System Design, Narayana Press, Denmark, 2003.