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# Assessing the Impact of Climate Change on Building Energy Performance: A Future-Oriented Analysis on the UK

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**Abstract:** This research explores how climate change will affect building energy use across the UK by analysing both a conventional reference building design and a net-zero energy (NZEBs) alternative to assess how each would perform under future weather conditions. Using climate projections from databases like Prometheus and Meteonorm, along with simulation tools like EnergyPlus and Freds4Buildings, the study evaluates the energy performance, costs, and GHG emissions of a case study building under current weather conditions, with 2030, 2050, and 2080 forecasts in three different UK locations: Exeter, Manchester, and Aberdeen. Results indicate that heating demand will decrease consistently over time across all locations by as much as 21% by 2080 while cooling demand will rise sharply. NZEBs proved more resilient to these changes, using less energy and producing fewer GHG emissions than conventional buildings, with 89% reductions in emissions even with increased cooling needs. Accounting for future weather helps both understand the risks of conventional design, with a number of scenarios experiencing overheating in 2080 and ensure NZEBs can meet their goals during their entire lifespan despite the increases in energy needs. The study highlights both the impact of accounting for future weather forecasts during design and the increasing relevance of net-zero energy designs in mitigating the effects of climate change while offering practical insights for architects, policymakers, and energy planners, showing why future weather patterns need to be considered in sustainable building design to ensure buildings will achieve their carbon targets throughout their life.

**Keywords:** climate change; building energy performance; net zero; future weather; overheating risk



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## 1. Introduction

In recent years, global environmental challenges, particularly climate change, have profoundly impacted various sectors, with the building industry being one of the most affected. As the effects of climate change become more pronounced, there is an increasing need for resilient, energy-efficient building designs that can adapt to both current and future climatic conditions [1]. The United Kingdom, in particular, faces substantial challenges, with projected temperature increases leading to significant shifts in energy demands for heating and cooling systems [2].

The construction and operation of buildings in the UK will need to adjust to these climatic changes by incorporating climate-adaptive designs and energy-efficient technologies. The use of energy simulation software and detailed weather data plays a crucial role in predicting the performance of buildings under varying climatic conditions [3]. Traditionally, such simulations have relied on historical weather data, which can be insufficient for designing future-proof buildings. To create long-term sustainable solutions, it is essential to integrate future climate predictions into building energy simulations [4].

While there has been significant research on building energy performance using historical climate data, a gap remains in understanding how future weather conditions will affect energy demands in buildings. The reliance on current and past climate data—such as typical meteorological year (TMY) data—limits the ability to predict long-term performance, especially in light of projected climate warming [5]. Historical data, while useful for assessing typical energy use, cannot account for the anticipated rise in average temperatures and extreme weather events [6].

Furthermore, existing weather datasets such as TMY, TMY2, and TMY3, while providing extensive data on current conditions, fall short of addressing the complexities of future climate scenarios. Future weather data files (FWDF) are necessary in order to provide a more forward-looking approach by integrating climate change projections under varying emission scenarios [7,8] (further discussed in Section 2.1). These tools allow for the examination of long-term impacts on energy performance, making them invaluable for energy simulations and policy formulation [9].

Several studies have explored the impact of climate change on building energy performance, focusing on the use of future weather data files to improve the accuracy of energy simulations. Moazami et al. (2019) investigated the application of dynamically downscaled future weather data and found that considering both typical and extreme climate conditions is crucial for assessing the energy robustness of buildings, highlighting the increase in extreme hot weather and peak cooling demand in Geneva [9]. In a similar vein, Troup et al. (2019) utilized an ensemble of global climate models (GCMs) to simulate future energy consumption in office buildings, revealing significant increases in cooling demands, especially in regions like San Francisco, where cooling needs were previously minimal [3]. Shen (2017) also examined the US building sector using downscaled hourly future weather data, projecting considerable impacts on residential and office buildings, including increased cooling loads and reduced heating demands [2].

Additionally, Jafarpur and Berardi (2019) highlighted the importance of utilising future weather files for energy performance simulations, demonstrating that these files can better account for variations in heating and cooling loads under climate change scenarios in Canadian buildings [10]. Similarly, Hosseini et al. (2021) proposed a machine-learning approach to generate high-resolution future weather data for building energy simulations, showing that more precise climate data could improve the prediction of future energy demands [11].

Moreover, Tootkaboni et al. (2021) compared various future weather data generation methods and their effects on building energy performance in Italy, underscoring the variability in performance predictions based on the type of data used and the characteristics of the buildings being studied [12]. Meanwhile, Ashrafian (2023) studied the impact of climate change on school buildings in Turkey, highlighting how the performance of highly efficient buildings today may become comparable to inefficient ones under future climate [13].

These studies collectively underscore the usefulness of using accurate, future-oriented weather data to predict building energy performance in a changing climate; however, when using a case study approach, they tend to only address a single building or building type, missing the opportunity to explore how different building types and designs might be affected by the change in climate to different extents. This study builds from them and aims to assess the impact of climate change on the energy performance of buildings in the UK, using historic, current, and future weather data. The choice to focus on the UK climate is due to the wide availability of past and future weather data and the peculiarity of a heating-dominated climate that will see the rise of cooling demand over the coming years. The primary objective is to quantify the changes in operational energy consumption—particularly heating and cooling demands—over time as climate conditions shift. The research explores both traditional (reference) buildings, which are designed to meet current UK building regulations, and net-zero energy buildings (NZEB), which are designed to minimize energy use and emissions through the integration of advanced technologies like photovoltaic (PV) systems and high-efficiency HVAC systems. By examining both conventional and net-zero designs, this study provides evidence of how different building types will perform under future climatic conditions.

This research makes several important contributions to the field of sustainable building design and climate-adaptive architecture. First, it highlights the importance of assessing the energy performance of new buildings by utilizing future weather data, allowing for a more accurate representation of future energy demands, and provides a methodology that can be easily replicated in other projects. Second, the study highlights the potential benefits of net-zero energy buildings in reducing future energy consumption and greenhouse gas emissions when assessed in the context of the changing future weather rather than limiting the analysis to historical data. In a future where cooling demands are expected to rise due to increasing temperatures, this research provides critical insights into how building designs in the United Kingdom will need to change and adapt to handle these shifts in energy usage. Additionally, by comparing different climate scenarios and their corresponding energy demands, this study supports the formulation of more effective building regulations and energy policies that align with the UK's commitment to reducing carbon emissions and promoting sustainable development [14]. This research can serve as a model for future studies in other regions, providing a replicable approach to assessing building performance under varying climatic conditions.

## 2. Methodology

As a preliminary step for this study, an analysis of current weather data files was performed to derive insights into prevailing climatic conditions in the UK. This preliminary analysis was performed through the use of the OneBuilding [15] database and with the support of the CBE Clima Tool [16] for rapid analysis of the different weather files in order to identify a limited number of locations to further study, as seen in Section 2.1.1. Subsequently, the three different UK locations identified have been further analysed in terms of future weather data. Future weather data files (FWDF) for the locations have been obtained from available sources such as Prometheus [17] and Meteonorm [18] and compared for consistency; further details about this step can be found in Section 2.1.2.

Subsequently, the investigation on future weather was extended to the domain of dwellings through the definition of a case study featuring both a conventional design in terms of energy performance for new UK domestic buildings and a net-zero design aimed at optimising energy performance through high-performance materials, HVAC systems, and renewable technologies. The case studies were then modelled and simulated through dynamic building performance simulation tools such as EnergyPlus [19] and FREDS4Buildings [20,21] to allow comparison of the energy behaviour of both building designs under future weather conditions in different UK locations. Further details on this can be found in Section 2.2.

### *2.1. The Weather Data Files*

Weather or climate data files are textual files that contain data about weather conditions for a specific location and period. They contain the data on temperature, atmospheric pressure, wind, humidity, and cloud cover. They can also be used in software to simulate the behaviour of buildings in a certain scenario.

#### 2.1.1. The Current Weather Data Files

There are different classes of current weather data files: TMY, TMY2, TMY3, TMYx, and EWDF.

The typical meteorological year (TMY) collates selected weather data for a specific location, listing hourly values of solar radiation and meteorological elements for one year [22]. Its data is frequently used in building simulation to assess the building design's expected heating and cooling performance. Designers of solar energy systems including solar domestic hot water systems and large-scale solar thermal power plants, also use it. Since they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location.

The second edition of the TMY is called "TMY2" and is based on 239 stations' data collected between 1961 and 1990. The TMY2 includes the precipitable water data (precipitable moisture), which is important in predicting radiative cooling. To account for the recent changes in climate, an updated TMY collection set called "TMYx" has been published, covering the period from 2006 to 2021 for about 16,000 locations globally [23,24].

The TMY3 data was designed to maximize both the number of stations and the number of years from which to characterise the typical conditions. At sites where data were available for 30 years, the base period for the TMY algorithm spanned from 1976 to 2005. The remaining sites' base time spanned from 1991 to 2005. In general, the TMY2 and TMY3 data sets were created using similar procedures [25].

Current weather data files for a number of locations around the globe are typically stored in publicly available databases, although, if necessary, they can be both generated manually or by a number of platforms able to interpolate from existing weather data locations. In this study, the main analysed databases are OneBuilding and EnergyPlus, and the CBE Clima Tool platform was used to support the preliminary analysis of the available data.

OneBuilding [15] hosts climate data specifically designed to support building simulations. The files primarily utilise the "EPW" format, although other formats are also available. The data consists of typical meteorological years (TMY) published by various organizations, with TMYx datasets being generated by the website's authors. TMYx files represent typical meteorological data derived from hourly weather data up to 2021 from the US NOAA's Integrated Surface Database (ISD). Currently, there are over 16,100 TMYx locations provided. The 2022/2023 release included full TMYx, 2007–2021 TMYx, but excluded the 2004–2018 TMYx. There is TMYx data available for all 249 countries listed in the ISO list [26], using WMO (World Meteorological Organization) designations for the sites and organized in WMO regions. Some regions may include duplicates of countries, such as the Russian Federation being listed in both WMO Region 2 (Asia) and WMO Region 6 (Europe). Climate files are divided into continents and countries. EnergyPlus [19] is an energy analysis and thermal load simulation program. Beyond its applications in building performance simulation, EnergyPlus has its own weather file database for 3034 locations, currently accessible in the EPW (EnergyPlus weather) format. This dataset includes 1494 locations in the USA, 80 locations in Canada, and over 1450 locations spread across 98 other countries worldwide. The weather data is organized based on WMO regions and individual countries.

The CBE Clima Tool is a web-based application designed to facilitate climate analysis, specifically catering to the needs of architects and engineers engaged in climate-adapted design. It provides users with the capability to analyse climate data for over 27,500 locations worldwide, sourced from both EnergyPlus and OneBuilding. Alternatively, users have the option to upload their own EPW weather file. The tool enables the analysis and visualization of data present in EPW files. Additionally, it computes various climate-related metrics, such as solar azimuth, altitude, and comfort indices, among others. Moreover, the tool allows the user to analyse and visualise climatic data via a map-based interface, easily access EPW files, and upload their own.

A combination of both databases and tools was used in this study to assess the availability and variability of current weather data files in the UK and select a subset of relevant locations to further analyse in terms of future weather data and the impact of climate change on building energy performance through the proposed case study.

#### 2.1.2. The Future Weather Data Files

A FWDF (Future Weather Data File) is a novel form of weather file that, starting from current weather data, depicts the anticipated annual weather conditions for a specific location in intervals of 10, 25, 50, 80, and 100 years into the future, such files can be generated with different methods [12]. For each future period, there exist the 10th, 50th, and 90th percentiles, corresponding to different warming levels. The 50th percentile reflects the warming midpoint. Given the inherent uncertainty in future climate conditions, a risk management approach is advised for cooling and heating system design. Practitioners may utilize multiple sets of files, considering the defined percentiles for risk-based decisions, where 10% and 90% signify unlikely extremes, 50% is the median estimate, and the range between 33% and 66% is generally considered equally likely. Simulation using different percentiles allows for informed, risk-conscious decision-making [27].

The emission scenario encompasses three levels: high (RCP 8.5), medium (RCP 4.5), and low (RCP 2.6). Each scenario represents a different trajectory for radiative forcing (rf) and assumptions about global annual greenhouse gas (GHG) emissions:

- RCP 2.6: This scenario follows a pathway where radiative forcing peaks at approximately 3 $W/m^2$ before 2100 and then declines. Additionally, it assumes that global annual GHG emissions (measured in $CO_2$-equivalents) peak between 2010 and 2020, with substantial declines thereafter.
- RCP 4.5: An intermediate stabilization pathway wherein radiative forcing is stabilized at around 4.5 $W/m^2$ after 2100. This scenario assumes that emissions peak around 2040 and subsequently decrease.
- RCP 6.0: Another intermediate stabilization pathway where radiative forcing stabilizes at approximately 6.0 $W/m^2$ after 2100. RCP 6.0 envisions that global annual GHG emissions (measured in $CO_2$-equivalents) peak around 2080 and then decline.
- RCP 8.5: This high pathway involves radiative forcing exceeding 8.5 $W/m^2$ by 2100 and continuing to rise for some duration. The RCP 8.5 scenario assumes that emissions will continue to increase throughout the 21st century [28,29].

Future weather data files can be obtained from various databases or manually generated. The most common databases for the UK are CIBSE, Weathershift, CCWorldWeatherGen, Prometheus, and Meteonorm. This study will focus on weather data generated by Prometheus and Meteonorm; however, a brief description of each database is included in this section.

CIBSE Weather Data Files

The CIBSE (Chartered Institution of Building Services Engineers) licenses historic weather data from the Met Office for 16 locations in the UK, with three situated in London. This weather data is synthesized into two CIBSE weather file types: design summer year (DSY) and test reference year (TRY). The UK Meteorological Office (MO) gathers weather data from stations across the UK, including climate variables like air temperatures, wind speed and direction, and air pressure measured at hourly intervals. The TRY consists of 12 separate months, each representing an average month derived from collected data. It is utilized for energy analysis and compliance with UK Building Regulations (Part L). On the other hand, the DSY represents a single continuous year, crucial for overheating analysis. Additional parameters include percentiles and Emission Scenarios. CIBSE weather data is available for purchase and includes projections for 2020, 2050, and 2080 [30].

Prometheus

The Prometheus database was developed by a team from the University of Exeter's Centre for Energy and the Environment, who led the Engineering and Physical Sciences Research Council-funded PROMETHEUS project, which aims to assist designers in creating new buildings tailored to the evolving local climate. The imperative prompted the project to rectify the flawed practice of modelling buildings using historical weather data, as relying on such data could result in new schools, hospitals, and care homes becoming unsuitable within 40 years. The project has received wider recognition, including in the Government report "Low Carbon Construction Plan—Government Response to the Low Carbon Construction Innovation and Growth Team" [31], with the team believing that this acknowledgment will help convince the building industry and its regulators of the urgency to address the challenges posed by climate change. [32] Prometheus offers test reference year (TRY) and design summer year (DSY), and future weather data files (FWDF) with medium and high emission scenarios, featuring percentiles at 10, 33, 50, 66, and 90 in the ".epw" format. The advantage of this software is its provision of data with various parameters. However, the drawbacks include the limited number of locations (51 in the UK) and the lack of updates, with current weather files based on data from 1961 to 1990, and the latest updates to the database ranging from 2010 to 2012, depending on location [33].

Meteonorm

Meteonorm [18] is a sophisticated climate database and software tool designed to provide reliable and accurate weather data for a wide range of applications, including building energy simulations, solar energy system design, and agricultural planning. The database encompasses over 8000 weather stations, five geostationary satellites, and an aerosol climatology-calibrated global grid dataset. Advanced interpolation models based on the available data are applied to deliver highly accurate weather data for any needed location. By combining Meteonorm's existing database, interpolation algorithms, and stochastic generation, the tool enables the calculation of typical years for any site across diverse scenarios and for any period spanning from 2010 to 2200. Meteonorm uses a straightforward model to generate realistic monthly time series for future periods. This model was developed by examining past variations and climate model forecasts. Compared to intricate, time-consuming downscaling methods based on regional climate models, Meteonorm provides a relatively uncomplicated approach to enhancing spatial and temporal resolution [34]. However, Meteonorm is not freely or fully publicly available as it is commercial software subject to licensing.

Weathershift

WeatherShift is an interactive online tool provided by IES that allows users to generate new simulation weather files representing future predicted climate data using any TMY, AMY, or XMY Weather File based on a range of emission scenario options. For each specified location and chosen future scenario, it generates three weather files representing 10th, 50th, and 90th percentiles of future warming [35]. Similar to other databases, WeatherShift is also not freely available, and access to the generated weather files is subject to payment of fees [36].

CCWorldWeatherGen

Lastly, CCWorldWeatherGen [37] (Climate Change World Weather File Generator) is a free, downloadable tool developed by the University of Southampton [38] that allows users to create future weather data files by "morphing" existing TMY weather data files to reflect the effects of climate change. It allows for different IPCC Climate Scenarios and support locations worldwide. However, due to its nature as a research-oriented tool and its being based on older versions of Microsoft® Excel (pre-2010) incompatible with current software versions, it can prove challenging to use.

### *2.2. Simulations*

Case Study

In order to assess the impact of climate change on buildings, a case study is defined as a newly built residential building under the different design variations detailed below and in Table 1. The case study represents a typical medium block of flats with 9–12 apartment units on three floors and an underground floor used for services. The case study is then modelled and simulated in EnergyPlus through the FREDS interface. The structure of Table 1 reflects the inputs required by the model. Simulation results in terms of energy use, and thermal comfort conditions are then used to compare the different building designs in different future weather conditions and different locations, as detailed in Section 3.

**Table 1.** Summary of building characteristics (differences between C1a and C2 shaded in green).

| | Case 1: Reference | Case 1a: Reference with Cooling | Case 2: Net-Zero |
|---|---|---|---|
| **General** | | | |
| location | Exeter-Manchester-Aberdeen | Exeter-Manchester-Aberdeen | Exeter-Manchester-Aberdeen |
| orientation | // | // | // |
| end use | Residential Detached | Residential Detached | Residential Detached |
| **Geometry** | | | |
| number of floors above the ground | 3 | 3 | 3 |
| length of south/north front | 30 | 30 | 30 |
| length of west/est front | 10 | 10 | 10 |
| floor to floor height | 3.5 | 3.5 | 3.5 |
| average floor survace | 300 | 300 | 300 |
| underground floor end use | Gymnasium | Gymnasium | Gymnasium |
| **Windows** | | | |
| window category | Double glazed with PVC frame | Double glazed with PVC frame | Triple glazed with PVC frame |
| glazing system | Double—Selective + clear—Air—4(12)4 | Double—Selective + clear—Air—4(12)4 | Triple—Clear glass + 2 low-e glasses—Argon—4(10)4(10)4 |
| total north facing surface | 60 | 60 | 60 |
| total south facing surface | 60 | 60 | 60 |
| total west facing surface | 24 | 24 | 24 |
| total east facing surface | 24 | 24 | 24 |
| **Construction** | | | |
| Construction preset | Heavyweight brick masonry with hollowbricks roof | Heavyweight brick masonry with hollowbricks roof | High capacity metal substructure wall with sandwich panel roof |
| External walls category | Solid wall—external insulation | Solid wall—external insulation | Metal substructure wall—external insulation |
| External walls construction: | Hollow bricks—380 mm | Hollow bricks—380 mm | Sandwich panel |
| External walls' insulation | Rock wool | Rock wool | XPS |
| External walls transmittance | 0.26 W/m$^2$K | 0.26 W/m$^2$K | 0.12 W/m$^2$K |
| Underground walls category: | Solid underground wall—external insulation | Solid underground wall—external insulation | Cavity underground wall—external insulation |
| Underground walls construction | Hollow bricks—380 mm | Hollow bricks—380 mm | Lightweight concrete blocks—200 + 50 + 100 mm |
| Underground walls' insulation | Rock wool | Rock wool | XPS |
| Underground walls transmittance | 0.26 W/m$^2$K | 0.26 W/m$^2$K | 0.12 W/m$^2$K |
| Roof category | Sloped concrete roof—external insulation | Sloped concrete roof—external insulation | Flat concrete roof—external insulation |
| Roof construction: | Sloped hollow bricks slab + false ceiling—200 + 50 mm | Sloped hollow bricks slab + false ceiling—200 + 50 mm | Flat polystyrene blocks slab + false ceiling—240 + 50 mm |
| Roof insulation | Rock wool | Rock wool | XPS |
| Roof transmittance | 0.18 W/m$^2$K | 0.18 W/m$^2$K | 0.1 W/m$^2$K |
| Ground floor category | Concrete slab—internal insulation | Concrete slab—internal insulation | Concrete slab—internal insulation |
| Ground floor construction | Concrete slab above ground—300 mm | Concrete slab above ground—300 mm | Concrete slab above ground—300 mm |
| Ground floor insulation | Rock wool | Rock wool | XPS |
| Ground floor transmittance: | 0.18 W/m$^2$K | 0.18 W/m$^2$K | 0.1 W/m$^2$K |
| **HVAC** | | | |
| Heating system | Condensing boiler | Condensing boiler | Water/ground source heat pump |
| Heating energy source: | Natural Gas | Natural Gas | Electricity |
| Thermostat heating setpoint: | 21 °C | 21 °C | 21 °C |
| Thermostat heating setback | 18 °C | 18 °C | 18 °C |
| Heating coefficient of performance | 0.91 | 0.91 | 4.7 |
| Heat recovery efficiency | 0 | 0 | 0 |
| Heating GHG emissions: | 202 g/kW | 202 g/kW | 193 g/kW |
| Heating energy price | 0.07 GBP/kWh | 0.07 GBP/kWh | 0.27 GBP/kWh |
| Cooling system | // | Air cooled chiller | Water/ground source heat pump |
| Cooling energy source | // | Electricity | Electricity |
| Thermostat cooling setpoint | // °C | 26 °C | 26 °C |
| Thermostat cooling setback | // °C | 28 °C | 28 °C |
| Coling coefficient of performance | // | 2.9 | 4 |
| Cooling GHG emissions: | // g/kW | 193 g/kW | 193 g/kW |
| Cooling energy price | // GBP/kWh | 0.27 GBP/kWh | 0.27 GBP/kWh |

**Table 1.** *Cont.*

| | Case 1: Reference | | Case 1a: Reference with Cooling | | Case 2: Net-Zero | |
|---|---|---|---|---|---|---|
| | | | PV system | | | |
| Type of photovoltaic [PV] modules | // | | // | | Mono crystalline silicon | |
| Peak power coefficien | // | | // | | 0.24 | |
| Total area of PV modules | // | | // | | 300 | |
| Slope of PV modules | // | | // | | 0 | |
| Azimuth angle of PV modules | // | | // | | 0 | |
| Electricity GHG emissions | // | g/kW | // | g/kW | 193 | g/kW |
| Electricity purchase price | // | GBP/kWh | // | GBP/kWh | 0.27 | GBP/kWh |
| Export Tariff | // | GBP/kWh | // | GBP/kWh | 0.10 | GBP/kWh |

Three different building variations are defined:

- Case 1: The reference building is defined in compliance with the minimum energy efficiency requirements specified in the UK building regulations code [39] and traditional materials, with the aim of serving as a standard for comparison with the net-zero building. Window parameters were sourced from the supplier's data sheets, although currently, in the UK, a shift toward electrification can be seen in heating systems; given the nature of the reference building, a more traditional choice of a condensing boiler with an average efficiency of 91% is made. Heating setpoint and setback temperatures are determined based on recommendations from The Energy Saving Trust and the World Health Organization (WHO) [40]. A cooling system was omitted due to the typical lack of such equipment in modern UK buildings.
- Case 1a is a variation of the reference building in which a cooling system compatible with the design choices is installed. This is necessary to compare future energy requirements with the net zero energy building alternative.
- Case 2: A net zero energy building (NZEB) is targeted by aiming at a highly energy-efficient design compatible with the possibility of onsite renewable energy generation in a quantity equal to or greater than the total amount of energy consumed onsite over a period of one year [41]. Advanced materials, the high-efficiency reversible water-ground source heat pump, and the PV system allow the high-efficiency building to compare with the previously defined reference building. The key input parameters have been taken from the Sustainability and Net Zero Design Guide [42], and the heat pump and PV system parameters have been taken from suppliers available on the market.

## 3. Results and Discussion

### *3.1. Selection and Comparison of Weather Data Files*

A total of 1032 current weather data files are available for the UK on the Onebuilding database, all the TMYx type, in addition to 10 weather files available in the EnergyPlus database in the TMY format from the IWEC database. Given the extensive number of weather files available, encompassing more than 300 locations, a pre-selection was made based on the geographic distribution of the locations and selection of the most current weather file when more than one was available in each location. This pre-selection resulted in a map encompassing 38 strategically spaced weather file locations across the UK, ensuring comprehensive coverage and representation of various geographic regions and climatic conditions within the country. Figure 1 shows the resulting map and weather file distribution.


**Figure 1.** Weather file locations assessed within the UK.

Each weather file location was then analysed in detail through the CBE Clima Tool platform, and a number of details have been collected, including latitude, longitude, year span of data collecting, climate zone, average yearly temperature, maximum temperature recorded, minimum temperature recorded, annual cumulative horizontal solar radiation, percentage of diffuse horizontal solar radiation. Moreover, the average annual heating degree days and cooling degree hours were calculated for each weather file. The selected weather locations span latitudes between 50.73° of Exeter and 60.45° of the Shetland islands, with temperatures ranging from the coldest (1%) −7.7 °C in Glenmore Lodge, to the hottest (99%) of 24.8 °C in Norwich. Annual cumulative horizontal solar radiation ranges from approximately 1200 $Wh/m^2$ of the southern coat to 900 $Wh/m^2$ of the northern locations. Annual degree days also show a strict correlation with latitude, ranging from an average of 3323 degree days on the southern coast to 4313 degree days in the most northern locations, with some inland locations in Scotland showing even higher-degree days. Based on the analysed data, 3 locations were identified that could represent this variation in local climate across the UK while still being significant locations in major cities, allowing for generalisation of the results obtained through the simulations. The selected locations are Exeter (3360 degree days), Manchester (3749 degree days), and Aberdeen (4123 degree days).

A more in-depth analysis of the weather from the three selected locations can be seen in Figure 2 below, focusing on the daily average dry-bulb temperature distribution (solid line) and daily temperature distribution (shaded area) and highlighting the differences in climate, showcasing warmer winters and summers in Exeter, against the colder climate seen in Aberdeen throughout the year. Manchester, being located toward the center of the UK in terms of latitude, shows winters that can approach the colder climate of the northern parts of the countries while also having warmer summers closer to the southern regions.

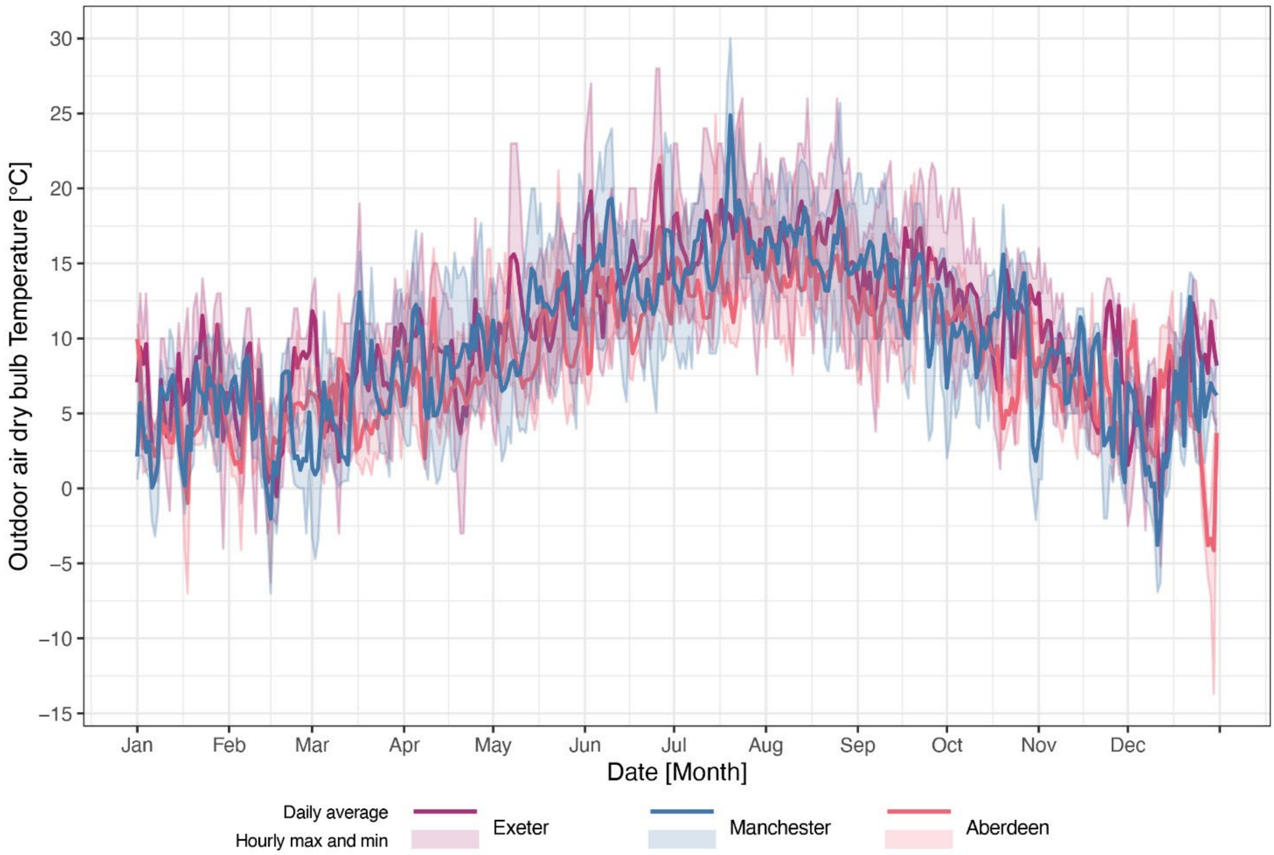


**Figure 2.** Exeter, Manchester, and Aberdeen daily average temperatures comparison.

Choice of the Future Weather Data Files

The analysed available databases of future future weather data files (FWDF) are Prometheus and Meteonorm.

To ensure consistency in the analyses, both future weather projections for each location and each target year have been compared against each other to assess if both databases provide similar data despite relying on different generation models. Prometheus provides FWDF for the years 2030, 2050, and 2080, each accompanied by various emission scenarios (Medium and High) and percentiles (10, 30, 50, 66, 90); meanwhile, Meteonorm generates the requested FWDF for a specified year based on IPCC scenarios (RCP 2.6, 4.5 or 8.5). For the present study, for each year, the medium scenario with a 50% percentile is used from the Prometheus database against the RCP 4.5 scenario in Meteonorm.

Figures 3–5 below, show a comparison between the two databases for Exeter, Manchester, and Aberdeen, respectively, for the projection year 2080. The analysis encompassed all future weather years; however, 2080 is chosen for a more in-depth comparison as being the furthest projection and expected to have the largest differences due to the divergence of the prediction models.

Despite the different sources of data and models applied to generate the future weather data, clearly visible in the significant differences in daily temperatures between the two databases, both Meteonorm and Prometheus result in comparable weather files with similar overall trends and temperature distribution. The Prometheus database tends to estimate slightly higher temperatures for 2080, on average 0.75 °C higher than Meteonorm and consistently throughout the year, as visible in the charted data. The hottest temperatures also tend to be higher in Prometheus, with an average difference between the databases of 1.6 °C, while the coldest temperatures tend to be closer but still higher in Prometheus by an average of 0.3 °C. Such observations are also corroborated by research conducted at the University of Lincoln by Sun [43], showcasing similar patterns when comparing the two databases.

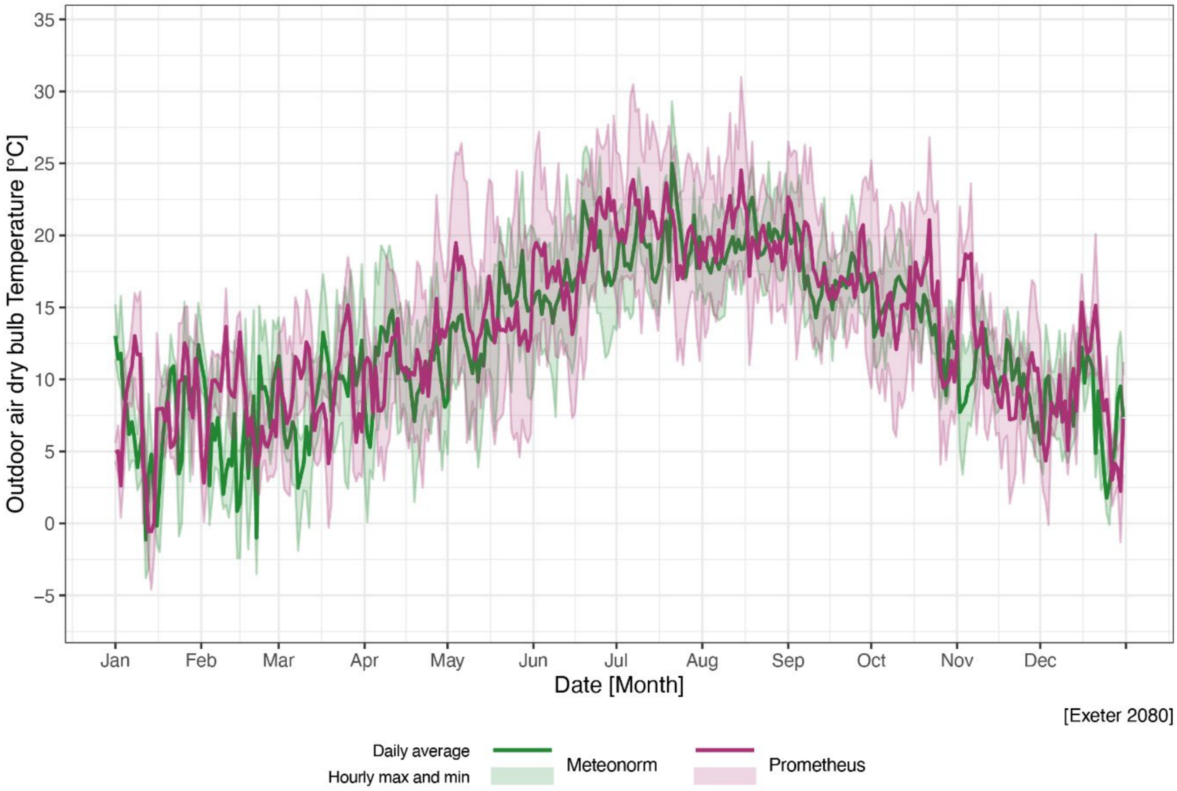


**Figure 3.** Exeter 2080: Prometheus and Meteonorm comparison.

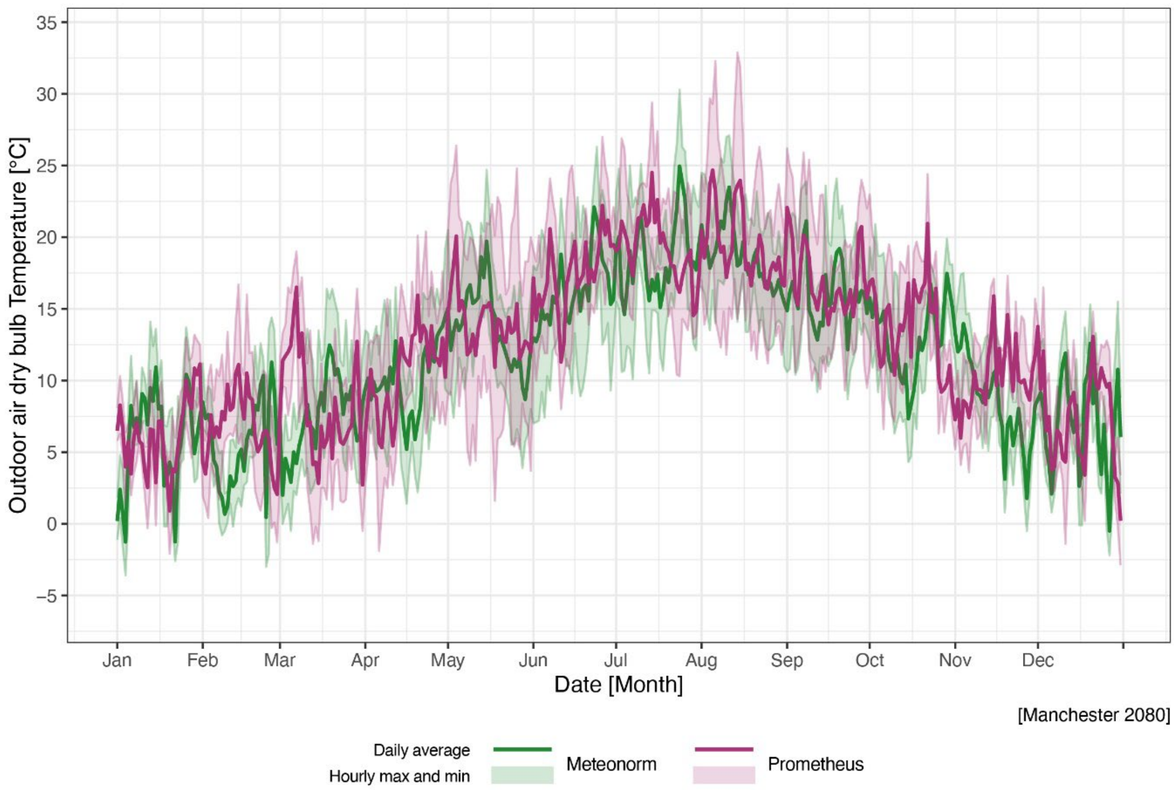


**Figure 4.** Manchester 2080: Prometheus and Meteonorm comparison.

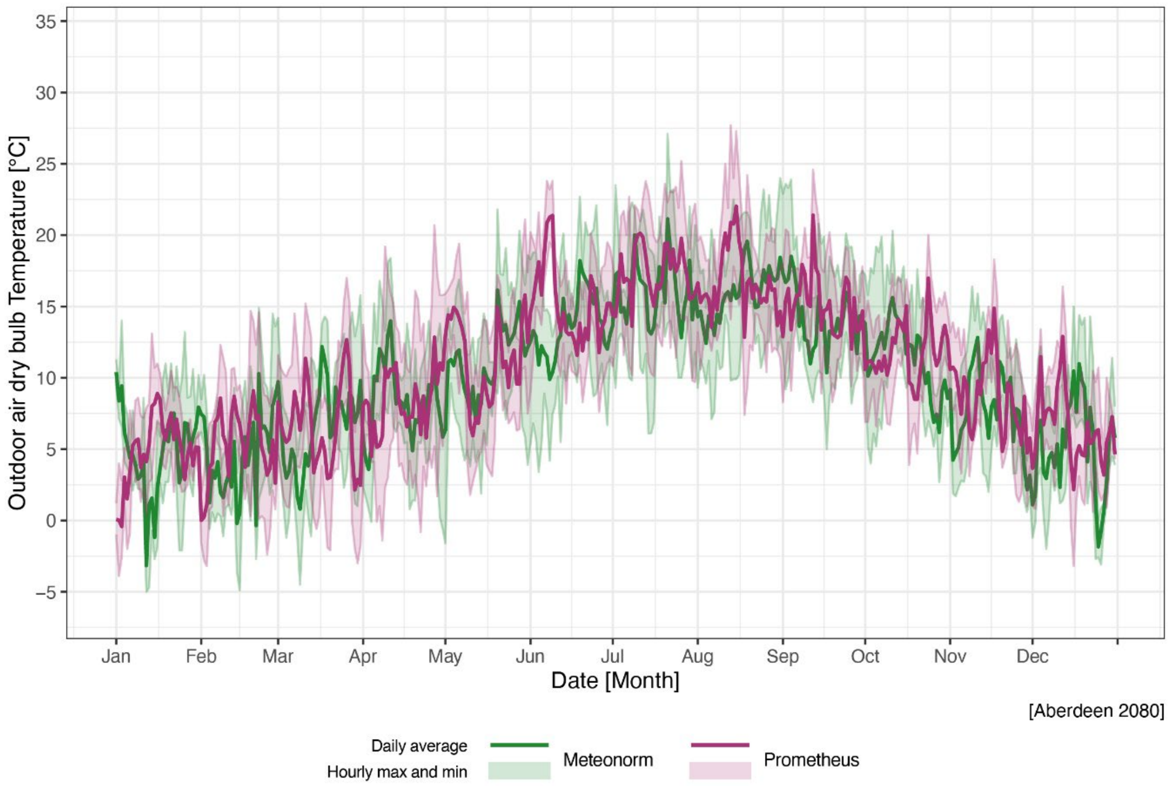


**Figure 5.** Aberdeen 2080: Prometheus and Meteonorm comparison.

Figure 6 below shows a boxplot summary of each weather file for each location and simulation year from both the Prometheus and Meteonorm databases.

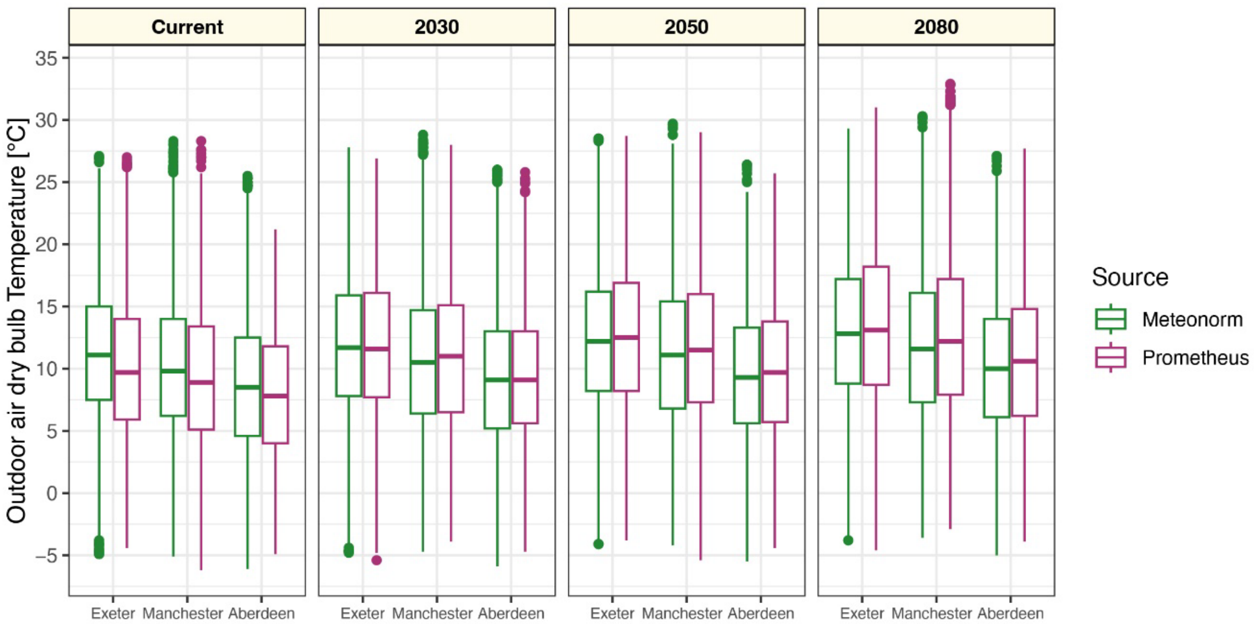


**Figure 6.** Boxplot comparison of Prometheus and Meteonorm weather files.

As expected, when looking at future projections, 2080 projections are the ones showing the highest divergence, with other projections showing significantly lower differences. Additionally, differences are similar in different locations, highlighting how the reason is likely in the projection models implemented rather than a difference in underlying assumptions. Another interesting highlight is how the current weather files showcase the greatest differences between the two databases; this is explained by the different time periods used to generate such files, from 1961 to 1990 for Prometheus, while Meteonorm uses more recent data from 2000 to 2019, which also explains why Meteonorm includes higher average temperatures in its current weather data compared to Prometheus.

Nonetheless, such differences are deemed to be marginal and within an acceptable tolerance for future weather forecasts, bringing to the conclusion that both databases, despite their differences, provide similar projections and weather data files. Considering these findings, the present study will proceed by applying Meteonorm-generated weather files to the case study, primarily due to their more recent nature, with the Prometheus database not having been updated in the last 12 years and the more recent data used to generate the "current" weather files.

### 3.2. Case Study Simulations

Following the selection of suitable weather data files, simulation models are developed through the FREDS interface and run through EnergyPlus for both the "reference" and "net zero" cases across all four simulation years (current, 2030, 2050, and 2080) with the aim of calculating heating and cooling needs and thermal comfort conditions. This comprehensive approach ensures a detailed evaluation of the performance and energy dynamics of the buildings under varying climatic conditions, thereby facilitating informed decision-making for our research objectives. Furthermore, based on the results of the simulations, energy consumption, GHG emissions, and energy costs are calculated for a more in-depth analysis.

Table 2 provides a summary of the simulation results in terms of heating and cooling energy needs for each combination of location, year, and design variation. Figure 7 provides a visual representation of such data for Exeter, improving the results' readability.

**Table 2.** Thermal energy needs for heating and cooling.

| | | C1: Reference | | C1:Ref. + Cooling | | C2: Net Zero | | C1a-C2 Differences | |
|---|---|---|---|---|---|---|---|---|---|
| | | Heating (kWh) | Cooling (kWh) | Heating (kWh] | Cooling (kWh) | Heating (kWh) | Cooling (kWh) | Heating (kWh) | Cooling (kWh) |
| Exeter | Current | 75,875 | 0 | 75,877 | 584 | 30,959 | 2012 | 44,918 | −1428 |
| | 2030 | 69,578 | 0 | 69,583 | 1440 | 28,482 | 3611 | 41,100 | −2171 |
| | 2050 | 65,097 | 0 | 65,099 | 3250 | 26,513 | 5825 | 38,585 | −2574 |
| | 2080 | 60,527 | 0 | 60,530 | 5108 | 24,337 | 8254 | 36,193 | −3146 |
| Manchester | Current | 92,155 | 0 | 92,170 | 828 | 38,903 | 1960 | 53,267 | −1132 |
| | 2030 | 85,394 | 0 | 85,404 | 2199 | 36,122 | 3718 | 49,281 | −1519 |
| | 2050 | 79,668 | 0 | 79,686 | 2294 | 33,670 | 4469 | 46,017 | −2175 |
| | 2080 | 73,477 | 0 | 73,482 | 3389 | 30,586 | 5933 | 42,896 | −2544 |
| Aberdeen | Current | 113,511 | 0 | 113,513 | 14 | 49,483 | 191 | 64,030 | −177 |
| | 2030 | 107,260 | 0 | 107,262 | 75 | 46,751 | 372 | 60,511 | −297 |
| | 2050 | 101,831 | 0 | 101,836 | 173 | 44,111 | 648 | 57,725 | −475 |
| | 2080 | 93,477 | 0 | 93,496 | 319 | 40,441 | 1033 | 53,056 | −714 |

A noticeable trend is a gradual decrease in heating energy consumption across all locations and under every design variation, accompanied by a significant increase in cooling energy consumption in cases where a cooling system is present, further highlighting how the weather is expected to become warmer over time in the UK in both summers and winters, with a more pronounced change in the southern regions. For example, in Exeter, heating demand decreases by 21% from 30,959 kWh currently to 24,337 kWh in 2080, while cooling demand rises dramatically from 2012 kWh to 8254 kWh, a 310% increase for the net-zero building design. Similarly, the heating demand for the reference case falls by 20%, and the cooling demand increases by 700%. Figure 8 highlights the variation in heating and cooling needs between the "current" and 2080 weather scenarios for each location and both C1a and C2.

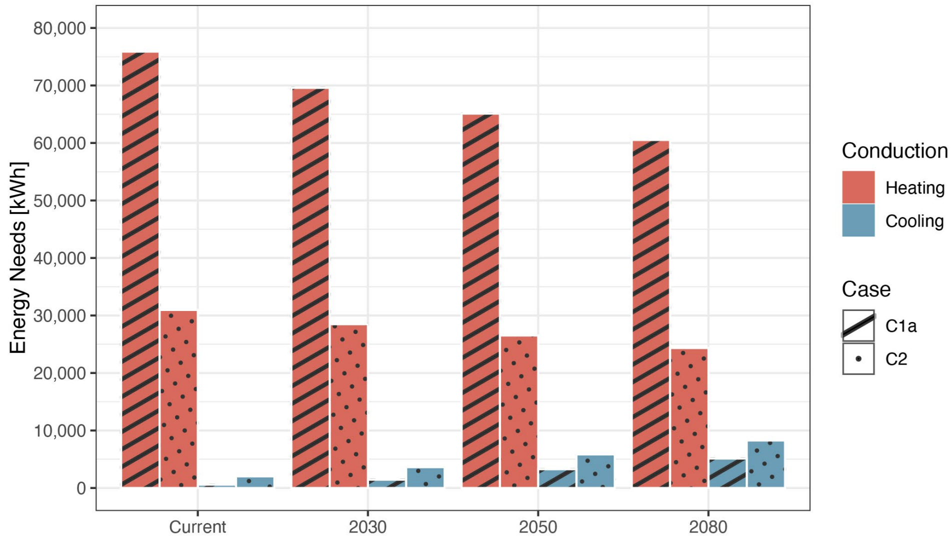


**Figure 7.** Heating and cooling needs for Exeter.

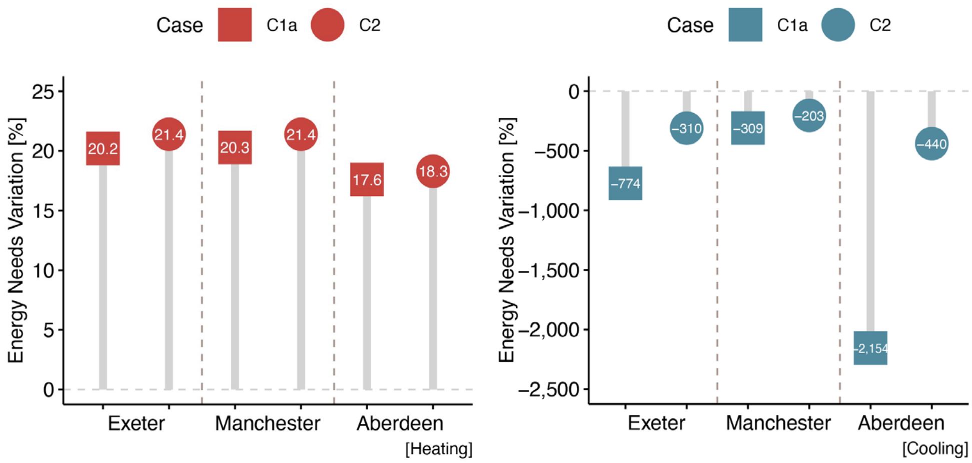


**Figure 8.** Variation in energy needs for C1a (reference) and C2 (Net Zero) buildings in each location between current and 2080 weather scenarios.

Other locations show similar trends to Exeter, with Manchester's heating demand dropping by 21% from 38,903 kWh to 30,586 kWh for the net-zero building and 20% from 92,170 kWh to 73,482 kWh, while cooling demand increasing by 203% from 1960 kWh to 5933 kWh, and 309% from 828 kWh to 3389 kWh. Aberdeen follows the same pattern, with heating demand decreasing by 18%, from 49,483 kWh to 40,441 kWh for the net-zero building, and 17% for the reference building, from 113,512 kWh to 93,496 kWh. Cooling demand is rising by 441%, from 191 kWh to 1033 kWh, and 2154% from 14 kWh to 319 kWh. These trends suggest a shift towards higher cooling requirements, affecting future HVAC needs and energy use.

It is notable how variations in heating needs are fairly uniform, in the 20% range; however, the net zero case has slightly higher percentage reductions in heating needs, similarly, although cooling variations reach extremely high percentage variations (up to 2154%) due to the very low energy needs in the current scenarios, it is also important to notice how percentage increases for the net-zero building are significantly lower than the ones for the reference building; further highlighting the increased climate resilience of the net-zero design option, compared to the reference one. Additionally, it is evident that the reference building exhibits significantly higher energy needs than the net zero building, as it is widely known, due to its poorer envelope performance. It is finally important to note that no passive cooling techniques, such as shading and natural ventilation, have been considered for this case study to highlight climate change's impact.

#### 3.2.1. The Phenomenon of Overheating for the Reference Building

Overheating is a phenomenon that occurs when the local indoor thermal environment reaches uncomfortable conditions due to an increase in operative temperature beyond those acceptable for human thermal comfort or those that may adversely affect human health. As the average temperature rises, as shown by the future weather files, there is an increased risk of such a phenomenon worsening, especially in the case of buildings that do not feature a cooling system, as it is common practice in the UK, even in new buildings.

The risk of overheating can be assessed in various ways. For this study, we decide on the simplest approach of setting constant thresholds for operative temperature. In such cases, there are two different criteria to check if there is overheating in a building [44]:

- Criterion A: applies to living rooms, kitchens, and bedrooms. It requires that the internal temperature does not exceed a defined comfort temperature for more than 3% of occupied hours over the summer period (1 May to 30 December)
- Criterion B: applies to bedrooms only and requires that the internal temperature between 10 pm and 7 am shall not exceed 26 °C for more than 1% of annual hours.

Due to the nature of the simplified models used in this analysis, the authors have opted for a simplified approach, limiting the assessment to only applying criterion A to the whole building and using a defined comfort temperature of 28 °C. Due to the specific approach adopted by Freds4Buildings in representing the dwellings, overheating was analysed by considering multiple sections within each building rather than examining each floor individually. Specifically, the analysis focused on evaluating the potential for overheating on the lowest floor, the intermediate floors (including the ground and first floor), and the uppermost floor of the buildings. This analysis is only performed for the C1 reference building, as this is the only scenario in which a cooling system is not installed. All other scenarios present no risk of overheating.

Table 3 above summarises the results of the analysis by indicating the number of hours in which each floor is at risk of discomfort due to overheating and highlighting in orange the years and floors where a significant risk of discomfort (more than 292 h per year) is present.

**Table 3.** C1 reference building overheating hours trend per zone (orange highlights significant risk of overheating).

| | | Overheating Risk | | |
|---|---|---|---|---|
| | | **Underground Floor** | **Intermediate Floors** | **Second Floor** |
| Exeter | Current | 0 | 22 | 3 |
| | 2030 | 6 | 150 | 30 |
| | 2050 | 35 | 564 | 151 |
| | 2080 | 47 | 951 | 318 |
| Manchester | Current | 8 | 31 | 7 |
| | 2030 | 47 | 237 | 120 |
| | 2050 | 11 | 271 | 110 |
| | 2080 | 68 | 487 | 203 |
| Aberdeen | Current | 0 | 0 | 0 |
| | 2030 | 0 | 0 | 0 |
| | 2050 | 0 | 6 | 3 |
| | 2080 | 0 | 18 | 6 |

Firstly, it is noticeable that as time progresses, areas previously unaffected by the risk of overheating begin to experience this phenomenon due to the gradual increase in temperatures. Secondly, there is a noticeable difference in overheating occurrence in the intermediate zones, consisting of two floors, compared to either the underground or the top floors. This was expected due to the geometry of the buildings and the central zones being “sandwiched” between the others, with less capacity to dissipate excessive heat. Additionally, the underground floor exhibits lower overheating occurrences, which is attributed to its naturally cooler surfaces over the summer due to contact with the ground. Lastly, the influence of latitude on overheating patterns is evident, with Exeter experiencing significant overheating as early as 2050 and worsening over time while overheating risk is absent in Aberdeen even in the year 2080. Nonetheless, it is essential to notice how, even in spaces that do not result in direct risk of overheating, the number of hours where overheating risk is present is consistently increasing over time in any location, even in a heating-dominated climate such as the UK, with significant increments between current weather and 2080 from essentially no risk of overheating to well above the 3% threshold in Exeter as an example. Moreover, such results are obtained through a simplified model that does not assess the building room by room; a more detailed modeling exercise is expected to result in even greater risks of overheating in critical spaces such as small rooms facing south with significant areas of transparent surfaces.

It is finally important to remember that if the dwelling is designed with an effective cooling system, there are no overheating risks, hence why this part of the analysis only focuses on the reference building; however, those buildings will incur an increase in energy use and GHG emissions, as seen in the next section.

#### 3.2.2. Results of the Simulation of the Reference Building

From the total energy needs summarised in Table 2, total energy consumption, costs, and GHG emissions related to heating and cooling needs for the buildings are calculated and summarised in Tables 4 and 5 for the C1 reference building (without cooling) and the C1a reference building (with cooling). Costs have been assumed to be equal to the UK market average for October 2023 for both Electricity and Gas, while GHG emission factors for energy vector have been derived from the UK Government GHG Conversion Factors for Company Reporting condensed set for 2022 [45]. Both costs and GHG emissions for the case study have been assumed constant in both time and space to ease the comparisons and highlight the impact of climate change; however, it is important to note that neither of such coefficients is likely to remain constant over time or in different locations, and in fact, regularly fluctuate, an in-depth assessment of the operational costs of a building would need to account for such fluctuations in order to represent the behaviour of the building [46] accurately. The current calculations also do not consider standing charges. The data was calculated for each year (Current, 2030, 2050, and 2080), and each location (Exeter, Manchester, Aberdeen) was accounted for in this case study.

It is first important to note how, from an energy consumption point of view, all the assessed locations in the UK are heating-dominated, with heating costs between 90% and 100% of total costs depending on year and location. Additionally, it is possible to notice how, due to the expected increase in temperature in all assessed locations, both costs and GHG emissions are expected to drop over time, even in the assumption of unitary costs and GHG emission conversion factors remaining constant, and even if accounting for the increase in cooling loads. This means reducing costs between 6% and 12% and GHG emissions between 20% and 25%, depending on location, between the current year and 2080. It is important to notice how this specifically applies to the case study and more widely to the UK climate and its future forecast, while other locations might see drastically different results depending on the weather.

**Table 4.** H and C consumptions, costs, and emissions for C1: reference building.

| | | Consumption | | Cost | | Total Costs | GHG Emissions |
|---|---|---|---|---|---|---|---|
| | | Heating (kWh) | Cooling (kWh) | Heating (GBP) | Cooling (GBP) | (GBP) | ($KgCO_2eq$) |
| Exeter | Current | 79,868 | 0 | 5591 | 0 | 5591 | 16,133 |
| | 2030 | 73,240 | 0 | 5127 | 0 | 5127 | 14,794 |
| | 2050 | 68,523 | 0 | 4797 | 0 | 4797 | 13,842 |
| | 2080 | 63,713 | 0 | 4460 | 0 | 4460 | 12,870 |
| Manchester | Current | 97,005 | 0 | 6790 | 0 | 6790 | 19,595 |
| | 2030 | 89,889 | 0 | 6292 | 0 | 6292 | 18,158 |
| | 2050 | 83,861 | 0 | 5870 | 0 | 5870 | 16,940 |
| | 2080 | 77,345 | 0 | 5414 | 0 | 5414 | 15,624 |
| Aberdeen | Current | 119,486 | 0 | 8364 | 0 | 8364 | 24,136 |
| | 2030 | 112,905 | 0 | 7903 | 0 | 7903 | 22,807 |
| | 2050 | 107,190 | 0 | 7503 | 0 | 7503 | 21,652 |
| | 2080 | 98,397 | 0 | 6888 | 0 | 6888 | 19,876 |

**Table 5.** H and C consumptions, costs, and emissions for C1a: reference building with cooling.

| | | Consumption | | Cost | | Total Costs | GHG Emissions |
|---|---|---|---|---|---|---|---|
| | | Heating (kWh) | Cooling (kWh) | Heating (GBP) | Cooling (GBP) | (GBP) | ($KgCO_2eq$) |
| Exeter | Current | 79,871 | 201 | 5591 | 54 | 5645 | 16,173 |
| | 2030 | 73,245 | 496 | 5127 | 134 | 5261 | 14,891 |
| | 2050 | 68,525 | 1121 | 4797 | 303 | 5099 | 14,058 |
| | 2080 | 63,716 | 1761 | 4460 | 476 | 4936 | 13,211 |
| Manchester | Current | 97,021 | 286 | 6791 | 77 | 6869 | 19,653 |
| | 2030 | 89,899 | 758 | 6293 | 205 | 6498 | 18,306 |
| | 2050 | 83,880 | 791 | 5872 | 214 | 6085 | 17,096 |
| | 2080 | 77,350 | 1169 | 5414 | 316 | 5730 | 15,850 |
| Aberdeen | Current | 119,487 | 5 | 8364 | 1 | 8365 | 24,137 |
| | 2030 | 112,908 | 26 | 7904 | 7 | 7911 | 22,812 |
| | 2050 | 107,195 | 60 | 7504 | 16 | 7520 | 21,665 |
| | 2080 | 98,417 | 110 | 6889 | 30 | 6919 | 19,902 |

### 3.3. Results of the Simulation of the Net-Zero Dwelling and Solar PV System

Table 6 below shows the same calculations for the net-zero C2 design variation. In order to allow direct comparison with the reference buildings, these calculations do not take into account renewable energy generation, which is discussed separately.

**Table 6.** H and C consumptions, costs, and emissions for C2: net-zero building.

| | | Consumption | | Cost | | Total Costs | GHG Emissions |
|---|---|---|---|---|---|---|---|
| | | Heating (kWh) | Cooling (kWh) | Heating (GBP) | Cooling (GBP) | (GBP) | ($KgCO_2eq$) |
| Exeter | Current | 6804 | 653 | 1837 | 176 | 2013 | 1439 |
| | 2030 | 6260 | 1172 | 1690 | 317 | 2007 | 1434 |
| | 2050 | 5827 | 1891 | 1573 | 511 | 2084 | 1490 |
| | 2080 | 5349 | 2680 | 1444 | 724 | 2168 | 1550 |
| Manchester | Current | 8550 | 636 | 2309 | 172 | 2480 | 1773 |
| | 2030 | 7939 | 1207 | 2144 | 326 | 2469 | 1765 |
| | 2050 | 7400 | 1451 | 1998 | 392 | 2390 | 1708 |
| | 2080 | 6722 | 1926 | 1815 | 520 | 2335 | 1669 |
| Aberdeen | Current | 10,875 | 62 | 2936 | 17 | 2953 | 2111 |
| | 2030 | 10,275 | 121 | 2774 | 33 | 2807 | 2006 |
| | 2050 | 9695 | 210 | 2617 | 57 | 2674 | 1912 |
| | 2080 | 8888 | 335 | 2399 | 91 | 2490 | 1780 |

Similar to the reference building, the net-zero building option also sees its heating and cooling-related costs and GHG emissions lower over time due to climate change despite its naturally higher cooling needs. This is true for both Manchester and Aberdeen, with drops of 6% and 18% respectively to 2080. However, Exeter highlights a different trend; in a highly insulated building such as the net zero case, the increase in cooling loads on the south coast of the UK starts competing with the decrease in heating loads, resulting in a marginal increase in price and emissions of 8% to 2080. Again, it is important to remember no passive cooling techniques, such as shading and natural ventilation, have been considered for this case study; such solutions would help alleviate the cooling loads of the building, especially for a highly insulated design in a heating-dominated environment such as the case study, likely reducing the cooling energy needs significantly.

One further step is required to assess if the building can meet the definition of net zero and understand if onsite renewable energy generation can balance out the existing energy and electricity requirements. Based on the annual energy consumption data of each location, available on an hourly basis through the simulations, we initially designed a photovoltaic system and associated battery storage. The system is aimed at balancing both the electricity heating and cooling needs (different in each location and year) and all other internal loads, such as lighting and equipment, estimated at 38,880 kWh and considered constant over time. Table 7 below provides a summary of the different PV systems and associated performances.

**Table 7.** Solar PV panels data.

| location (-) | Solar PV Area ($m^2$) | n-Panels (-) | Annual Electricity Need (kWh) | Annual PV Generation (kWh) | Annual Electricity Balance (kWh) | Annual Electricity to/from Grid (kWh) |
|---|---|---|---|---|---|---|
| Exeter | 155 | 60 | 46,337 | 46,551 | −214.1 | 13,406 |
| Manchester | 225 | 87 | 48,066 | 48,543 | −476.8 | 16,517 |
| Aberdeen | 259 | 100 | 49,817 | 50,098 | −280.8 | 16,474 |

Firstly, it is important to note how each location requires a different amount of PV panels to balance its electricity needs; this is due only partly to the greater heating energy needs of northernmost locations and primarily due to the lower levels of solar radiation available. Annual cumulative horizontal solar radiation in Exeter equals 1081.9 kWh/m$^2$, versus 990.6 kWh/m$^2$ and 882.4 kWh/m$^2$ in Manchester and Aberdeen, respectively. Nonetheless, each location shows the potential of reaching net zero definition by installing a suitable amount of PV panels on the rooftop of the building, with the annual energy balance of the building being negative, showing a surplus of energy produced thanks to the solar panels, same thing for the energy produced by the solar panels sent directly to the grid. Since each system is designed based on “current” energy needs, it is important to note that, due to the decrease in energy needs for both Manchester and Aberdeen, the building is expected to maintain its definition of net zero throughout its lifetime, under the present future climate forecasts. Special note must be given to the Exeter case, as due to its increase in cooling energy requirements, with the current amount of PV generation, the building would fail to meet the definition of net zero by 2080, as the electricity requirements will outgrow the renewable energy generation; however, the lifespan of PV panels is expected to be in the range of 25–35 years; therefore once the system needs to be renewed it will be necessary to install a larger number of panels (61, based on the calculations used in this study, assuming to other parameter is changed). This is a marginal issue in the present case study due to both the small increase and a large amount of available space; however, it helps highlight a critical risk of buildings designed to be net zero today being unable to meet the definition in the future due to climate change and increases in energy requirements.

Lastly, it is important to remember the definition of net zero does not require all electricity needed to be directly generated onsite. Therefore, a certain amount of electricity is still going to be exchanged with the grid, depending on the size of the battery storage.

Although designing and installing enough storage to become completely autonomous is technically possible, this is typically not financially feasible. In the present study, onsite storage was sized based on a balance between maximising onsite use while limiting the financial investment; this resulted in the sizing of 8, 9, and 10 13.5 kWh batteries for Exeter, Manchester, and Aberdeen, respectively, limiting the amount of electricity exchanged with the grid to 28–33% of the total, primarily during the winter months when solar radiation is lower.

### 3.3.1. Comparative Analysis

A direct comparison of total heating and cooling costs for the different cases can be seen in Figure 9. It is important to note that, in order to allow direct comparison, the PV system present in the net zero (C2) is not accounted for at this stage.

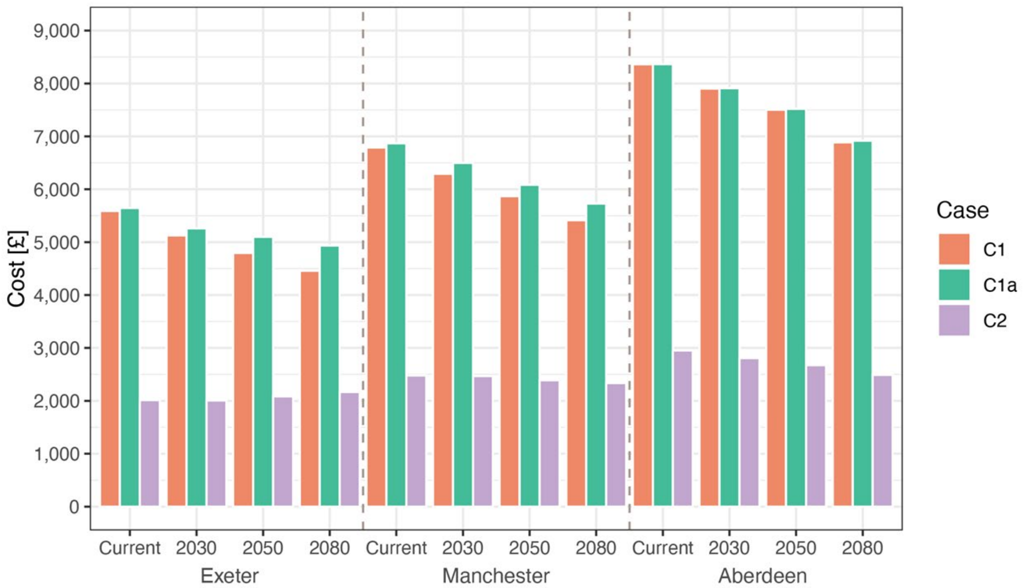


**Figure 9.** Heating and cooling cost comparison for all locations and years (dashed lines separating different locations).

The cost data for the reference building and its net zero counterpart from the current year to 2080 reveal significant trends and differences for each location. The reference building's costs decrease from GBP 5311 in the current year to GBP 4237 by 2080, representing a 20.2% reduction. Similarly, a 20.3% and 17.7% reduction can be seen in Manchester and Aberdeen, respectively. On the other hand, the net-zero building starts with a much lower cost of GBP 2013, representative of its energy-efficient design, increasing slightly to GBP 2168 by 2080 in Exeter, showing an overall increase of 7.7%; Manchester and Aberdeen instead follow the trend of the reference building with drops of 6% and 16% respectively to 2080. Despite the variations, costs for the net-zero building remain consistently significantly lower than the reference building, ranging between 35% and 44% of its costs. Interestingly, across all building types and locations, the gradual decrease in costs as time progresses is almost linear, with heavily heating-dominated climates such as Aberdeen showing very similar reductions, 17.6% for the reference building and 16% for the net zero one to 2080. If renewable generation from PV systems were to be taken into account, costs associated with the net-zero scenario would reduce further; however, they would not reach zero, as electricity would still need to be exchanged with the grid, at least in part, to cover shortcomings of the PV system during winter months. Nonetheless, even in the unlikely worst-case scenario that all electricity required for both heating and cooling is taken from the electricity grids at times when both the PV generation is absent and the battery is empty, and assuming an export tariff of only 0.10 GBP/kWh (below current market availability in the UK) cost would be 42% lower and range from GBP 1268 in Exeter to GBP 1859 in Aberdeen, both under “current” weather conditions.

Figure 10 below, summarises the trend of green gas emissions in $KgCO_2eq$ for all case studies. Again, PV systems for the net-zero building are discounted in this analysis to allow for a more direct comparison.

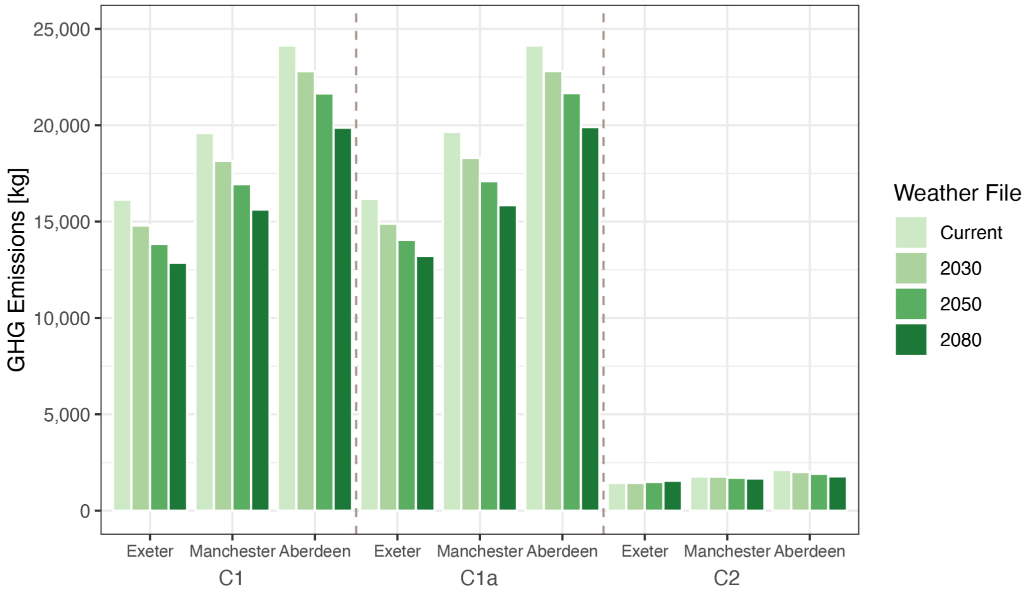


**Figure 10.** Greenhouse gas emissions for heating and cooling (no PV).

GHG emissions show trends similar to those previously seen in terms of energy and costs. For the reference buildings (C1), emissions decrease over time: Exeter’s emissions drop by 20.2% from 16,133 $KgCO_2eq$ to 12,870 $KgCO_2eq$, Manchester’s decrease by 20.3% from 19,595 $KgCO_2eq$ to 15,624 $KgCO_2eq$, and Aberdeen’s fall by 17.7% from 24,136 $KgCO_2eq$ to 18,876 $KgCO_2eq$. Introducing air-cooled chillers (C1a) slightly increases emissions, with Exeter’s emissions rising by approximately 0.3% to 16,173 $KgCO_2eq$, Manchester’s by 0.3% to 19,653 $KgCO_2eq$, and Aberdeen’s by 0.01% to 24,137 $KgCO_2eq$. Emissions in both reference cases are heavily dominated by natural gas used for heating. Net-zero buildings equipped with reversible ground source heat pumps exhibit the lowest emissions, maintaining significantly lower levels throughout the years due to lower energy requirements and electricity use as the energy vector. Exeter’s net-zero building starts at 1439 $KgCO_2eq$ and slightly increases to 1550 $KgCO_2eq$ by 2080, while Manchester’s starts at 1773 $KgCO_2eq$ and decreases to 1669 $KgCO_2eq$. Aberdeen follows a similar trend, starting at 2111 $KgCO_2eq$ and decreasing to 1780 $KgCO_2eq$. GHG emissions for the net-zero building in different locations are much closer (~14% range between Exeter and Aberdeen) compared to the emission spectrum of the reference building (~49% range between Exeter and Aberdeen), showcasing the increased climate resilience of an efficient net-zero design. Additionally, even in the worst-case scenario (Exeter 2080), the net-zero building still accounts for a reduction of 89% of GHG emissions compared to the reference building. These trends demonstrate that while all buildings’ GHG emissions improve over time, energy-efficient net-zero buildings equipped with advanced heat pump technology achieve substantial reductions in GHG emissions compared to reference buildings and maintain such reductions over time, highlighting the effectiveness of sustainable building practices and advanced HVAC systems in minimizing environmental impact. Again, this analysis also does not take into account the electricity generation from PV systems in the net-zero energy design, as GHG emissions for this scenario would otherwise equal 0 $KgCO_2eq$ in each location and each year of assessment.

### 3.3.2. Limitations

The present study is aimed at assessing the UK geography, a country that is currently dominated by cold and wet winters and mild summers; although temperatures are projected to increase, and some effects of this can be seen in raising cooling requirements and overheating risk in the southernmost regions, the general UK weather is still likely to remain heating dominated in the near future; therefore findings from the case study cannot be extended to other climatic regions. However, the methodology proposed in the paper can be extended to other regions and help understand the impact of climate change under different future weather conditions. Additionally, this study only aims to compare two design alternatives (reference and net-zero building) without isolating the impact of each feature on the overall energy consumption; nonetheless, the proposed methodology can be applied to such analysis.

Similarly, the design alternatives for the case study are defined at their design stage, but no assumption is made about changes and improvements throughout the lifecycle of the building, which are likely to happen in reality due to the time span of the analysis (50+ years) this is both to provide a fixed comparison point and due to the challenges of predicting what technology might be available in buildings by 2080; nonetheless an in-depth approach assessing the whole lifecycle of the building in each stage is possible through the presented approach, and would pose as an interesting frame to further this research.

The study shown uses a simplified modelling approach as implemented by the FREDS4Buildings platform; depending on the specific design of each building, such choice can lead to underestimating overheating risks in the summer, especially if small rooms are designed to be south-facing and with significant glazing. In such cases, a more in-depth modelling approach might be required. Moreover, the case study approach does not consider any passive cooling solutions, such as ventilation or shading, which are seldom used in the UK but are likely to be effective in tackling the rising cooling energy costs and risk of overheating; this is considered beyond the scope of the current study although, from a practical perspective, it is fully expected such measure will become a common feature to limit overheating and reduce energy needs in the UK.

Lastly, both energy costs and GHG emissions factors have been assumed constant for this study, both in time and space. This is a simplification aimed at allowing a more direct comparison; however, it does not reflect the real world; a more in-depth analysis would need to take into account different values for each location and variations over time both in terms of years, by using future projections for both energy costs and GHG emissions and within the same year, as such values can fluctuate on a daily basis.

## 4. Conclusions

This work examined the impact of climate change on building energy performance in the UK, comparing the energy demands and greenhouse gas (GHG) emissions of conventional "reference" buildings to a net-zero energy (NZEBs) alternative under both current and future climate scenarios for 2030, 2050, and 2080. Different future weather databases are first assessed, highlighting both the challenge of varying and outdated current weather file and, in the case of Prometheus and Meteonorm, despite different data and projection models, future weather forecasts are comparable in nature. The Meteonorm weather data is then used in conjunction with EnergyPlus and Freds4Buildings to run dynamic simulations of each design variation for a case study building and compare their sustainability.

Across all scenarios, heating demands decreased by approximately 20% between the current period and 2080, aligning with rising average temperatures. In contrast, cooling demands rose significantly, especially in warmer, southern regions such as Exeter, where cooling energy needs in NZEBs increased by 310%, from 2012 kWh currently to 8254 kWh by 2080. This trend underscores a shift in the UK towards rising cooling needs, a noteworthy finding in a traditionally heating-dominated climate.

NZEBs demonstrated substantially lower overall energy consumption and GHG emissions compared to reference buildings, even under scenarios with increased cooling demands. The reference building's GHG emissions range from 13,211 kg $CO_2$e to 24,137 kg $CO_2$e in the different scenarios, while the net-zero building emits just over 2000 kg $CO_2$e in its worst scenario, showcasing a reduction of 89% or higher compared to the reference building, without accounting for onsite renewable energy generation. These results validate the effectiveness of NZEBs in achieving resilience and sustainability under future climatic conditions. Costs follow a similar trend, with savings ranging between 55% and 65% in all scenarios due to the different energy sources considered and can further increase when solar PV panels are considered.

Two further findings are highlighted by taking into account future weather forecasts that would otherwise be lost. Firstly, even in a heating-dominated climate such as the UK, a reference building without cooling systems may become at risk of overheating over time, as shown in both Exeter, with 564 h of overheating by 2050, and Manchester, with 487 h by 2080. Secondly, even in such a cold climate, the climate change and increase in cooling loads highlight the concern of net-zero buildings designed today potentially not meeting the net-zero requirements in the future; this is visible as an example in the way the Exeter net-zero building, with electricity needs surpassing the electricity generation in 2080, raising the need to potentially either oversize the PV panels or at least accommodating for the need to increase the size of the PV field over time. Although this is only a marginal issue in the current case study, it raises concerns about such a phenomenon in warmer climates.

These findings suggest an urgent need for policy adaptations that account for future climate scenarios in building regulations. Policymakers could benefit from incentivising the adoption of net-zero designs, which consistently achieved GHG reductions of 80% or more compared to conventional buildings; meanwhile, regulations could also encourage the use of future weather data files (FWDF) in energy simulations to guide resilient building designs.

While this study provides valuable insights into future building energy performance in the UK, the work should be extended to other climatic regions in order to create a more general understanding of the impact of climate change in other climatic regions, such as warmer southern European locations, to assess the generalizability of net-zero designs in varied climate contexts. Expanding these analyses could provide a broader understanding of the role of NZEBs in achieving climate resilience globally and contribute to refining energy standards and sustainability goals.

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