Climate Change and Residential Energy Use in Europe

Assessing Future Energy Demands and Renewable Generation Potentials

Yang, Yuchen

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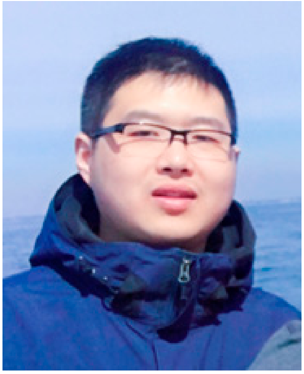
YUCHEN YANG
FACULTY OF ENGINEERING | LUND UNIVERSITY



This licentiate dissertation is a product of research conducted by Yuchen Yang. Since 2019, Yuchen has dedicated his research to the impact of climate change on building energy performance.

Climate change and the corresponding expected extreme weather conditions have been widely recognized as potential problems. The construction industry is taking various actions to achieve sustainable development, implement energy conservation strategies, and provide climate change mitigation. In addition to mitigation, it is crucial to adapt to climate change and investigate the possible risks and limitations of mitigation strategies. Although the importance of climate change adaptation is well-understood, there are still challenges in understanding and modeling the impacts of climate change and the consequent risks and extremes.

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Climate Change and Residential Energy Use in Europe – Assessing Future Energy Demands and Renewable Generation Potentials

Yuchen Yang

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LICENTIATE DISSERTATION

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Faculty opponent
Salvatore Carlucci

Professor, Sustainability and Built Environment Division
The Cyprus Institute, Nicosia, Cyprus

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This licentiate dissertation aims to assess the impact of climate change on the building energy performance and indoor thermal comfort in 38 major European cities distributed in five difference climate zones. In addition, this study also investigates the potential of renewable energy generation considering solar PV and wind energy generations. To do this, an ensemble of multiple future climate scenarios with high temporal and spatial resolutions have been used in this work, enabling us to account for climate variations and extreme events. A set of future climate big data generated by RCA4 regional climate model (RCM) were used. In total, 13 future climate scenarios covering five global climate models (GCMs) and three representative concentration pathways (RCP 2.6, RCP 4.5 and RCP 8.5) were used for the 90-year span of 2010-2099, divided into three 30-year periods (2010-2039, 2039-2069 and 2069-2099).

Results show that extreme long and short-term climate events can cause significant changes in energy demand, particularly peak loads during extreme events. This work provided more insights into the importance of considering both long- and short-term variations of climate, including extreme events, when assessing future energy solutions and the energy performances of building stocks.The availability of fine temporal and spatial resolution climate data is crucial for assessing the plausible energy demands of buildings; however, it is important consider climate uncertainties, multiple scenarios, and extreme climate events.Finally, the database of results for each city and climate zone allows decision makers and designers to count for future climate uncertainties in the early stages of building design.

Key words: Climate change; Building energy performance; Future building energy demand.

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Yuchen Yang

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MADE IN SWEDEN

“To strive, to seek, to find, and not to yield”

Alfred, Lord Tennyson 1833

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Acknowledgment

I would like to thank my colleague from the building physic and building service division, who have provided support, motivation, as well as raised critical questions regarding the content of the project.

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Abstract

In recent years, climate change and the corresponding expected extreme weather conditions have been widely recognized as potential problems. The construction industry is taking various actions to achieve sustainable development, implement energy conservation strategies, and provide climate change mitigation. In addition to mitigation, it is crucial to adapt to climate change, and to investigate the possible risks and limitations of mitigation strategies. Although the importance of climate change adaptation is well-understood, there are still challenges in understanding and modeling the impacts of climate change, and the consequent risks and extremes.

This licentiate dissertation aims to assess the impact of climate change on the building energy performance and indoor thermal comfort in 38 major European cities distributed in five difference climate zones. In addition, this study also investigates the potential of renewable energy generation considering solar PV and wind energy generations. To do this, an ensemble of multiple future climate scenarios with high temporal and spatial resolutions have been used in this work, enabling us to account for climate variations and extreme events. A set of future climate big data generated by RCA4 regional climate model (RCM) were used. In total, 13 future climate scenarios covering five global climate models (GCMs) and three representative concentration pathways (RCP 2.6, RCP 4.5 and RCP 8.5) were used for the 90-year span of 2010-2099, divided into three 30-year periods (2010-2039, 2039-2069 and 2069-2099).

Results show that extreme long and short-term climate events can cause significant changes in energy demand, particularly peak loads during extreme events. This work provided more insights into the importance of considering both long- and short-term variations of climate, including extreme events, when assessing future energy solutions and the energy performances of building stocks.The availability of fine temporal and spatial resolution climate data is crucial for assessing the plausible energy demands of buildings; however, it is important consider climate uncertainties, multiple scenarios, and extreme climate events.

Finally, the database of results for each city and climate zone allows decision makers and designers to count for future climate uncertainties in the early stages of building design

摘要

应对气候变化，已经成为本世纪最为迫切的现实问题。一方面，人类共同行动，减缓气候变化，实现可持续性发展；另一方面，研究探讨应对气候变化适应性的举措，减少气候变化带来的伤害及损失，这成为同一课题的两个方面。前者为本，后者为标，标本共治，我们才能拥有一个可期待的未来。

近年来，建筑业面对气候变化、能源消耗带来的诸多问题，正在研究对策、逐步采取有效的行动，试图减少和消除气候变化带来的负面影响，并在节能方面不断地探索和努力，以求建立一套因应气候变化的适应性的机制。作为城市主要组成部分的建筑物，在降低能源消耗的篇什上，大有文章可做。特别是欧洲国家，多年来在评估能效比、因应气候变化的适应性方面做了大量的开先河的工作。然而，如何实现低能耗而又不损害温暖季节的室内热舒适性，依然是一个艰巨的挑战。

本篇论文的目的在于掌握和分析气候变化对未来几个欧洲主要城市的建筑能效和室内热舒适性的影响，同时探讨可再生能源发电的潜力。为此，需要考虑未来气候大数据的集合，其中包括极端事件在内的最新气候模型。总体而言，本研究基于 90 年内（2010-2039、2039-2069 和 2069-2099）13 种未来气候情景和三个代表性浓度路径（RCP 2.6、RCP 4.5 和 RCP 8.5）并以小时分辨率作为实验基础而作出的结论。

本文的结果提供了一个全面的图景，它说明了考虑长期和短期气候变化以及欧洲建筑能源性能中的极端事件的重要性。这项研究表明，极端的短期气候事件可能导致能源需求发生重大变化，尤其是极端事件期间的峰值负荷。随着更大更频繁的极端天气事件的发生，量化极端事件对住宅建筑存量性能

的影响对于确保未来城市的气候适应力变得尤为重要。精细的时间和空间分辨率气候数据的可用性对于评估气候不确定性和极端事件，评估建筑物的合理能源需求非常有用。对气候变化影响的全面评估对于为未来向可持续城市的转型奠定基础至关重要。概括作结:每个城市和气候区的结果数据库可让决策者和设计师在建筑设计的早期阶段计算未来的气候和气候不确定性。

List of publications

Paper I: Climate Change and Energy Performance of the European Residential Building Stocks – A Comprehensive Impact Assessment Using Climate Big Data from the Coordinated Regional Climate Downscaling Experiment

Yuchen Yang, Kavan Javanroodi, Vahid M. Nik

Submitted to Applied energy (published).

Paper II: Climate change and renewable energy generation in Europe – Long-term impact assessment on solar and wind energy using high resolution future climate data and considering climate uncertainties.

Submitted to Energies MDPI

Yuchen Yang, Kavan Javanroodi, Vahid M. Nik

Paper III: Impact assessment of climate change on the energy performance of the building stocks in four European cities

Yuchen Yang, Kavan Javanroodi, Vahid M. Nik

E3S Web of Conferences,12th Nordic Symposium on Building Physics (NSB 2020)

Paper IV: Assessing the impacts of climate change on the German building stock

Yuchen Yang, Vahid M. Nik

Proceedings of the International Building Performance Simulation Association. Vol. 16. S. 3563-3568 6 s.

1 Introduction

Climate is changing and its impacts and consequences are already being recognized as potential threats to sustainable development [1]. Rising temperatures, changes in precipitation and extreme weather have exacerbated the sea level rise and induced more frequent heat waves [2]. According to the Paris Agreement, the current global warming is about 1.0°C above the pre-industrial levels, and it may reach 1.5°C between 2030 and 2052 at current rates [3]. In this regard, the Intergovernmental Panel on Climate Change (IPCC) issued a special report on global warming of 1.5°C on the background of strengthening the global response to climate change, discussing the impact level of global warming exceeding 1.5°C before industrialization and related global issues [4].

Due to the frequent extreme weather events, the impact of climate change on peak power demand will reach to a level that far exceeds the annual net demand [5]. In this regard, the development of sustainable and reliable energy solutions plays an important role in enhancing the mitigation and adaptation of cities to climate change. Buildings have strong potential to reduce energy consumption and greenhouse gas emissions since they are the main component of cites, inducing over 30% of the world's total greenhouse gas emissions [6], that also accounts for 32% of the world’s total final energy use.The building energy demand is expected to double by 2050 [7]. In Europe, the largest proportion of building energy consumption is heating and cooling, accounting for 70% of residential building energy consumption, indicating the huge potential of buildings in reducing energy consumption and greenhouse gas emissions [8].

By recognizing the importance of climate change in different fields and sectors, assessing the possible impact of climate change has become an interesting research topic in energy and building studies [9]. Future weather data sets are widely used to perform the impact of climate change on buildings [10] while their syntheses have been discussed in several works [11][12]. Extensive reviews are available about the methods for generating future weather files [13][14]. Many studies have focused on the impact of climate change on the energy use of residential buildings. Nik et al. [15] conducted a study that assessed possible changes and uncertainties in the future energy performance of the Stockholm residential stock considering multiple future climate scenarios from Coupled Model Intercomparing Project (CMIP) phase 3. Their results show that future heating demand will decrease about 30% during 2010-2039, lower than before 2011, while cooling demand will increase for 25%. Peng

Xu et al. [16] applied a global climate model in buildings typical of California's mild Mediterranean climate zone, and predicted different emissions scenarios in the future 2039, 2069, and 2099 building energy consumption. The results show that cooling demand will increase by more than 50%. Shen et al. [17] analyzed the future energy consumption of residential buildings in four cities in the United States, representing four different weather conditions and estimated the increase or decrease in annual total energy demand based on geographic location. Several researchers also predict that the future heating demand will decrease as well as the cooling demand will increase[18][19][20].

The frequency of extreme climate events also have impact on the indoor thermal comfort. One major challenge in climate change mitigation and adaptation of buildings and urban energy systems is to achieve low energy demand of buildings without compromising thermal comfort [21], especially for the future climate with more frequent and stronger extreme events. This becomes more challenging while passive or less active solutions are promoted . A thermally comfortable environment indicates a reasonable control of indoor temperature, which usually consumes a large amount of energy [22]. Most thermal comfort studies focus on adaptive thermal comfort, whereas a few have considered future climate scenarios. For example, Lomas et al. [23] used the adaptive comfort model to study the effect of future climate change on the overheating of the hospital ward, suggesting to installing fans as a simple measure to improve thermal comfort. Shen J et al. [24] used the future climate data to conduct a detailed analysis of the house in Rome and Stockholm. They adopted an adaptive comfort model to analyse the future climate change trend, showing that the demand for cooling and dehumidification in Rome will rise from 5.3% to 23.6 %, while heating and humidification requirements in Stockholm will be reduced from 67% to 53%, and cooling and dehumidification requirements will be slightly increased from 0% to 1.5%. Hwang et al. [25] studied the impacts of the urban heat island effect and global warming on residential thermal comfort and cooling energy, based on A1B future climate scenarios from the IPCC Special Report on Emissions Scenarios (SRES).

Climate change not only change future energy demand, but also affect the generation of renewable energy. Compared with traditional fossil fuels, renewable energy availability is closely related to meteorological conditions (for example, the amount of solar radiation and wind). Previous attempts to describe the future state of wind and solar energy are usually using the Global Circulation Models (GCMs) or downscaled Regional climate models(RCMs) from the Coupling Model Intercomparison Project (CMIP), which referred to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) AR5 model[26]. The output of these models is directly used in climate change impact modeling to assess the impact of climate change. Research on the impact of climate change on wind and solar resources also follows a similar pattern(e.g.[27,28]). Regarding the proper use of GCM output, it is necessary to recognize how wind and solar variables are represented in GCM. For example, in GCM, wind speed is clearly resolved as the average value of a finite volume in space[29]. For solar radiation, it is parsed as surface solar irradiance, and GCM can generate spatiotemporal continuous surface solar irradiance maps on regional and global scales. However, there has been little discussion of the potential changes in surface solar irradiance. It is mainly due to the large error of the model for predicting cloud quantities and the uncertainties of GCM's estimation on cloud cover[30] [29]. Cloud output is usually estimated based on the relative humidity value in each GCM cube, which is also considered the highest uncertainty in current GCM application[29,31]. Recent studies about the effects of climate change on energy generation focus on renewables, especially wind, hydropower, and solar energy. For example, Fant et al. [29]Through a set of predictions of eight global climate models (GCM), the impact of climate change on solar and wind energy resources in southern Africa, and it was found that the changes in wind and solar potential by 2050 are expected to be small. They pointed out that although wind energy and solar potential are expected to change very little by 2050, GCM has great uncertainty in solving wind and solar potential.

This thesis aims to investigate the impacts of climate change in European building stock over five different climate zones in 38 major cities considering the long and short-term climate variations on the probable heating and cooling demand and indoor thermal comfort. Moreover, the impacts of climate change on the future renewable energy potential is investigated in 7 tagert cities over five climate zones. The specific objectives of this study are:

1) Investigating impacts of climate change in 38 European cities over five different climate zones.
2) Investigating future heating and cooling demand and indoor thermal comfort.
3) Future renewable energy potential on the 7 target cities
4) Future climate uncertainties.
5) Energy saving retrofitting strategy under climate change.

Thesis structure

Paper I: Climate change and energy performance of European residential building stocks – A comprehensive impact assessment using climate big data from the coordinated regional climate downscaling experiment

The aim of this work is to conduct impact assessment by assessing the energy performance and indoor comfort of 38 European cities, using climate big data, considering the most recent climate models and including extreme events. In this regard, each city considered 13 future climate scenarios over 90 years with hourly temporal resolution (2010-2039, 2039-2069 and 2069-2099). According to the TABULA webtool, energy simulations are performed by modelling 252 buildings in Europe which resulting in the 788,400 hours simulation for each city. A relevant literature review was perform for the recent works published after 2017 on the impact assessment of climate change in paper I.

Paper II: Climate change and renewable energy generation in Europe – Long-term impact assessment on solar and wind energy using high resolution future climate data and considering climate uncertainties

The aim of this work is to quantify the impact of climate change on renewable energy generation (Wind turbine and PV output) by assessing the future energy conditions in seven European cities from five different climate zones in Europe (Narvik, Gothenburg, Munich, Antwerp, Salzburg, Valencia, and Athens). Thirteen future climate scenarios are considered using the outcomes of RCA4 regional climate model (RCM) for the period of 2010-2099.

Paper III: Assessing the impacts of climate change on the German building stock

The aim of this study is to investigates the impacts of future climate uncertainties in the new generation of future climate data sets according to AR5(5th assessment report of IPCC) on simulating the energy performance of buildings by studying the building stock in Germany (Potsdam). Four different climate models and RCP 4.5 and RCP 8.5 were used in the assessment. for three 30-year periods between 2010 to 2099.

E3S Web of Conferences,12th Nordic Symposium on Building Physics (NSB 2020)

Paper IV: Impact assessment of climate change on the energy performance of the building stocks in four European cities

This study considers different future climate series in four different European cities (Kiruna, Stockholm, Valencia, and Madrid). Based on climate change, the energy simulation was performed from 2010-2099, and the study also put forward to the energy-saving strategy result evaluations.

IBPSA: International Building Performance Simulation Association Conference

2 Weather data

This chapter mainly discusses the state of the art of weather data, which is the key data used to perform the energy simulation in this study: global climate model (GCM), regional climate model (RCM), emission scenarios, etc. High-quality weather data are essential to obtain an accurate result. This chapter also discusses widely used methods for predicting future weather data (dynamic downscaling and statistical downscaling) and provides an overview of the available weather data sets for building simulation.

2.1 Global Climate model (GCM)

The most advanced tool for climate simulation today is the coupled atmosphere-ocean general circulation models (AOGCM). These general circulation models are driven by, for example, solar radiation, representative concentration pathways (RCP). The resolution of GCMs is quite coarse usually 100–300 km which is not suitable for building simulation which downscaling is needed to perform the local impact studies , and the direct output is not recommended for impact assessment [32]. Therefore, one of the two main downscaling methods, i.e., dynamic and statistical, should be used to downscale the GCM data. In this work CMIP5 GCMs was dynamically downscaled to the regional scale, using the he most recent regional climate projections of the Coordinated Regional climate Downscaling Experiment (EURO-CORDEX)

2.1.1 CMIP5 project

The fifth stage of the coupled model comparison project(CMIP5) [33] is a project of the World Climate Research Program (WCRP), which brings together more than 50 models from more than 20 model groups around the world, providing a platform for comparison, testing and improvement of these mainstream models in the world. In view of the important role of models in climate change research, the CMIP5 global climate model is also the focus of assessment in the IPCC fifth assessment report (AR5[34]). Based on the simulation results of these models, AR5 predicts possible future climate changes under different emission scenarios, providing an important reference for policy makers and multidisciplinary research. Compared with the third phase of the coupled model comparison plan (CMIP3), the CMIP5 model has become more complex, and the Earth system model has been introduced for the first time on the basis of the traditional atmosphere-ocean coupling model. The earth system model has added biogeochemical processes to realize the global carbon cycle process and dynamic vegetation process, and can simulate the interaction of aerosols, changes in atmospheric chemistry, and ozone processes that change over time. In addition, the horizontal resolution of most CMIP5 modes has been improved

In CMIP5, the projected scenarios of future climate change have undergone major changes, which are different from the SRES (A2 A1B and B1) used in IPCC AR4. The CMIP5 database allows access to the variables output by each individual model. The output is usually provided in time series, with different time steps, including daily, monthly and annual time steps; from 2006 to 2099 [35].The new emission scenarios are named after the magnitude of the radiative forcing reached at the end of the 21st century and are called representative concentration. pathway (RCP), which is a future emission scenario simulated based on many assumptions about future development. There are four types of scenarios: RCP8.5 is a higher emission scenario. Lower emissions continue to increase, and the radiative forcing will rise to 8.5W/m2 by 2099; RCP6.0 and RCP4.5 are medium emission scenarios, and by 2099 the radiative forcing will be 6.0 W/m2 and 4.5W/m2, respectively; RCP2.6 is in the low emission scenario, the radiative forcing under this scenario first increases and then decreases, and will decrease to 2.6 W/m2 by 2099.

2.1.2 Statistical Downscaling

Among the statistical downscaling methods, one of the methods most widely used in building simulation is the “morphing technique” developed by Belcher et al.[36] CIBSE (Chartered Institution of Building Services Engineers) used this method in 2008[37] and they generated a typical weather test reference year (TRY) and a design summer year (DSY) for building simulation. The morphing method has also been implemented in the Weather File Module of the WeatherShift commercial tool. They used the future climate data from the GCM used in the IPCC Fifth Assessment Report (AR5) and can access the future climate data in three future time periods: 2026-2045, 2056-2075 and 2081-2099. Moazami et al. Comparing the future climate predictions from CCWWeatherGen and WeatherShift [38], it is concluded that WeatherShift is only modifying several climate variables other than those have important impact on buildings, such as global solar radiation. However, the downgrade of statistical data only reflects changes in average weather conditions, not extremes, leading to underestimation of the impact of climate change and unable to explain unprecedented extreme event [39].

2.1.3 Dynamical Downscaling (Regional Climate Models)

The Regional Climate Model (RCM) is a “dynamically reduced” climate model from the global climate model, and its spatial resolution is small (10 to 50 km). RCM only represents a specific area of the world, so the grid has a higher spatial resolution and can better represent local climate influences. RCM can simulate smaller-scale climate phenomena, such as rain, snow, storms, etc. RCMs also have perfect time resolution, allowing them to better represent extreme events. For local adaptability research, RCM has been proven to be a good representative of other extreme events in space, such as heat waves and other extreme climate conditions[40] [41]

2.1.3.1 EURO-CORDEX

Euro Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) has become the main reference frame for regional downscaling research[42]. Its main goal is to evaluate and improve different RCMs through a better understanding of regional and local climate phenomena and uncertainties. The purpose of the project is also to generate and maintain a consistent database that is useful for global The region has been forecasting reductions for many years, and these data can be used in building simulation weather files. The EURO-CORDEX projector can be used in Europe with a grid resolution of 12.5 km, and in other parts of the world, it is about 50 km. CORDEX has established a collection of multiple dynamic and statistical models driven by CMIP5.

2.2 Climate models

This section briefly explain the characteristics of the climate models used to perform the future energy simulation, for more information regarding the climate models see [41,43]. As describe in the pervious selection, dynamically downscaled weather data, generated by RCM which provide a physically consistent representation of climate parameters and extreme event are used in this work. Methods regard generating future weather file were discussed in previous studies, for example.[38,40]. The CMIP5 data have been dynamically downscaled to regional scale using EURO-CORDEX, climate date have been synthesized using the fourth generation of the Rossby Centre RCM, namely RCA4 with the spatial resolution of 12.5km and the temporal resolution down to 15 minutes. Five GCMs used in this work are (1) CNRM-CM5: developed at CERFACS, Toulouse, France, the fifth version of the ocean-atmosphere model initially [44], (2) ICHEC-EC-EARTH: Collaboration between ICHEC (Irish Centre for High-End Computing) Met Éireann. EC-EARTH developed by many European national meteorological service agencies, (3) IPSL-CM5A-MR: the coupled model by the Institut Pierre Simon Laplace des Sciences de l'Environnement Global, IPSL Global Climate Modelling Group, Paris, France [45], (4) MOHC-HadGEM2-ES: is the coupled Met Office Hadley Centre (MOHC), and (5) MPI-ESM-LR: the coupled Max Planck Institute Earth System Model. Future climate simulations are conducted for hourly data of three 30 years periods, including 2011-2039 (period 1 as NT) 2041-2069 (period 2 as MT), and 2071-2099 (period 3 as LT). Each city has 13 climate scenarios multiply by three periods, which result in 39 weather data for each city. Methodology

This chapter briefly describes the NZEB European climate zone, the TABULA webtools, building stock database and the establishment of building energy model based on TABULA webtools.

2.3 NZEB European climate zone

The target cities were selected based on the European nearly zero-energy building climate zone (NZEB). The NZEB climate zone divided European countries in 5 European climate zones which based on Köppen-Geiger classification, HDD (heating degree-days), CDD (cooling degree-days), solar radiation and even night ventilation. The NZEB climate zones was shown in Table 1 and Figure 1, along with the relevant Köppen-Geiger classification.

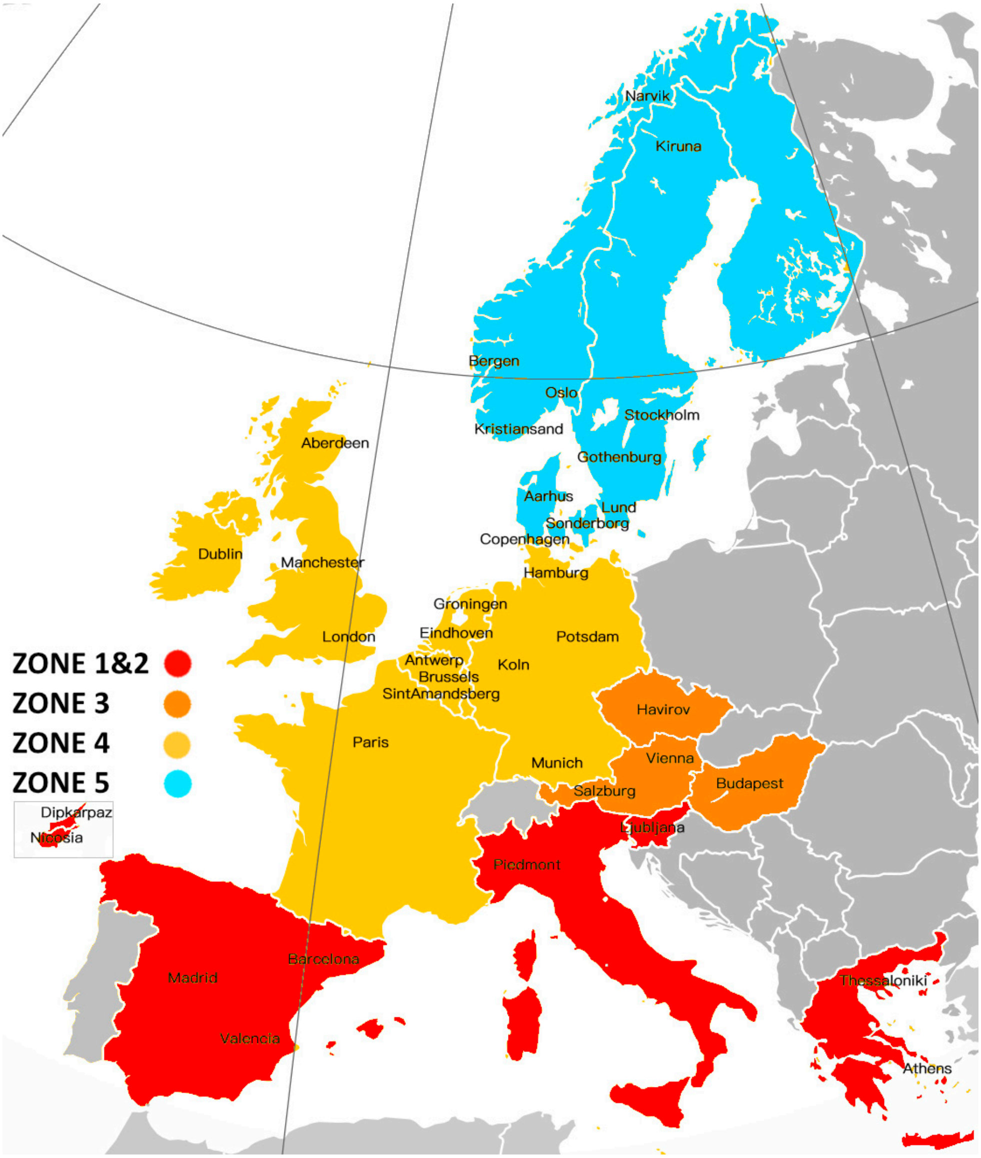

Figure 1. Target cities in NZEB climate zone

Table 1 Cities in NZEB climate zones in respect to Köppen-Geiger zone

Zone	Cites	Köppen-Geiger zone
Zone 1&2	Barcelona, Madrid, Valencia, Piedmont, Athens, Thessaloniki, Dipkarpaz, Nicosia	Csa/Cfb
Zone 3	Salzburg, Vienna, Ljubljana, Havirov, Budapest	Dfb
Zone 4	Hamburg, Koln, Munich, Potsdam, Aberdeen, London, Manchester, Dublin, Paris, Antwerp, Brussels, SintAmandsberg, Eindhoven, Groningen	Cfb/Dfb
Zone 5	Gothenburg, Kiruna, Lund, Stockholm, Bergen, Kristiansand, Narvik, Oslo, Aarhus, Copenhagen, Sonderborg	Dfc
Csa	Temperate with dry, hot summer.	
Cfb	Temperate without dry season and warm summer.	
Dfb	Temperate continental climate and humid continental climate without dry season with warm summer.	
Dfc	Cold, without dry season and with cold summer.	

3 Energy simulation

This chapter describes the building database (TABULA webtools) used for building energy simulation in this project, as well as the building models in IDA ICE. This chapter also discusses the mathematical models for calculating renewable energy (solar and wind energy) and the statistical methods.

3.1 TABULA Webtool

From 2009 to 2012, TABULA developed residential building types for 13 European countries. Every country's typology includes a classification scheme, according to the size of the building, age, and the parameters of the further carry on the grouping, as well as representatives of a group of buildings types of model building. In addition, TABULA also provides a variety of air-conditioning systems to match the type of building. Each reference building has a typical energy consumption value and estimates the energy savings through different retrofit measures. The method mainly aims at the energy consumption of residential heating and living hot water. In cooling, air conditioning, lighting, electrical appliances and so on are not considered, but can certainly be added in the future. The results of this process have been published by project partners in the national "handbook of architectural typology", prepared in their respective languages and accompanied by statistical data on building and supply systems

In many countries, the classification by reference to building types is a concept already in use at the national and/or regional levels. Architectural typology was classified based on climate zone, architectural year, architectural type and architectural shape [46]. In the European and national levels, however, because of the lack of a common definition, lack of knowledge or update the data of the existing building, difficult to agree on building types, some problems are emerging. Therefore, TABULA first aims to create a unified structure, at the European level classifying reference architecture type: the project designed for residential buildings and extended for other purposes.

In TABULA, architectural typology is defined as the classification of parameters that typically exist in a building. Architectural typology refers to the systematic description of the definition of typical buildings and the definition of architectural types themselves. The emphasis is on the evaluation and improvement of building energy performance: therefore, the concept of typology focuses on building parameters related to energy consumption. Architectural typologies are classified according to three specific parameters:1: location and climate zone. For a country characterized by a single climate zone, a single national architectural typology can be developed. However, where there are significant differences in climatic conditions and typical architectural features, such as appearance and construction principles, a complete typology must be developed for each region. 2: Construction period involving construction principles and materials. Each country should define different construction cycles, reflecting changes in building practices and energy requirements of building codes. 3. Building size and shape. The project considers four different building sizes: single-family homes, terraced homes, multi-family homes, and apartment buildings.

3.2 TABULA building matrix

In TABULA building matrix (see Figure 2), the building was classified by the construction period, where each country has a differet construction period. The construction period is an important part of the TABULA classification because different construction rules and materials are used in different periods, such as window sizes and wall materials, which greatly impact the energy demand for building energy use. With the changes in energy-related building regulations, the establishment of the TABULA database is mainly guided by the construction period, statistical survey, and building category [47]. The building stock which is subdivided into the several time frame. The example was shown in Figure 2 to Figure 5, which is selected from each climate zone, Spain(zone 1&2), Austria (zone 3), Germany(zone 4), and Sweden(zone 5). The TABULA building matrix consists of few exemplary buildings. Those exemplary buildings were sorted by year and building type. The building matrix also provides detail of building date, building energy system data. It is convenient to acquire enough information that could convert into a simulation model. As we can see from Table 2 to Table 4 shows the detailed building data, countries from zone 5, which is heating dominated country, has the best U-value, followed by zone 4 and zone 3. For each type of housing, TABULA also provides the heating demand in kWh/m^2, which also provides important parameters for the subsequent establishment of the basic model and model verifications.

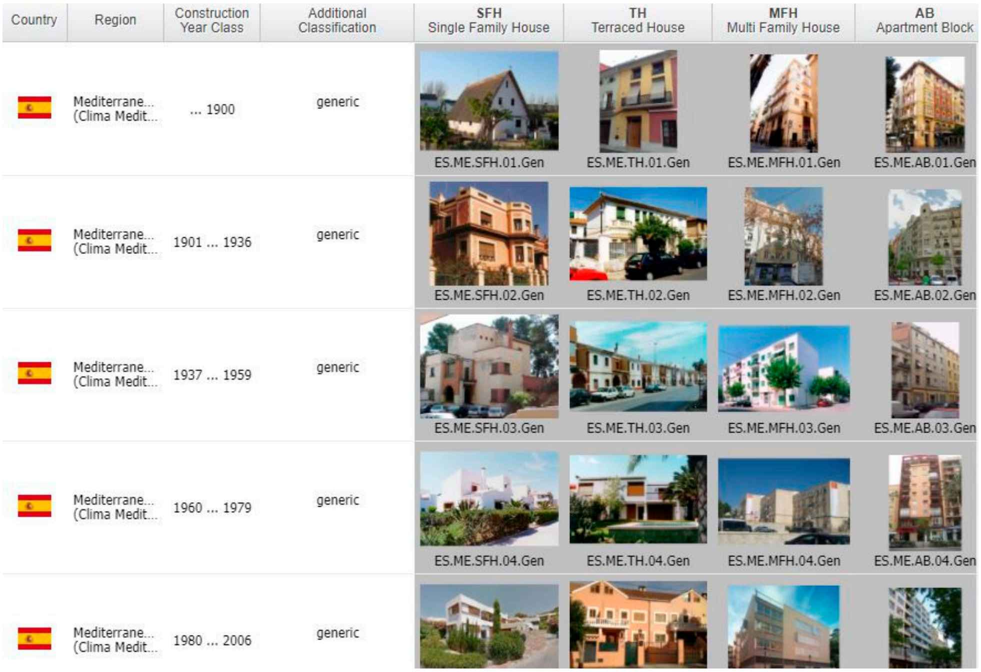

Figure 2 TABULA building matrix-Spain building typology (zone 1&2)

Table 2 Spain single family house building data.

Construction period	Before 1900
Floor area	202 m^2 U-value 2.9 W/(m^2K)
Heating Supply system	Gas central heating, poor efficiency
Region	Mediterranean region
Window	Area 28.5 m^2 U-value 4.59 W/(m^2K)
Wall	Surface area 193.9 m^2 U-value 2.94W/(m^2K)
Roof	Area 85 m^2 U-value 4.18 W/(m^2K)
Heating demand	14.8 kWh/m^2

Figure 3 TABULA building matrix-Austria building typology (zone 3)

Table 3 Austria single family house building data.

Construction period	Before 1919
Floor area	159m^2 U-value 1.69 W/(m^{2}K)
Heating Supply system	Oil central heating
Region	National region
Window	Area 28.5 m^2 U-value 2.20 W/(m^{2}K)
Wall	Surface area 267 m^2 U-value 1.10W/(m^{2}K)
Roof	Area 85 m^2 U-value 4.18 W/(m^{2}K)
Heating demand	135.8 kWh/m^2

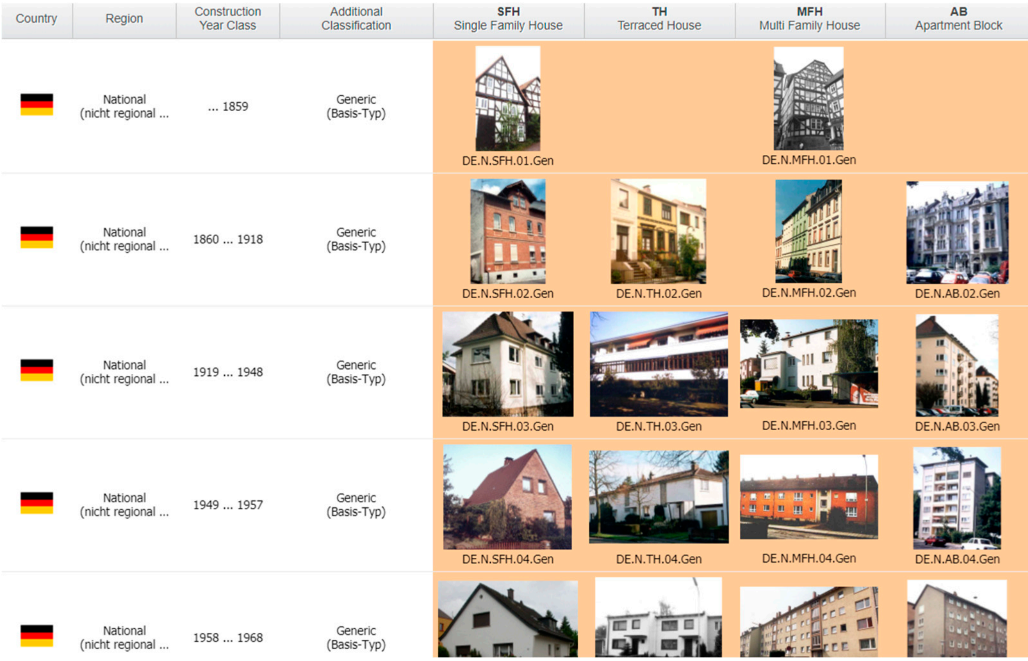

Figure 4 TABULA building matrix-Germany building typology (zone 4)

Table 4 Germany single family house building data.

Construction period	Before 1859
Floor area	219 m^2 U-value 2.9 $W/(m^2K)$
Heating Supply system	Gas central heating, poor efficiency
Region	National region (EnEV 2009)
Window	Area 28.8 m^2 U-value 2.9 $W/(m^2K)$
Wall	Surface area 169.8 m^2 U-value 2.6 $W/(m^2K)$
Roof	Area 134.3 m^2 U-value 2.00 $W/(m^2K)$
Heating demand	167.3 kWh/m^2

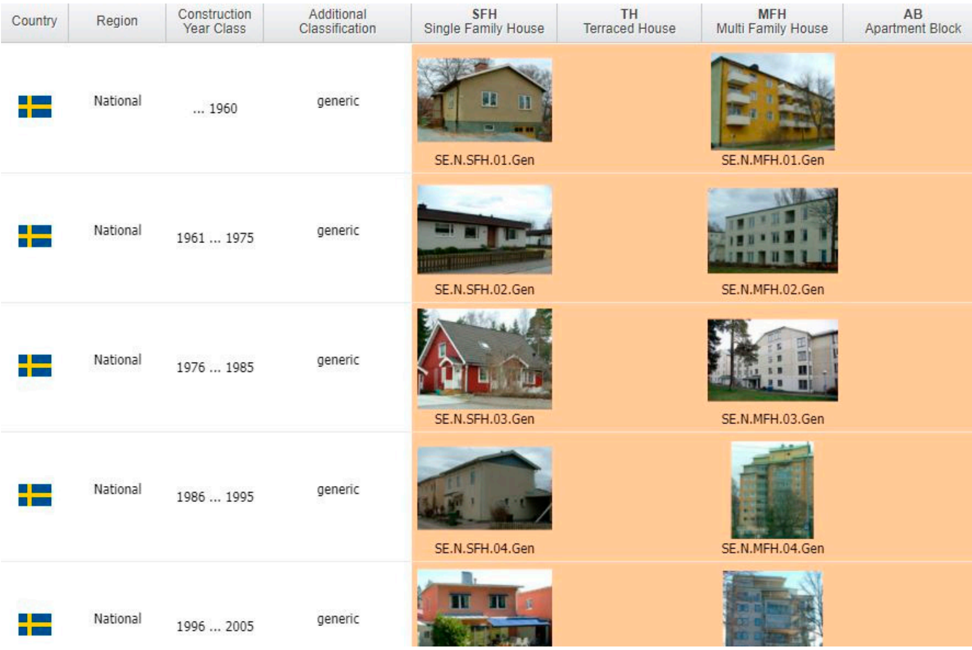

Figure 5 TABULA building matrix-Sweden building typology (zone 5)

Table 5 Sweden single family house building data.

Construction period	Before 1960
Floor area	105 m^2 U-value 0.28 W/(m^2K)
Heating Supply system	Heating system with fuel, oil
Region	National region
Window	Area 28.8 m^2 U-value 2.34 W/(m^2K)
Wall	Surface area 125 m^2 U-value 0.6 W/(m^2K)
Roof	Area 100 m^2 U-value 0.29 W/(m^2K)
Heating demand	198.6 kWh/m^2

3.3 Building energy and indoor thermal comfort models

The IDA ICE (IDA Indoor Climate and Energy) software developed by EQUA[48] and verified by the Swiss Federal Material Testing and Research Laboratory

(EMPA) [49] was used to perform the numerical simulation of the building and its indoor comfort. TABULA has provided enough information to establish the building model; for example, according to the data provided in Table 5, a reasonable building model can be established for Sweden single-family house with a length of 12.5 m, a width of 8 m, and 2.34 m high.

The heating and cooling setpoint was set using hybrid cooling strategies, combining natural ventilation and mechanical ventilation. When the indoor temperature is above 24°C while the outdoor temperature is below 24°C, natural ventilation will engage simply by windows opening, and when the indoor and outdoor temperatures are above 26°C, windows will be closed and the mechanical ventilation system becomes engaged. This is done by IDA ICE PI control (see Figure 6).The PI control connected with the zone and ambient gives the opening signal when it reaches a certain temperature.

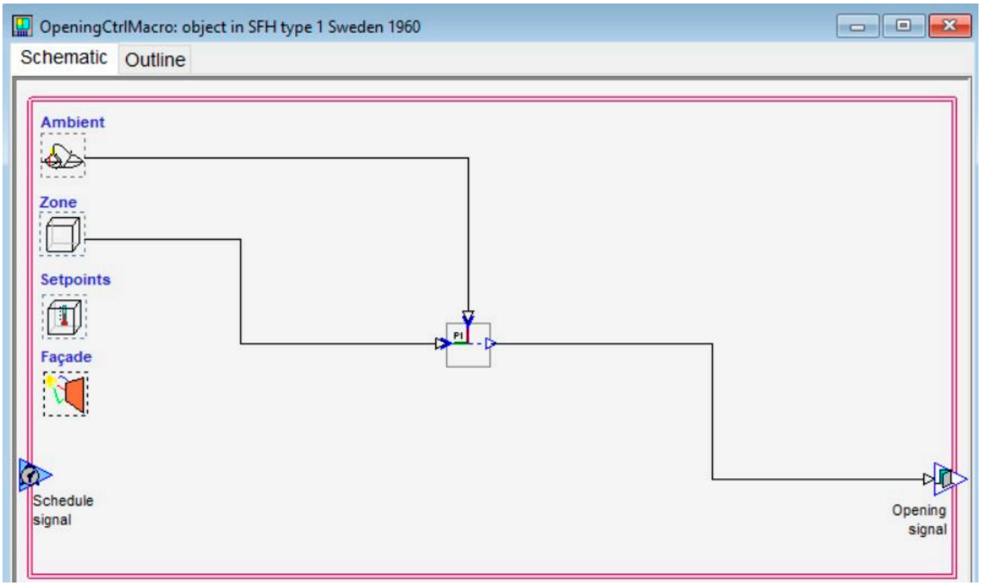

Figure 6 IDA ICE PI opening control

Energy modeling was first established for each building according to the TABULA database in IDA ICE., ensuring that the size and U-value of the building model are the same as those provided by TABULA. Figure 7 shows an example of a different case type produced in IDA ICE. These models became our basic models and were verified against reference energy demand values (Table 6 and

Table 7) of past climates using the typical weather year (TMY) weather files of the corresponding cities. TMY data includes a set of hourly values for a year, including different climate variables representing the most typical months of the past 30 years, usually based on observed climate conditions (past climate conditions) [50].

Table 6 The average heating demand for residential buildings in the European countries according to TABULA.

Country	City	Heating demand (kWh/m^2)
Austria	Salzburg	205.21
Belgium	Sint-Amandsberg	160.9
Cyprus	Nicosia	128.1
Czech Republic	Havířov	112.5
Denmark	National	119.3
France	Paris	104.5
Germany	Potsdam	112.5
Greece	National	83.5
Hungary	Budapest	76.5
Ireland	Dublin	151.3
Italy	Piedmont region	136.1
Netherlands	National	135.7
Slovenia	National	149.5
Spain	Valencia	11.6
Sweden	National	144.5
United Kingdom	National	108.3

Table 7 Estimations of specific cooling demands by country from Stratego (Halmstad University) [51], ENTRANZE [52]

Country	Office Building （kWh/m^2）	Residential Building（kWh/m^2）	Average（kWh/m^2）
Austria	83	38	49
Belgium	50	23	28
Cyprus	145	65	77
Czech Republic	64	29	37
Denmark	30	13	18
France	71	32	42
Germany	74	33	46
Greece	146	66	84
Hungary	103	46	59
Ireland	0	0	0
Italy	114	51	60
Netherlands	37	16	22
Slovenia	95	43	58
Spain	130	59	69
Sweden	46	21	27
United Kingdom	47	21	28

Several standards for evaluating indoor thermal comfort are formulated with reference to PMV indicators, to give values of environmental parameters that can give the best thermal comfort conditions to guide the design and control the indoor thermal environment. For example, ASHRAE Standard 55-20040 gives the recommended value of indoor operating temperature for offices(sitting position, light physical labor, metabolic rate 1.2met) and indoor wind speed not exceeding 0.2m/s [53]. In summer, the clothing thermal resistance is specified as 0.5clo, and at 50% relative humidity, the set temperature range of the indoor air conditioner can be taken within the range of 24°C -27 °C; in winter, the clothing thermal resistance is specified as 1.0clo, at 50% relative humidity. The range of air-conditioning set temperature is 20.5 °C - 24.5°C.

In this study, the psychrometric chart was used to reflect the indoor thermal comfort condition. Combining the Givoni building bioclimatic chart [54], the ideal comfort zone is shown in Figure 8. Zone ABCDE is an improved version of the ASHRAE comfort zone and the reason for not using the ASHRAE comfort zone primarily due to the ASHRAE comfort zone is more suitable for buildings with ventilation systems, while most residential buildings in Europe were using nature ventilation. This comfort zone was defined as the optimal thermal condition under which the body's heat balance can be maintained with minimal additional effort[55]. It should be noted that the indoor thermal comfort in this paper is confined to the physical aspect, which is the impact of the environment on human comfort. Other aspects such as the Physiological aspect[56], Psychological aspect[57] are not considered.

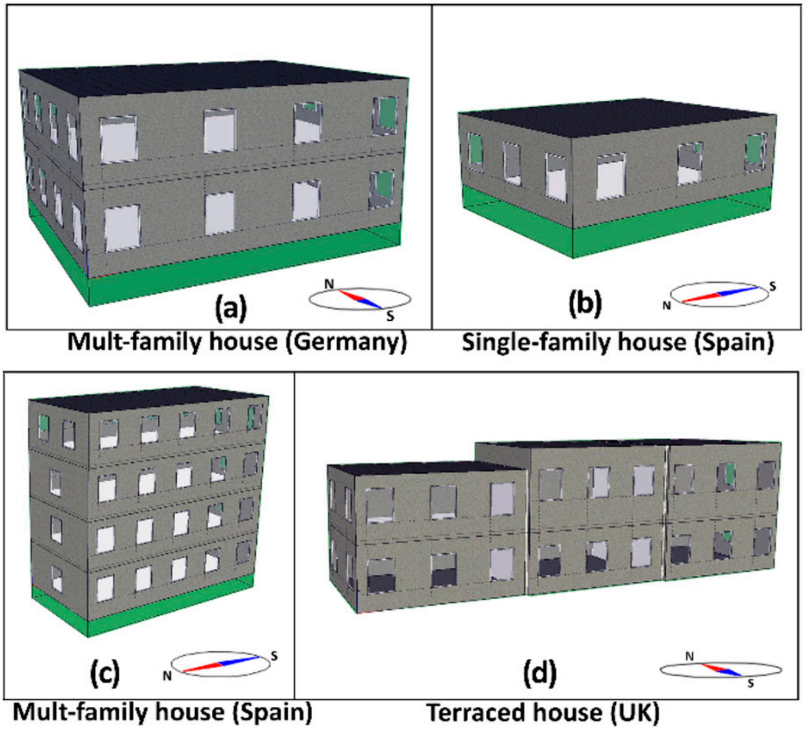

Figure 7 TABULA building types in IDA ICE models

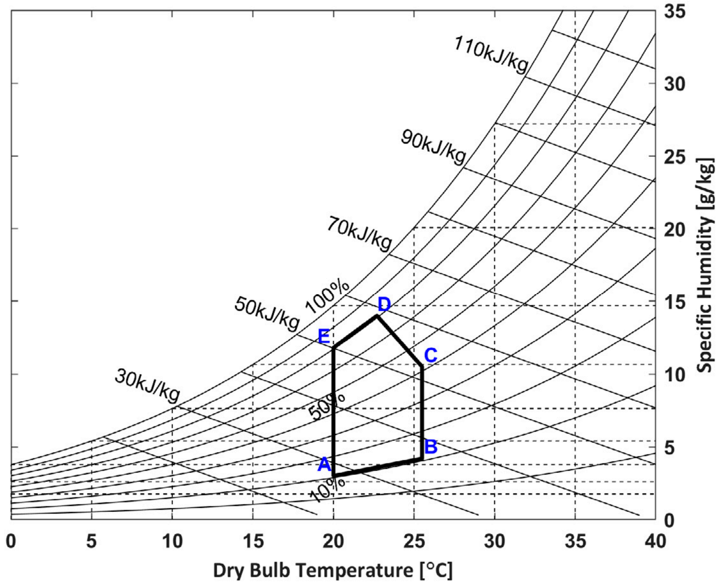

Figure 8 Building bioclimatic chart

3.4 Wind and solar model

3.4.1 Wind output

The conversion from wind speed to power density (power per unit area, kW/m^2) includes the use of a power-law function [58,59] to obtain the corresponding wind speed value according to the height of the sub-car (according to Equation 1, the wind speed V_0 (m/s) Extrapolated from 10 m (H_0) to 80 m (H), which is the current average hub height of onshore wind turbines [60]. The power-law exponent α of the offshore hub used in this study is 0.142. Among them, V (m/s) is the wind speed at the hub height H(m) that can be calculated. The wind speed V will be used as an input variable later to calculate the hourly wind power output which has been extracted from the weather data. Equation 2 can calculate the average power based on a series of average wind speeds in the selected area. Cp is the maximum power coefficient and its theoretical value is 0.59 according to Betz's law [61]. P/A is the power density kW/m2 (A is the fan blade area), and ρ is the air density (1.225 kg/m2). For the power density function, see This function closely matches the observed long-term distribution of average wind speed, and it is widely used to quantify wind power generation [62,63].

$$\frac{V}{V0} = (\frac{H}{H0})^{\alpha} \qquad (1)$$

$$\frac{P}{A} = \frac{1}{2}\rho V^3 Cp \qquad (2)$$

3.4.2 Solar output

Photovoltaic (PV) projection relies on the photovoltaic power generation model Equation (3) uses two parameters as input variables, namely total horizontal irradiance G (W/m2) and ambient temperature T (Kelvins) to calculate photovoltaics Power generation per hour. It should be noted that this study only considered the power generation of 1 square meter and did not consider the inclination of the solar panels. P/A in kW/m^2 refers to the electric power generated per unit surface of the photovoltaic module.

$$\frac{P}{A} = 0{,}128G - 0.239 \times 10^{-3}T \qquad (3)$$

3.5 Statistical Methods

As we discussed in the previous section, the weather data and consequently the building simulation result cover 2010 to 2099 with hourly time step, which results in multiple large datasets. Therefore, the use of appropriate statistical methods is particularly important. This section mainly discusses two statistical methods used in this study

3.5.1 Regression analysis

Linear regression uses the least square function called linear regression equation to model the relationship between one or more independent variables and dependent variables. This function is a linear combination of one or more model parameters called regression coefficients. When performing linear regression analysis on variables in statistics and using the least-squares method for parameter estimation, R-squared (R^2) is the ratio of the sum of squares regression (SSR) to the sum of squares total (SST), see equation (1) below. This equation ŷi (Y hat) is the predicted value of y, which can be considered the average value of the response variable. The R-squared is between 0 and 1. The closer to 1, the better the regression fitting. It is generally believed that the goodness of fit of the model over 0.8. This method was used in Paper I to assessing the heating and cooling trend and in Paper II to assessing the future renewable energy trend.

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^{n}(\hat{y}_i - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (4)$$

3.5.2 Spearman's rank correlation

Spearman's rank correlation is a non-parametric method that was used It uses a monotonic equation to evaluate the correlation of two statistical variables. This method was used in Paper II to assess the correlation between climate change (temperature) and renewable energy output. The Spearman's rank correlation coefficient Rs can take values from +1 to -1, in which +1 indicates a perfect positive correlation, and -1 indicates a perfect negative correlation of the ranks. When the correlation coefficient is closer to zero, which means the weaker correlations between two variables. The correlation coefficient Rs can be calculated in the following equation (2), where N is the number of the observations and d is the difference between ranks.

$$Rs = 1 - \frac{6\Sigma d^6}{N(N^2-1)} \quad (5)$$

4 Result

This chapter provides a short summary of the appended paper on which this thesis is paper-based. This chapter includes a literature review of previous studies, followed by the major finding and the relevant result for future heating and cooling demand, thermal comfort, and renewable energy generation as well as some example figures to present the highlighted result.

4.1 Review of the previous studies

A comprehensive review was performed to review the recent works published after 2017 on the impact assessment of climate change on the energy performance of buildings (see Figure 9). The list of papers can be found in the Appended Paper I Table 1.

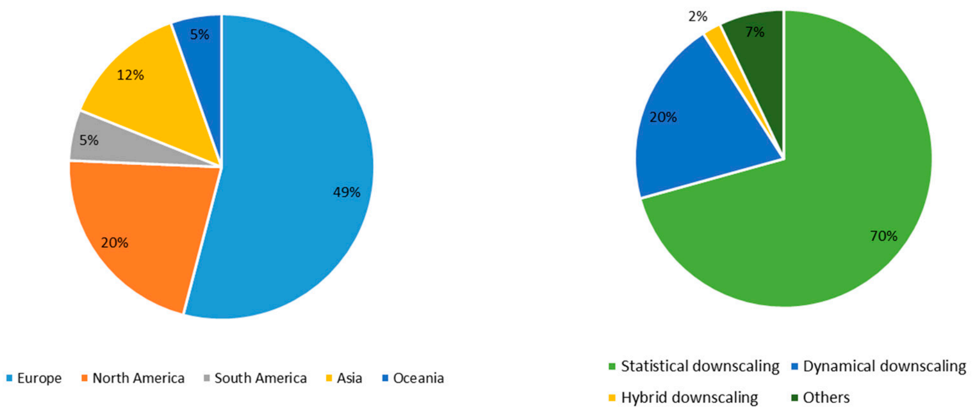

Figure 9 Analysis of literature published after 2017 assess the impact of climate change on the energy performance of the buildings (41 articles).

As we can see from Figure 9, more than 49% of the studies were performed in Europe, followed by 20% in North America. More than 70% (29) were based on statistically downscaled data, and 20% are based on dynamical downscaling. Among the 29 papers, 10 of which were using the data generated by

CCWWeatherGen, which is based on only one GCM (HadCM3) and only A2 scenarios. As described in the previous chapter, the statistical downscaling method did not consider extreme conditions such as heatwaves, making the result bias and the old IPCC SRES scenarios replaced by the RCPs.

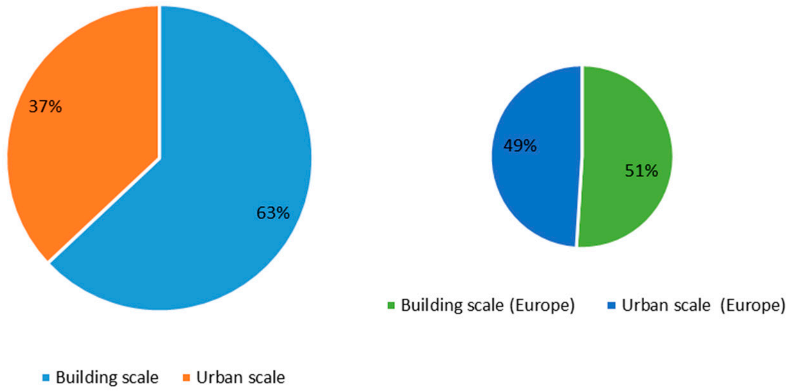

Figure 10 Analysis of literature published after 2017 assess the impact of climate change on energy performance on a different scale.

Among the 41 studies (Figure 10) 63% (26) was performed at the building scale (e.g., standalone residential building), and 49% (15) were performed at the urban scale (e.g., considering multiple building types in Europe, this number was 48% and 51% respectively. Only one study considered multiple countries and climate regions at the urban level in Europe.

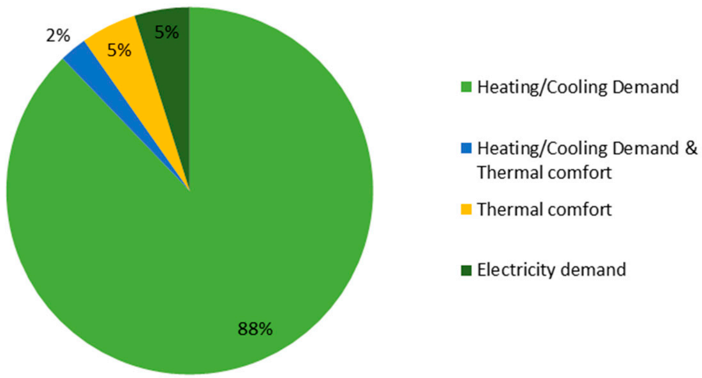

Figure 11 Literature published after 2017 assessing building energy performance and thermal comfort considering future climate scenarios

Figure 11 shows that 88% of the studies focus on heating and cooling demand. and only 2% assessing the building energy performance and thermal comfort at the same time. Only 5% of thermal comfort studies considered future climate scenarios, while the other 5% focused on electricity demand.

4.2 Future temperature distribution

Figure 12,the boxplot shows the temperature distribution for the future climate scenarios, which combine all five GCMs and three RCPs for three 30-year period. Each boxplot represents 13 climate scenarios × 30 years × 8760 h (3,416,400) data point. The purpose of this is to consider all possible conditions in the assessment, because it is known that all climate models have been validated, but none of them can be considered the best.

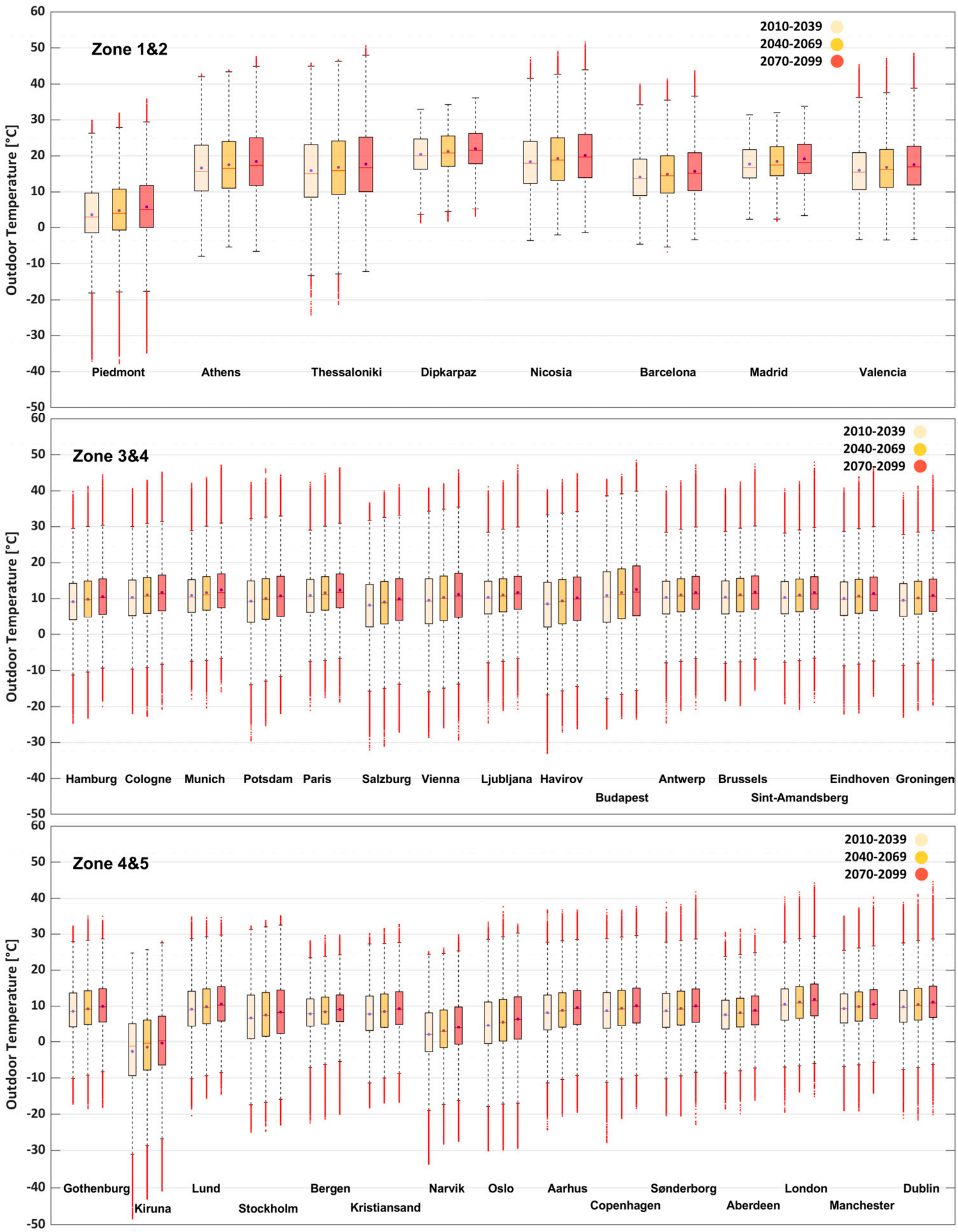

Figure 12 Temperature distribution for 38 cities

4.3 Future Energy projection

The energy result for each city can be found in the appended Paper I. The main purpose of this paper was to conduct impact assessment by assessing the energy performance and indoor comfort of 38 European cities, considering the most recent climate models and including extreme events. In Paper I, Future climate simulation was performed under three 30-year time perods 2011-2040 as near-term (NT), 2041-2070 as medium-term (MT), and 2071-2099 long-term (LT). The result includes the average values of annual heating/cooling demand, standard deviation (see Figure 13 and Figure 14), and the seasonal, hourly energy demand values.

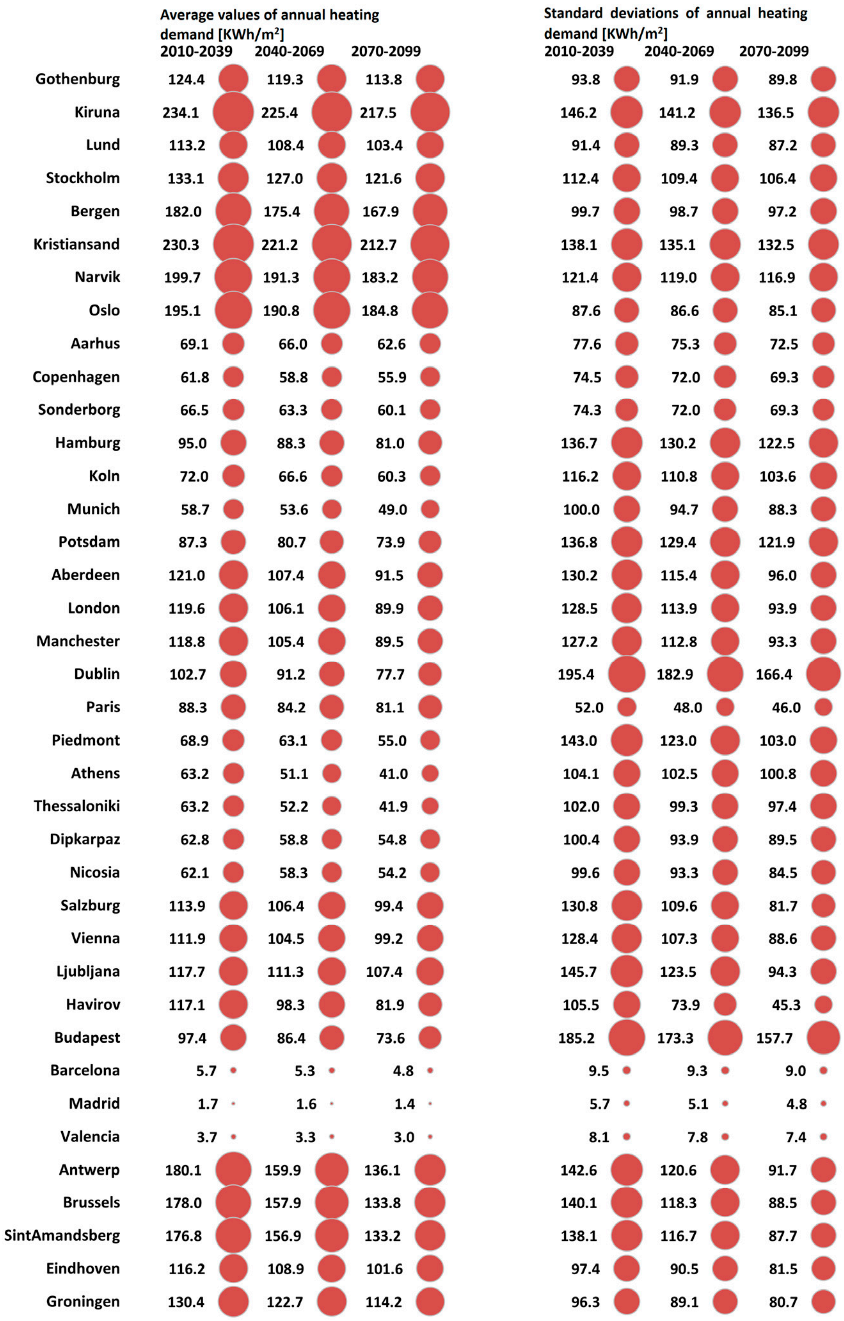

Figure 13 Future heating demand (average and standard deviations) considering 13 future climate scenarios with five GCMs and three RCPs

	Average values of annual Cooling demand [KWh/m²]			Standard deviations of annual Cooling demand [KWh/m²]		
	2010-2039	2040-2069	2070-2099	2010-2039	2040-2069	2070-2099
Gothenburg	4.8	6.7	8.5	18.6	22.0	27.0
Kiruna	1.0	1.2	1.5	12.2	13.7	19.2
Lund	6.6	8.4	10.4	11.3	13.5	16.7
Stockholm	3.4	4.8	6.5	15.3	18.9	22.3
Bergen	1.5	1.7	2.1	7.1	8.3	9.7
Kristiansand	1.0	1.1	1.3	6.1	7.0	8.0
Narvik	0.9	1.1	1.3	6.7	7.6	8.8
Oslo	2.7	3.1	3.4	7.1	8.1	9.3
Aarhus	1.7	2.4	3.5	18.4	28.1	40.7
Copenhagen	3.8	5.5	7.7	12.6	27.4	37.2
Sonderborg	3.4	4.6	5.9	19.2	22.2	36.0
Hamburg	24.1	28.2	33.2	22.1	33.3	35.3
Koln	28.2	32.2	36.3	21.0	24.3	37.3
Munich	38.1	42.2	46.5	22.2	24.9	35.3
Potsdam	26.4	30.2	34.5	25.3	27.9	37.6
Aberdeen	34.6	38.1	41.2	31.1	34.2	37.0
London	36.1	39.8	43.0	22.5	25.8	38.8
Manchester	33.9	37.4	40.5	29.8	33.0	45.9
Dublin	19.7	21.7	23.4	34.7	36.5	38.1
Paris	40.1	51.4	60.8	25.6	27.4	34.8
Piedmont	18.3	19.3	20.1	19.5	27.1	37.4
Athens	67.1	69.6	72.4	27.3	29.6	44.2
Thessaloniki	60.2	62.6	65.3	28.2	31.8	47.3
Dipkarpaz	68.0	74.9	80.8	30.0	36.1	42.2
Nicosia	70.9	78.1	84.5	22.8	29.2	32.1
Salzburg	35.7	39.4	42.5	23.1	26.3	29.2
Vienna	37.2	41.1	44.4	24.5	27.9	31.0
Ljubljana	41.1	45.3	48.9	22.6	26.3	29.6
Havirov	29.2	30.1	31.0	11.8	17.0	22.1
Budapest	42.9	47.2	50.9	25.7	29.5	33.0
Barcelona	43.7	47.1	48.9	15.2	17.2	18.5
Madrid	51.7	54.8	57.9	29.6	30.6	41.7
Valencia	49.0	52.7	56.6	35.7	37.8	40.0
Antwerp	27.8	30.6	33.0	19.0	21.5	23.8
Brussels	28.9	31.9	34.5	20.1	22.8	25.2
SintAmandsberg	27.2	30.0	32.5	38.0	40.5	42.8
Eindhoven	8.0	8.4	8.8	27.1	27.7	28.1
Groningen	7.3	7.7	8.1	26.9	27.0	27.2

Figure 14 Future cooling demand (average and standard deviations) considering 13 future climate scenarios with five GCMs and three RCPs

The regression analysis was performed to assess the annual average heating and cooling demand trend for 13 climate scenarios and for each city, which is more evident to identify the trend. Four cities from different climate regions (Stockholm, Athens, Munich, and Brussels) were selected to assess the average yearly heating demand by using regression analysis in Figure 15 during 2010-2099. The heating demand in the four cities shows a downward trend. The rate of decline in heating demand in the four cities is different. Among them, the heating demand in Brussels has the steepest decline rate, with a more scattered distribution of the annual values around the trend line (scattered points are more dispersed around the regression line). Munich and Stockholm show almost the same decline rate with a relatively narrow distribution around the trend line. Athens also shows broader distribution around the trend line.

The cooling regression analysis for the same cities is shown in Figure 16, the cooling demand is on the rise. Among the four cities, Munich has the most apparent upward trend. Munich has much broader distribution among other cities, Follow by Stockholm, Brussels, and Athens. Compared with heating demand, the distribution point of cooling demand is more concentrated, and it is more stable than the heating demand under the influence of climate change.

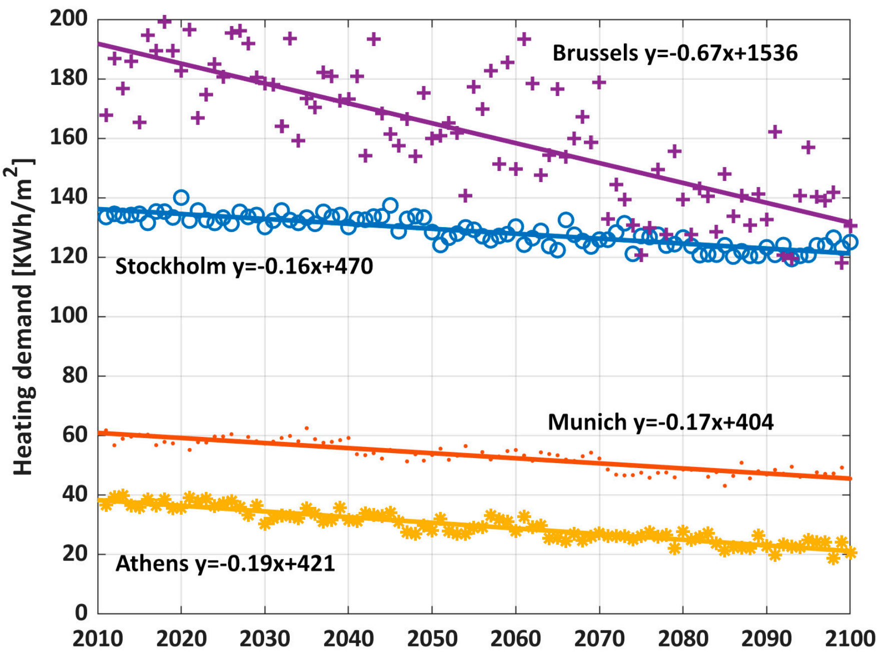

Figure 15 Regression analysis of average heating demand

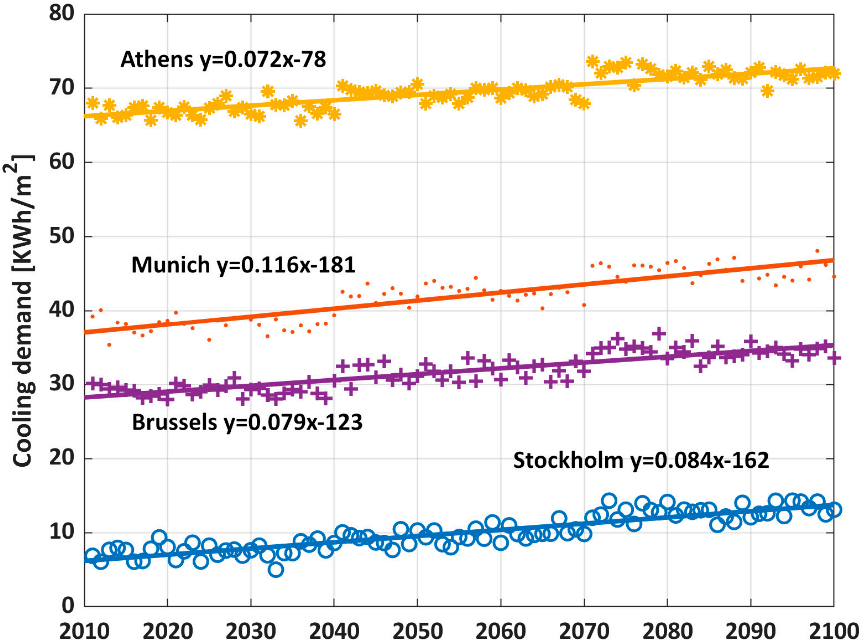

Figure 16 Regression analysis of average cooling demand

4.4 Thermal comfort result

This section presents the results of the indoor thermal comfort assessment of the buildings under consideration during the three time periods. By using the psychometric chart, which is more evident to reflect the indoor thermal comfort conditions. The Indoor condition distribution was shown in Figure 17 to Figure 20, and the analysis is based on three sets of data: RCP 2.6 (blue), RCP 4.5 (yellow) and RCP 8.5 (red). Each set of data uses climate data from three GCMs: ICHEC-EC-EARTH, MOHC-HadGEM2-ES and MPI-ESM-LR. Therefore, instead of 13 climate scenarios, 9 climate scenarios are used in this section. The point inside the comfort zone indicated the total comfort hours for each 30 year period. The percentage of the comfort hours were also calculated in this study (see attached Paper I)

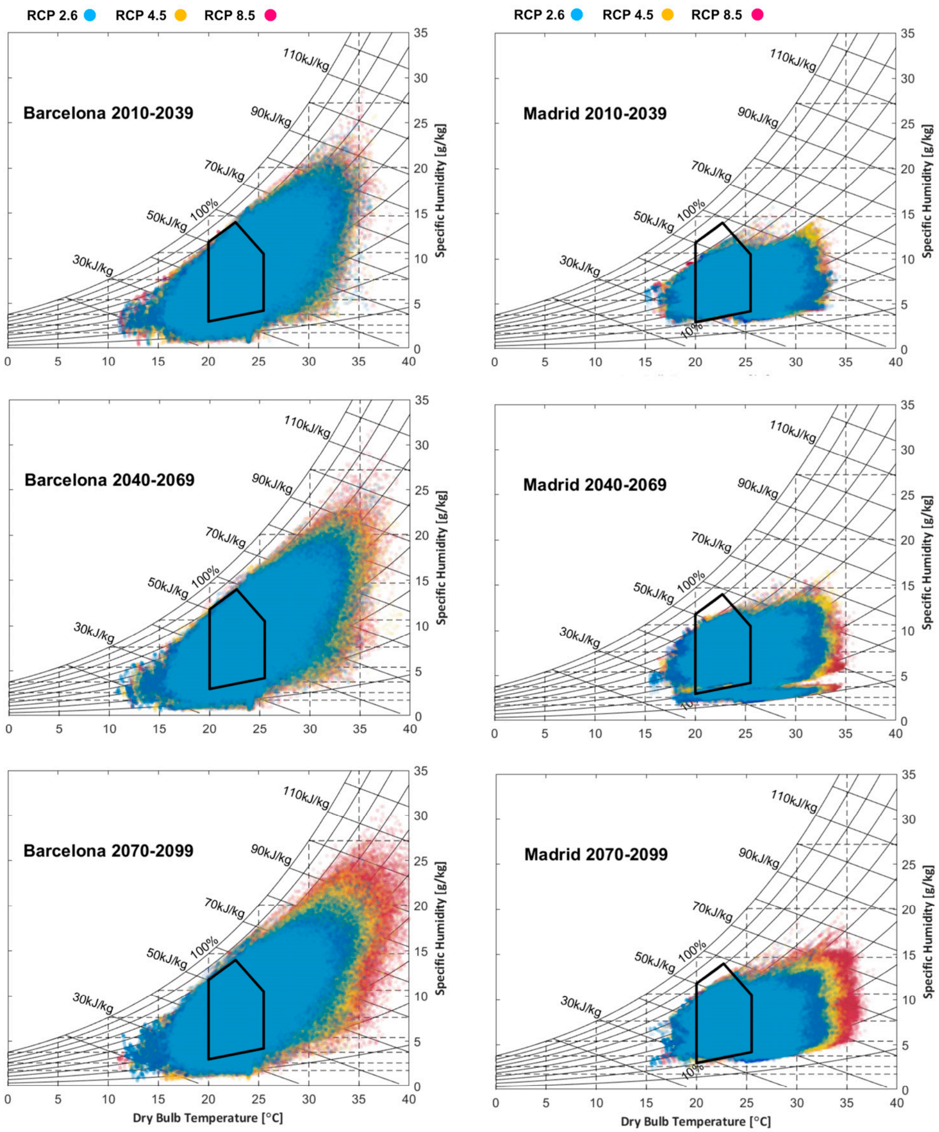

Figure 17 Thermal comfort zone for Barcelona and Madrid (zone 1&2) constructed in psychrometric chart.

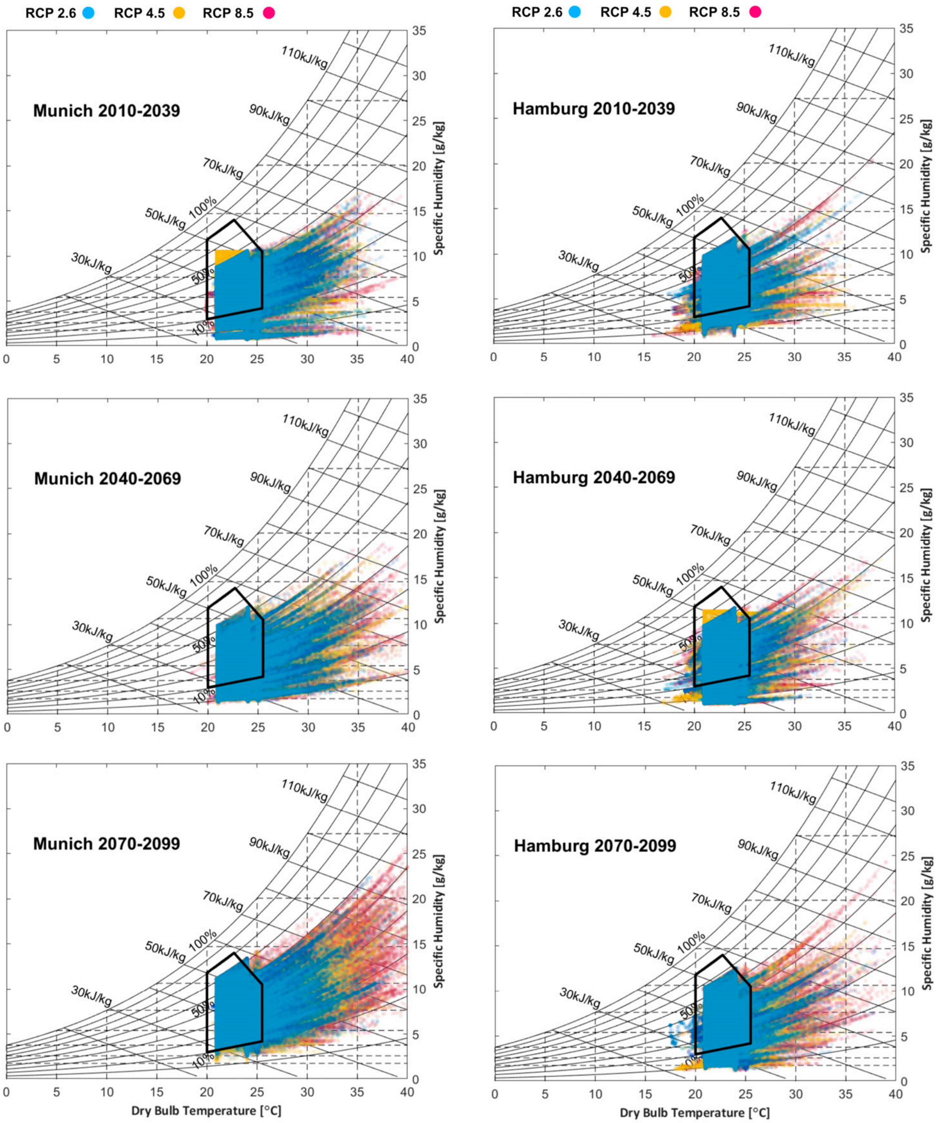

Figure 18 Thermal comfort zone for Munich and Hamburg (zone 4) constructed in psychrometric chart.

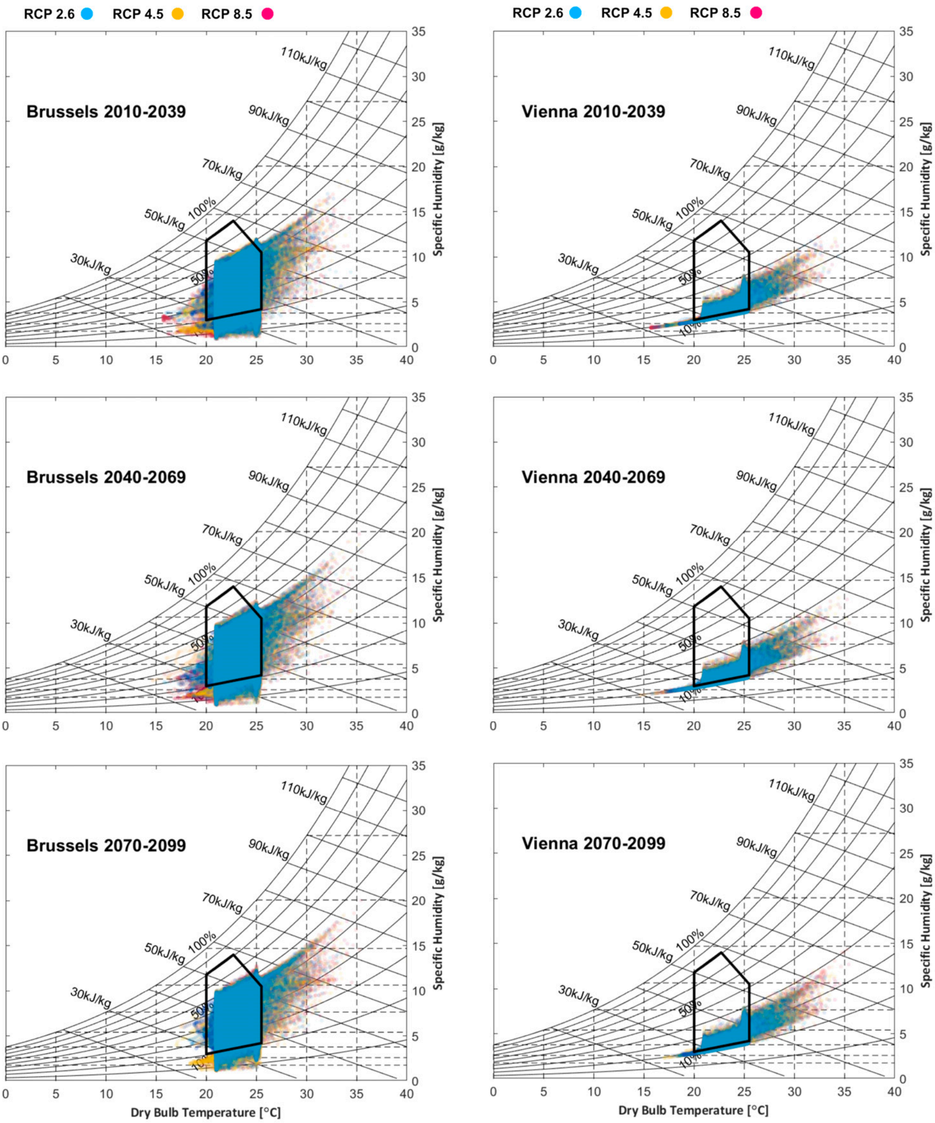

Figure 19 Thermal comfort zone for Brussels and Vienna (zone 3) constructed in psychrometric chart.

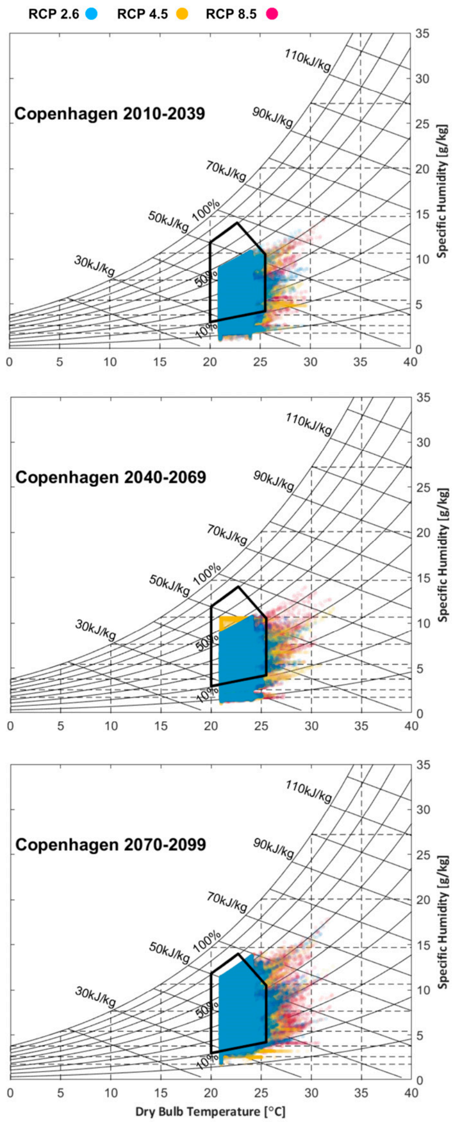

Figure 20 Thermal comfort zone for Copenhagen and Gothenburg (zone 5) constructed in psychrometric chart.

4.5 Renewable energy projection

In Paper II, five GCMs are provided to evaluate the impact of climate change on solar and wind power generation projection, and these models are used to evaluate climate predictions based on the scenarios of RCP 2.6, RCP 4.5 and RCP 8.5 in seven European cities, see Figure 21 for PV output and Figure 22for wind turbine output.

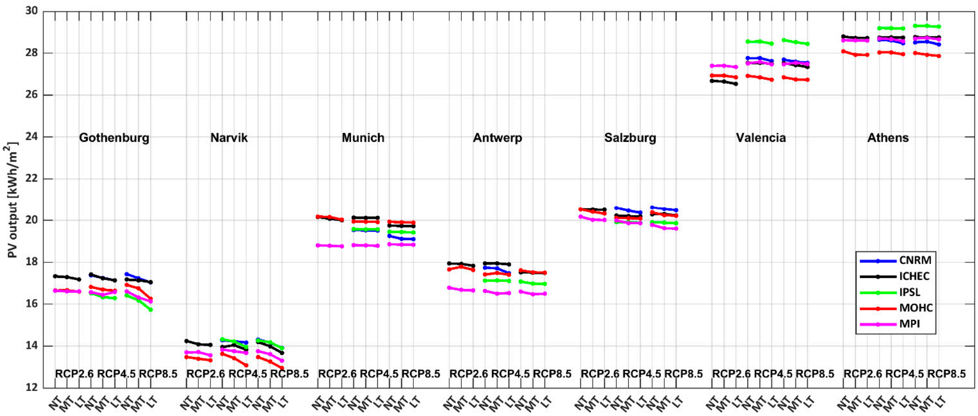

Figure 21 PV output projection for five GCMs and three RCPs during NT, MT and LT

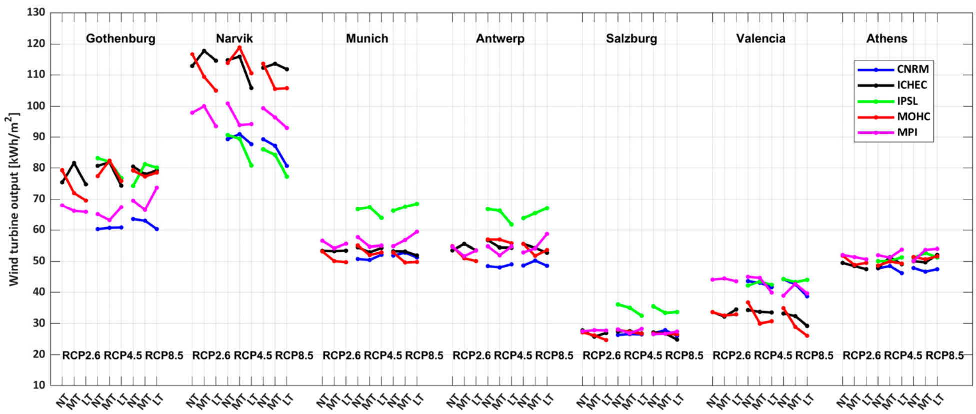

Figure 22 Wind output projection for five GCMs and three RCPs during NT, MT and LT

5 Discussion and Conclusion

This chapter first provides discussion on the interpretation of the results, followed by the major contribution of this study, the concluding remarks, and the suggestions for further research.

5.1 Climate change

Due to climate change, the outdoor temperature rises everywhere, which naturally increases average and extreme temperatures. For example, in many European cities, the probability of reaching above 35°C will increase, while in some other cities, it will exceed 40°C, such as in Athens in zone 5. The highest average temperatures are in Dipkarpaz (Cyprus) and Madrid (Spain); however, the annual changes in these two cities are smaller than those of other cities. In cold climate regions (zone 5) cities such as Kiruna (Sweden) and Narvik (Norway), the range of extremely cold temperatures will be reduced, and extremely low temperatures will be less. As the outdoor temperature rises, it can be preliminarily implay that, on average, the demand for heating in the future will decrease, and the demand for cooling will increase.

5.2 Future energy demand and indoor thermal comfort

5.2.1 Heating demand

It can be seen from the average and standard deviation of the heating demand value over the 30-year period. Obviously, heating demand decreases from one period to the next. This trend is also confirmed by the regression analysis, for all of the cities the regression coefficient (R^2) is above 0.7 which indicated a better regression fitting.

For the cities in Zones 1 and 2 (warm cities with high summer cooling demand), the average heating demand between NT and MT fell between 5.4% and 19.2% (Athens 19.2%, Nicosia 6.2%); for MT and LT, it varies between 6% and 19.7% (19.7% in

Athens and 6.9% in Nicosia). The average heating demand reduction between NT and MT in Zone 3 and Zone 4 countries is between 4.6% and 16%, and the average heating demand reduction between MT and LT is between 3.6% and 16%. The three Belgian cities (Antwerp, Brussels, and St. Armandsberg) have the largest decline between each time period: the decline between NT and MT is 11%–12%, and the decline between MT and LT 14%-15%. Other cities have similar trends, such as Havirov (zone 3), with a 16% drop in heating demand over time. Among them, three cities are in the UK, heating demand of MT is 11% less than that of NT, and the heating demand of LT is 14%-15% less than that of MT. The relative decline in heating demand is less than the result of statistical downscaling for example, the CCWorldWeatherGen project that Aberdeen, decreased by 31% in 2050, and 45% in 2080 [64]

The heating demand in the Nordic countries (Zone 5) has the smallest drop between NT and MT, from 2.7% to 4.8%. For example, the decline between NT and MT in Gothenburg is 4% and 4.5% between MT and LT, respectively, which is smaller than the value in the results of statistical downscaling weather data, for example, Gothenburg, reduced by 24% in 2050, and 36% in 2080 [64]. There will still be c considerable extreme cold conditions in the future, in which the standard deviation of heating demand varies little between each time periods, that is, between 2% and 29% between the first two time periods, and between the last time periods which is 2% and 38% (smaller changes in cold cities). These results are different from previous studies based on the IPCC SRES scenarios, for example, based on AR4, such as [65][66], the relative decrease 30% (A2 scenario[67]) in heating demand during the 30-year period.

5.2.2 Cooling demand

The average value and standard deviation of the cooling demand in all cities will increase over time. The regression analysis also confirms this trend; for all of the cities, the regression coefficient (R^2) is above 0.8; this number is higher than heating demand, indicating a better regression fitting and the semi−steady trend of an increase.

For the cities in Zone 1 & 2, the cooling demand increase between NT and MT (3.7%-10.5%), between MT and LT is 3.6%-8%. For example, between NT and MT in Athens was 3.7%, and between MT and LT was 4%. For Nicosia, the value between NT and MT is 6.2%, and the value between MT and LT is 6.9%.

For most cities in Zones 3 and 4, the average cooling demand between NT and MT has increased by 3%–28.2%, and between MT and LT has increased by 2.9%–18.2%. The relative increase in cooling demand is significantly higher than the relative decrease in heating demand. For example, the average cooling demand in Paris increased by 28% during the MT period and by more than 18.2% during the LT period (compared to the previous period). These values exceed the relative reduction in heating, which is a reduction of 4.6% and 3.6%, respectively, during similar periods.

For cities mainly dominated by heating in winter (zone 4&5), due to climate change, the cooling demand of these cities has significantly changed, and the average cooling demand has the most considerable change. For example, in the three Swedish cities (Gothenburg, Kiruna, and Stockholm), the average cooling demand growth between NT and MT is between 25% and 40%, and between MT and LT is 23% and 36%. The same trend can be found in three Danish cities (Copenhagen, Aarhus, and Sundeborg); the cooling demand growth between NT and MT is 35%–44%, and between MT and LT is 28% –45%. The standard deviation of the cooling demand in the last period has increased significantly, indicating that the frequency and intensity of heatwaves will increase significantly by the end of this century.

5.2.3 Indoor thermal comfort

The percentage of comfortable hours decreases as the number of RCP increases by time. For cities in zone 1&2, The increased discomfort hours caused by overheating indicate that the current cooling capacity cannot cope with climate change. For example, in Barcelona and Madrid, overheating hours during LT increased, reaching 35% in Madrid and 27% in Barcelona. This indicates that there will be greater demand for cooling buildings in the future, leading to greater loads on the electricity grid.

The percentage of comfortable hours in cities located in Zone 3 exceeds 86%, but the impact of climate change is still visible. For example, in Germany, overheating hours increase with time; in Munich and Hamburg, the discomfort time due to overheating is 0.2%–0.4% at LT. The comfort hours in zone 4 which is above 87%, which zone 5 is above 98%. Although climate change will affect the energy demand of buildings in Zones 4 and 5, the energy performance of these buildings is less affected by climate change than in other regions.

5.3 Future energy projection

The overall PV and wind energy potential in the future will not change significantly due to climate change. An overall decrease in photovoltaic potential is found in all climate scenarios, but the relative change is minimal, about -0.01% to -2.17% RCP8.5 in Gothenburg, Antwerp, Munich and Athens increased slightly by 0.6%-2.3% for wind turbine potential. Seasonal projection indicate that the wind potential is higher during the winter season in Narvik, which has the highest potential. In contrast, the photovoltaic potential is higher in summer, and Athens has the highest photovoltaic potential. Another result found that the temporal complementarity between solar and wind resources exists mainly on a seasonal scale for most cities. For example, Narvik has the strongest complementary potential in winter, the wind power output in winter is about ten times that of photovoltaic power. Spearman correlation shows that temperature is positively correlated with PV output and negatively correlated with wind output. According to the assessment of seasonal changes, the uncertainty associated with different climate scenarios has the most significant impact on renewable energy production. The impact of climate change is evident in both solar and wind energy potential. For solar energy, due to the choice of climate model (climate uncertainty), the difference is as high as 23%, and due to the time period (climate change), the difference is minimum and can be ignored. The difference in wind energy is much higher due to climate uncertainty, the difference is as high as 45%; 25% is due to climate change. Spearman's rank correlation explores the uncertainties associated with photovoltaic and wind energy projections. The results further confirm the uncertainty related to the projection of PV and Wind energy, which In some GCMs, the outdoor temperature has a strong correlation with PV output (e.g., strong positive correlation between 0.4 to 0.5 in Narvik) and wind turbine output generation (e.g., strong negative correlation for IPSL in Antwerp, Munich and Salzburg in all periods and RCPs s, with a correlation coefficient of -0.27 to -0.33)

5.4 Research contribution

This work conducted an extensive assessment of the impact of climate change on the energy performance and thermal comfort of residential buildings in 38 European cities belonging to five different climate zones in Europe. Building information extracted from TABULA and three other European projects, namely STRATEGO, ENTRANZE and BPIE, were used to conduct the numerical modeling of the representative residential buildings in IDA ICE. This research used a comprehensive set of future climate data sets, considering three RCPs (RCP 2.6, RCP 4.5 and RCP 8.5) and five GCMs, resulting in 13 different future climate scenarios over three 30 years periods (2010-2099). Using the climate data from RCA4 RCM enabled us to have an ensemble of future weather data with fine temporal and spatial resolutions, reflecting a wide range of long-term and short-term variations in climate, including the extreme weather events with hourly resolution.

Results provide a comprehensive overview of the future energy demand and indoor thermal comfort in the European building stocks. This work further demonstrates the importance of considering long-term and short-term climate changes (including extreme events) when performing the impact assessment studies. This result further proved that short-term extreme climate events had caused significant changes in energy demand and peak loads in different climate zones in Europe, which is essential when assessing the energy and climate resilience of buildings and urban areas. The availability of climate data with fine spatial and temporal resolutions is beneficial in assessing the reasonable energy needs of buildings; however, it is important to consider climate uncertainty, multiple scenarios, and extreme weather events. This comprehensive impact assessment of climate change lays the solid foundation for the sustainable energy transition of cities.

5.5 Future research

The future work needs to dive into the possible changes and uncertainties in future energy performance using a wider range of architectural prototypes, finer spatial resolution of building stock, and socio-economic parameters. For energy-saving techniques, one of the major parts of the reduction in energy consumption can be achieved through a deep retrofitting of existing building stocks. Further research can focus on the long-term retrofitting strategies to support the European Green Deal, which is the renovation of the building stock into a highly energy-efficient and decarbonised building stock by 2050. In this regard, investigating the hygrothermal performance of buildings is also important, especially in countries like Sweden that the building performance can downgrade due to moisture related issues. The building life cycle assessment (LCA) can also be introduced into future research, which this method has been increasingly applied to explore the life cycle environmental impacts of buildings. Such an assessment can include the whole life cycle of buildings, e.g., production, use, end of life, and analysis of different building materials and building types. Future work also can consider urban climate models, wider architectural prototypes, finer spatial resolution of building stock, and socio-economic parameters. Performing this type of analysis (and its results and data sets) will enable decision-makers, engineers, and designers to consider future climate change in their work from the early design stages.

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