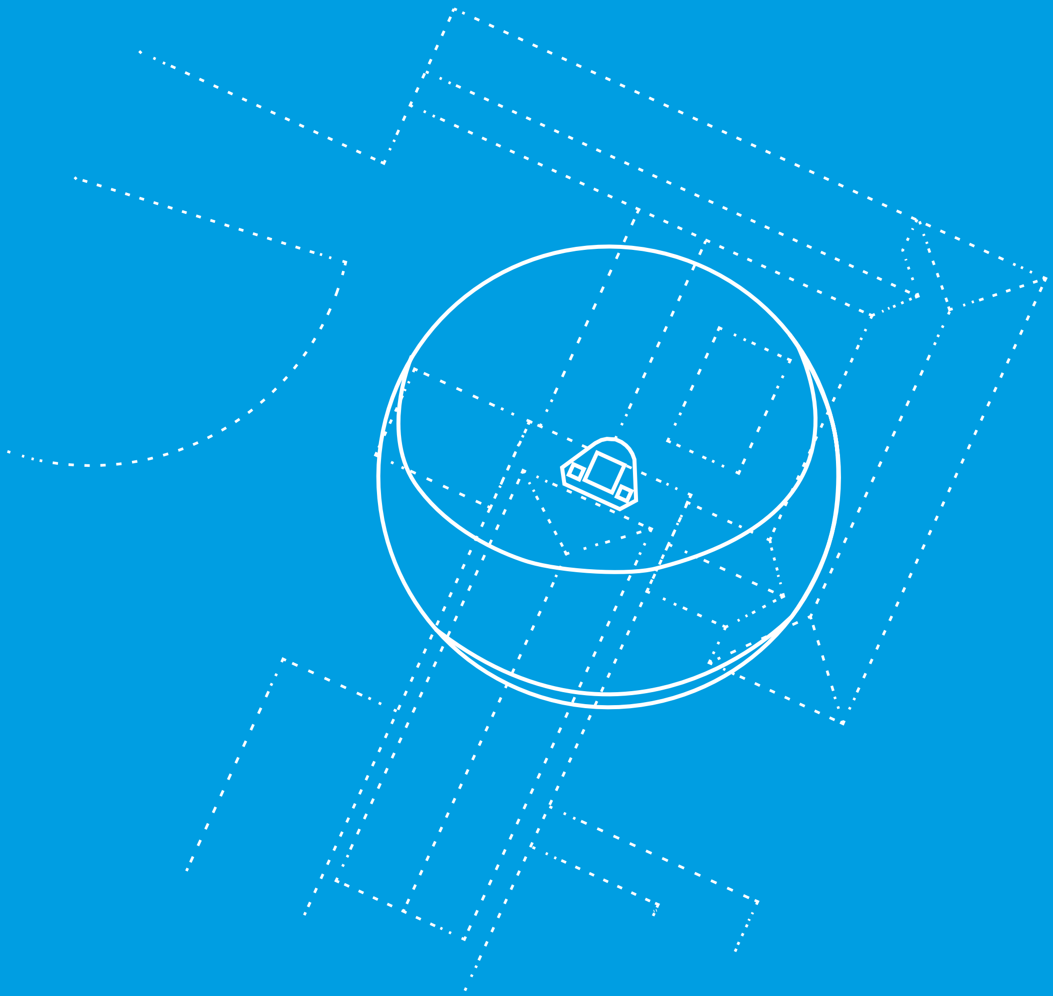
Energy and CO_2 saving potential of a weather and emission predictive building control

Christian Hepf



Technische Universität München
TUM School of Engineering and Design

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Für meine Eltern Sibylle und Michael

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Abstract

Due to their significant energy and resource consumption, buildings are at the forefront of the current conversation about mitigating climate change. Accounting for 28% of global carbon emissions, the heating energy consumption of buildings plays a crucial role in this debate. The shift towards renewable energies and the trend of the electrification of the heating sector using heat pump systems are subjects of controversial discussions in German society. However, it is undeniable that the growing digitization and the transition towards a carbon-neutral Europe by 2050 pose significant challenges but also harbor substantial potential to drastically the reduce energy consumption and carbon emissions of the built environment through intelligent building control strategies.

This study investigates the impact of a simple control based on dynamic weather and carbon emission data of the power grid on building performance. The ensuing fundamental hypothesis is explored: A simple, predictive building control based on dynamic carbon emission and weather data leads to substantial emission and energy savings without compromising thermal comfort. This hypothesis supports the notion that savings can be achieved through a simple control, forming the basis for successful implementation in the built environment. The research is divided into four main parts. The thermodynamic simulation model in TRNSYS is initially validated using measured weather and temperature data from a test facility, called Solarstation. Subsequently, the influences of weather- and emission predictive control (WEPC) are individually tested with the validated simulation model. Finally, the two concepts are combined and evaluated at five different climate locations through a combination of the software tools TRNSYS, EnergyPlus, and Python for the years 2020 and 2050.

The parametric simulation results demonstrate the successful and effective implementation of the WEPC in all five climate zones. It becomes evident that heating and cooling energy savings of up to 50 kWh/(m^2a) and a reduction of 5 to 25% in carbon emissions can be achieved for various building types. The results affirm the initial hypothesis of keeping building energy concepts simple and reveal that energy and emissions can be saved through simple, predictive control based on weather and emission data. Additionally, it is evident that thermal mass in buildings and decentralized storage systems are helpful for realizing the energy transformation of Europe towards a climate-neutral built environment in 2050.

Kurzfassung

Aufgrund ihres erheblichen Energie- und Ressourcenverbrauches stehen Gebäude mitten im Diskurs notwendiger Maßnahmen zur Eindämmung des Klimawandels. Mit einem Anteil von 28% an den weltweiten CO_2-Emissionen spielt der energetische Gebäudebetrieb alleine für das Heizen eine zentrale Rolle in dieser Debatte. Der Wandel hin zu erneuerbaren Energiequellen und der Trend der Elektrifizierung der Wärmeversorgung von Gebäuden durch Wärmepumpen werden in der deutschen Gesellschaft kontrovers diskutiert. Ungeachtet dessen steht dennoch außer Frage: Die anhaltende Digitalisierung und das übergeordnete Ziel eines CO_2-neutralen Europa bis 2050 bringen einerseits enorme Herausforderungen mit sich. Andererseits birgt jene Transformation große Potenziale, um durch intelligente Regelungsstrategien Heiz- und Kühlenergie und folglich CO_2-Emissionen drastisch einzusparen.

Diese Dissertation widmet sich der Aufgabe, welchen Einfluss eine simple, auf Wetter und Emissionsdaten basierende Regelung auf die energetische Performance eines Gebäudes hat. Dabei wird die grundlegende Hypothese aufgestellt: Eine einfache, prädiktiven Regelung von Gebäudetechnik auf Basis von dynamischen Wetter- und CO_2-Emissionsdaten der Stromversorgung führt zu Emissions- und Energieeinsparungen, ohne den thermischen Komfort im Raum zu beeinträchtigen. Dies unterstützt den Ansatz, dass bereits durch eine einfache Optimierung der Regelung hinreichende Einsparungen erzeugt werden können, was Grundlage für eine erfolgreiche Implementierung in die gebaute Umwelt darstellt. Die vorliegende Arbeit gliedert sich in vier Hauptteile. Zunächst wird ein thermodynamisches Simulationsmodell in TRNSYS mit Wetter- und Temperaturdaten eines Messraums, der Solarstation, validiert. Anschließend werden die Einflüsse einer wetter- und emissionsprädiktiven Regelung separat mit dem validierten Modell getestet. Abschließend werden die beiden Konzepte zusammengeführt und durch eine Kombination der Softwareprogramme TRNSYS, EnergyPlus und Python für die Jahre 2020 und 2050 an fünf verschiedenen Klimastandorten evaluiert.

Die Ergebnisse der parametrischen Studie zeigen eine erfolgreiche und effektive Implementierung der Regelung in allen fünf Klimazonen. Es wird deutlich, dass für unterschiedliche Gebäudetypen Heiz- und Kühlenergieeinsparungen von bis zu 50 kWh/(m^2a) sowie eine Emissionsreduktion von 5 bis 25% möglich sind. Die ursprüngliche Hypothese, eine Optimierung einfach zu halten, kann durch die Ergebnisse bestätigt werden. Sie zeigen somit, dass durch eine einfache, prädikative Regelung substanziell Energie und Emissionen eingespart werden. Zudem wird deutlich, dass die thermische Masse eines Gebäudes sowie dezentrale Speichersysteme unerlässlich sind, um die energetische Transformation hin zu einer klimaneutralen, gebauten Umwelt in Europa bis 2050 umzusetzen.

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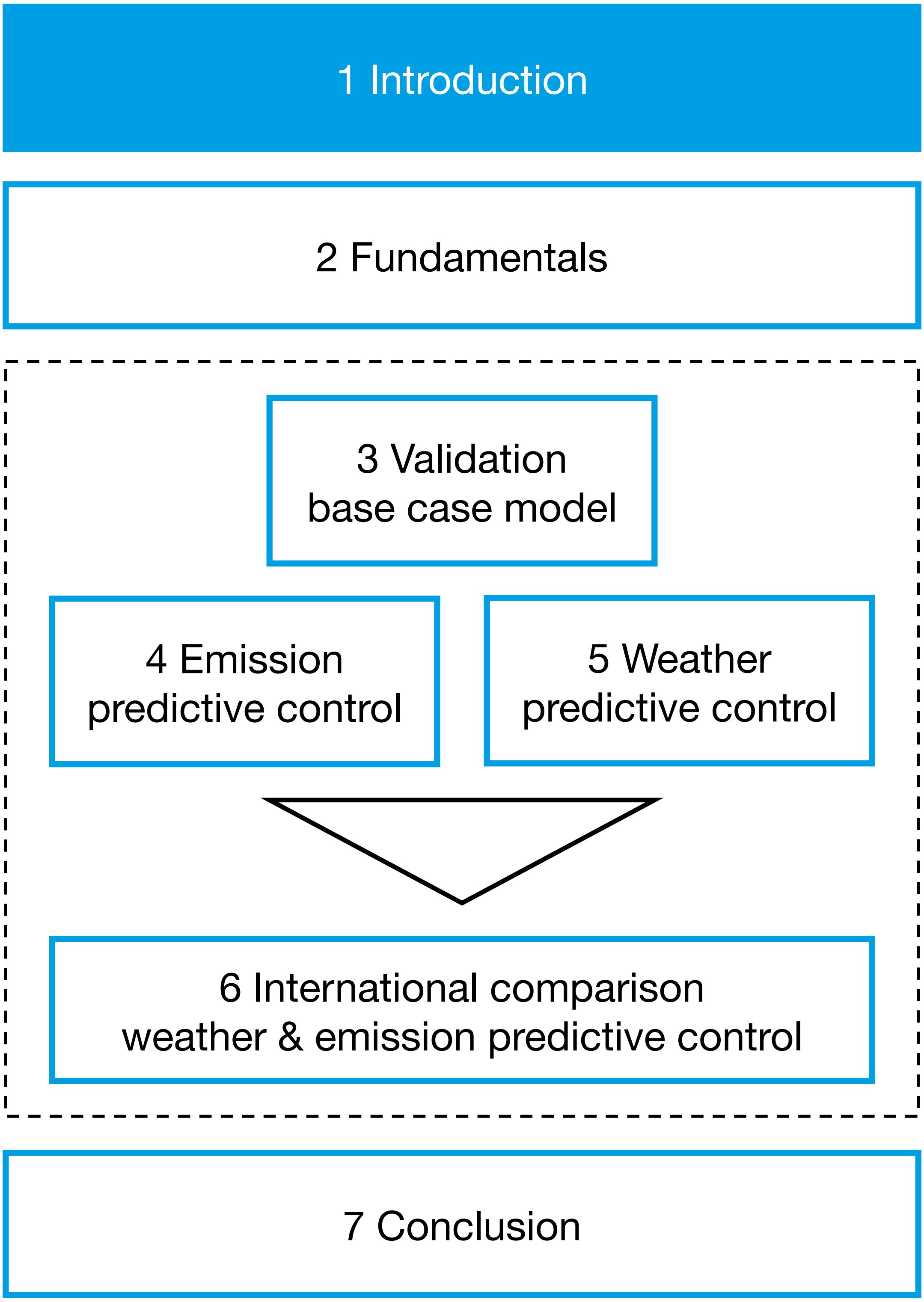
List of Abbreviations

Af	Tropical rainforest
ANN	Artificial neural networks
ASHRAE	American society heating, refrigerating and air-conditioning engineers
CAD	Computer aided design
CFD	Computational fluid dynamics
Cfb	Temperate climate no dry season warm summer
Csa	Temperate climate dry, hot summer
Cwa	Temperate climate dry winter hot summer
CO_2	Carbon dioxide
COP	Coefficient of performance
Dfc	Continental climate, no dry season, cold summer
DIN	Deutsches Institut für Normung
DWD	Deutscher Wetter Dienst—German Weather Forecast Service
EF	Emission factor
Eps	Energy price simple
EPp	Energy price predictive
EFs	Emission factor simple
EFp	Emission factor predictive
GeG	Gebäudeenergiegesetz—German Building Energy Code
IPCC	Intergovernmental Penal Climate Change
MPC	Model predictive control
OTH	Over temperature hour
PID	Proportional integral derivative control
PMV	Predicted mean vote
PPD	Percentage of people dissatisfied
PV	Photovoltaics
RPC	Representative Concentration Pathways
TABS	Thermally activated building structures
TMY	Typical meteorological year
TRNSYS	Transient systems simulation
UTH	Under temperature hour
VOC	Volatile organic compounds
WEPC	Weather-and-emission-predictive-control
WPC	Weather-predictive-control

List of Symbols

A	Net Area of room	(-)
A_{mod}	Surface area of solar panel	(m^2)
AC	Air change rate	(1/h)
C	Total electricity costs	(EUR)
C_W	Heat capacity	(-)
e	Euler’s number	(-)
E_{dyn}	Total CO_2 emission dynamic	(kg CO_2)
E_{stat}	Total CO_2 emission static	(kg CO_2)
EF	Average emission factor over year	(kg CO_2)
ef(t)	Hourly emission factor	(CO_2/kWh)
f_c-value	Reduction factor of a sun protection device	(-)
G_{mod}	Irradiation on solar panel	(W/m^2)
$\dot{m}$	Specific mass flow	(kg/s)
nb(t)	Percentage of net load per hour	(-)
η_{MM}	Level of efficiency of mismatching	(-)
η_s	Level of efficiency of spectral	(-)
η_{WR}	Level of efficiency of inverter	(-)
OTh	Overtemperaturehour	(-)
P_{CL}	Cooling power	(W)
P_{HT}	Heating power	(W)
Pnet (t)	Power provided by the net	(kWh)
Q_{cool}	Cooling demand (annual)	(°C)
Q_{heat}	Heating demand (annual)	(°C)
$Q_{sol,future}$	Solar radiation of a future time step	(W/CO_2)
rad_{sur}	Radiation on surface	(W/m^2)
sp(t)	Domestic electricity price	(EUR /kWh)
t	Time steps ahead	(h)
Tair	Air temperature of a room	(°C)
$Tamb_{m24}$	Average ambient dry bulb air temperature over last 24 h	(°C)
$Tamb_{future}$	Ambient dry bulb air temperature at a future time step	(°C)
Top	Operative temperature of a room	(°C)
T_{out}	Return temperature	(°C)
$T_{supply,}$	Supply temperature	(°C)
$\delta T_{Qsol,future}$	Temperature difference caused by incoming solar radiation	(°C)
UTh	Undertemperaturehour	(h)
X_t	Value of parameter t time steps ahead	(-)


1 Introduction
2 Fundamentals
3 Validation base case model
4 Emission predictive control
5 Weather predictive control
6 International comparison weather & emission predictive control
7 Conclusion

1 Introduction

Summary

This thesis '*Energy and CO_2 saving potential of a weather and emission predictive building control*' aims to shed light on possibilities and constraints for a smart but simple control strategy for building technology in order to support the EU Carbon Roadmap to reach climate neutrality by 2050. Therefore, holistic studies are conducted resulting in multiple research publications that form this consecutive doctoral thesis.

This first chapter opens up the research topic of the dissertation, starting by illustrating the background of the approach. Thereafter, the problem statement which consists of four central research potentials, leads the way for the ensuing overall aim and research hypothesis with the linked research questions of this doctoral thesis. Finally, the research method, as well as the research strategy, terminate this chapter, aiming to close the research gaps and to promote further research supporting the overall goal of creating a climate-responsive built environment and minimizing global warming and climate change.

1.1 Background

Globalization, international migration, pandemics, and the ongoing digitalization with its second wave of artificial intelligence are all major topics that dominate the media and news worldwide and challenge humankind worldwide. Moreover, the biggest crisis of it all, climate change, is happening right now and affects life on Earth. The main reason for climate change is the greenhouse gas emissions caused by humankind. If emissions remain at current levels and the global temperature rises more than 1.5°C, irreversible tipping points in various ecosystems around the world are reached, leading to short-, mid-, and long-term environmental consequences that threaten human life on Earth. [1-1]

Global citizens around the world try to draw attention to this issue. In particular, younger generations fear for their future and perform actions like sticking their hands to famous paintings and blocking traffic in metropolitan areas or organizing peaceful, international demonstrations to keep this threat in the public's mind. These measures by organizations such as Fridays for Future or the Last Generation try to show the urgency and severity of the current situation.

With the Paris Climate Agreement in December 2015, 195 parties signed the agreement to limit global warming to 1.5 °C pre-industrial levels [1-2]. These aims echoed through numerous national and international institutions and led the way for the EU Green Deal of 2019, scrutinizing the roadmap for the EU to become climate-neutral by 2050 [1-3]. To fulfill the contractual obligations, the Federal Republic of Germany agreed, according to their Climate Action Plan, to the reduction of Carbon dioxide emissions in six different sectors [1-4]. The Climate Report 2022 of the German Federal Ministry for the Environment states that the contribution of the building sector is essential to reach the set energy and climate goals, as it is responsible for a share of about 13.6% of the total direct greenhouse gas emissions in Germany [1-5]. Taking the indirect emissions from the energy sector and the grey emissions from the industrial sector into account, the share increases up to 26%. At the international level, the numbers are even higher. According to the United Nations Environment Programme, 38% of the overall carbon emissions are connected to the building sector [1-6].

To attain the goal of climate neutrality the German building sector mainly focuses on climate-friendly housing. To accomplish this, buildings must undergo renovations targeting the energy performance. These are subsidized by the Federal Government of Germany and linked to the German Building Energy Law (GEG), updated in 2021 [1-7]. The GEG outlines requirements for the building and its technology systems to drive an increase in energy efficiency and a transition to renewable energies. On the one hand, this controversially discussed law addresses the quality of the thermal envelope of buildings. On the other hand, the energy supply of the buildings is addressed by exchanges regarding the energy source. Therefore, the main building technology system of the future will be electrical heat pumps, which will act as the connection between renewable energies and the electrification of the building energy sector.

With electricity starting in the 19th century in Europe, the electrical energy sector has changed its characteristics completely. At the beginning of the electrical energy revolution, energy was generated in a small supply island, where supply and demand were coordinated on top of each other. This has only been possible as fossil fuels such as gas, oil, and coal were the dominant energy sources. In the 20th century, the energy grid and the types of energy sources, like nuclear, hydro, solar, and wind energy, were largely extended. Since then the complexity of the system and the interconnectivity between supply and demand is rising every year. In combination with the burgeoning trend of environmental responsibility, the fluctuation in the grid is becoming the main challenge to performing the transition to a renewable energy-dominant electrical grid. Balancing the energy grid is becoming increasingly difficult, and several actions must be taken [1-8]: A widespread extension of the electrical energy grid; the addition of peak load power plants; decentralized energy generation and personal energy usage; the integration of additional storage units store surplus electrical energy; potential demand side management; alternative, local storage units like buildings or electric cars.

With the ongoing developments of globalization, electrification, and digitalization, the previously outlined interconnectivity demands strong intelligent and smart control strategies at all levels. CO_2 is the main metric to evaluate these. With the global trend of optimizing the energy performance of buildings and, in parallel, transforming the electrical energy grid, architects and engineers take a major role in performing this sustainable transition to a climate-friendly, built world. Consequently, the initial intention of buildings to create a shelter protecting humankind from the local weather conditions is often put into the background, resulting in a decrease in thermal comfort. However, this is not only a burden, but it goes hand in hand with the possibility of new, smart solutions. Therefore, intelligent control strategies for building technology can play a major role in decreasing buildings' operational carbon and contribute to the overall goal of climate neutrality. This thesis outlines a concept that combines the mentioned criteria, using the CO_2 emission and weather data and their forecasts to decrease the energy demand and optimize the CO_2 performance of a building while providing thermal comfort for the users.

1.2 Problem Statement

The overall solar radiation cumulates to 7,500 times the global energy consumption of the world's population and generates further renewable energy sources such as wind, biomass, and hydropower [1-9]. This entails the fact that the transition to a climate-friendly building energy sector is not a matter of if, but rather a matter of how. However, this also shows that a robust building energy performance is mainly influenced by the adaptation of the building to its local weather conditions. Nevertheless, the energy performance of a building goes hand in hand with the thermal (and visual, olfactory, and acoustical) comfort in the room. In addition to the climate location, the building construction influences the functionality of the building. This is called thermal mass/inertia, which turns out to be one of the key parameters for a climate-friendly building. Given the emerging trend of digitalization and the increasing number of electrical devices providing thermal energy, in-time local weather data comes into play and holds great potential for climate-friendly energy performance optimization. In terms of the frequently discussed energy efficiency of buildings, the phenomenon of the performance gap is a key indicator. It describes the gap between the intended and actual building performance. All these factors present challenges to the modern building energy sector, but they also hold significant potential for energy and emission savings. The following four subsections provide a deeper understanding of the energy and CO_2-saving potentials of the key parameters: Weather Data, Thermal Comfort, Thermal Inertia, and Performance Gap.

1.2.1 Potential - Weather Data

As a result of ongoing climate change, extreme weather conditions are becoming more frequent worldwide. This demands the adaptation of existing and new buildings as well as of their technology to the upcoming challenges to ensure the appropriate accommodation of human beings. For the existing building stock in particular, the adaptation of the building technology can improve the energy performance and, therefore, increase comfort conditions. In that case, the use of local weather data is the key parameter to realize a successful climate adaptation and to create a climate-friendly energy system. The real-time availability of local weather data and its forecasts necessitates smart control strategies. Climate adaptation and the tracking of weather dates back to the early phases of humankind and since then are key elements for daily life. With the global network of globalization and migration worldwide, weather data is densely available. With over 10,000 manned and automatic weather stations in combination with more than 1,000 upper air stations, plus the weather data from over 7,000 ships, 3,000 aircraft, and 230 satellites the weather data grid is widely spread as illustrated in the following Figure 1-1 [1-10]. These weather stations provide historical weather data and, in some cases, accurate weather predictions for specific locations. Based on the dense availability of weather data, a worldwide weather prediction is very well possible and opens up huge energy-saving and thermal comfort optimization potentials that are addressed in this study.

Figure 1-1: Overview of weather stations worldwide (own representation based [1-10])

1.2.2 Potential - Thermal Comfort

People spend 80-90% of their time indoors. [1-11] With rising energy prices, the question of the appropriate room temperature is part of a broader technical, political, and social debate. On an international level, different parameters and concepts exist to evaluate thermal comfort in a room. The predicted mean vote (PMV), the Percentage of People Dissatisfied (PPD), and simplified overtemperaturehours in accordance with the running mean outdoor air temperature are used for the evaluation. This strengthens the fact that thermal comfort is a very individual feeling and depends on many more parameters. Although the focus of this thesis is not on re-evaluating thermal comfort, it acknowledges that thermal comfort is also influenced by factors such as daily well-being, individual stress levels, age, gender, and other difficult-to-measure variables. This results in the common strategy to evaluate comfort in a range as it is not only one single temperature or number. Figure 1-2 illustrates the comfort ranges for the indoor operative temperatures and for the concept of the PPD and PMV. It is also visible that within this comfort range concept, a certain flexibility exists. This flexibility in thermal comfort has the potential for energy savings by using the built environment as thermal storage and bridging the phases of discomfort. Furthermore, the category ranges are currently debated in their validity. Recent literature argues that a wider comfort range and more personal flexibility to allow individual adaptation is perceived as more comfortable and could be traced back to more indoor heat [1-12–16]. This again would strengthen the concept and extend the energy-saving potential within the range of thermal comfort.

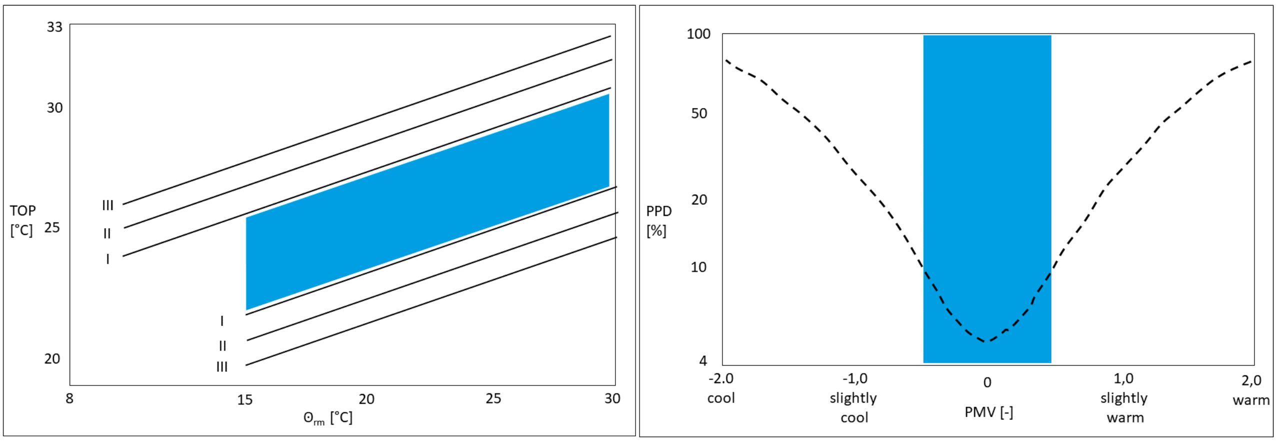


Figure 1-2: Energy saving potential in the concept of thermal comfort outlined for the operative temperature (left) and the thermal comfort parameter PMV (right) (own representation based on DIN 15251 [1-17] left and DIN EN ISO 7730 [1-18])

1.2.3 Potential - Thermal Mass/Thermal Inertia

In the burgeoning building turnaround, many Western countries set up funding programs to improve the thermal building envelope. This leads to heating energy savings. Another approach to decrease the heating and cooling energy of a building is to increase the thermal mass of a building. Thermal mass describes the ability of materials to store/reject heat based on temperature changes in a room and has a significant impact on the energy consumption of a building [1-19]. Building constructions are categorized into three classes within the norms: light-, middle-, and heavyweight, less than 50 Wh/(Km^2), less than 130 Wh/(Km^2), and more than 130 Wh/(Km^2). The term thermal inertia refers to the rate at which a mass absorbs or loses its heat. Especially in fluctuating temperature conditions in a room, thermal inertia can help to balance the comfort conditions. Consequently, the building constructions support heating and cooling the room, as illustrated in the following Figure 1-3.

With the increase in electrical heat pumps in combination with active layers systems for heating and cooling, the thermal mass activation is rising. Thereby multiple aspects like air, geothermal sources or water can serve as an energy source. A geothermal connection to a heat pump holds great potential for a very efficient building energy system [1-20]. As the inert thermal mass changes its conditions slowly, this delay can be used as an additional storage system. Hence one approach is to charge the thermal mass in surplus phases with the heat of renewable energies while unloading and vice versa. Intelligent control strategies can address these potentials and decrease the energy and CO_2 performance of a building. Previous studies have shown that this can transform the building into one piece of a thermal storage grid. [1-8, 1-21, 1-22]

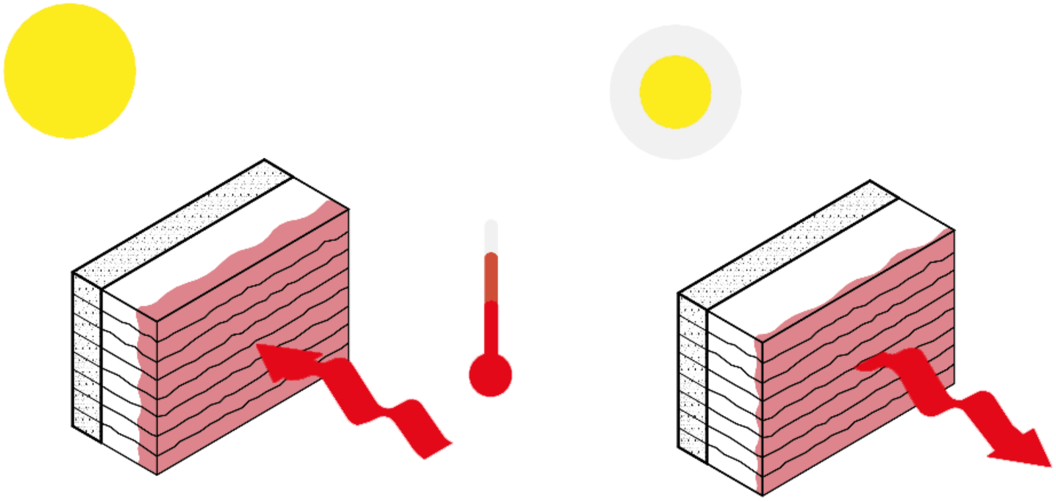


Figure 1-3: Effect of heating and cooling through thermal mass (own representation)

1.2.4 Potential – Performance Gap

The main challenge for the building industry in the next decades is the transition to decarbonized buildings. The rising complexity of standards for comfort as well as energy performance often lead to a lack of addressing energy efficiency while simultaneously not fulfilling user satisfaction. This discrepancy is referred to as the Performance Gap. Numerically, the Performance Gap is the ratio between the actual and intended energy performance of a building. More often research studies show that the measured energy performance of a building is multiple times higher than the calculated energy demand [1-23, 1-24]. A large British study revealed that within almost 60,000 educational buildings, including 85% of governmental schools, 95% did not reach the initially calculated energy demand [1-25].

Technically, the Performance Gap can be caused by four main triggers. The first is a change in the climate called the “ambient gap”, where a different climate has been considered for the initial dimensioning of the building technology. The second trigger is the 'norm gap,' which describes variations in calculations due to the simplified assumptions used in standard guidelines. A third reason for this deviation is the unexpected behavior of the users (e.g., occupancy times, comfort levels) and their interaction with the building technology, referred to as the 'user gap. Moreover, there are differences and errors in the building technology systems called the “technical gap”, which can also lead to discomfort and an increase in energy demand. [1-26, 1-27]

The Performance Gap questions the “Efficiency first” strategy of modern politics and asks for a more holistic and flexible solution. As all previous sections outline, flexibility and the ability to adapt to fast-changing circumstances by using in-time data set the mark for a smart approach. The availability of data is not a problem anymore. An adequate and simple way to use data is key to a successful energy concept. If it is too data-intensive, it does not apply to the users or even the building’s operational services, potentially leading to discomfort and adding to the Performance Gap. Finally, the focus has to be on the user and the integration into a concept. All these aspects are supposed to lead to a simple and robust energy concept for buildings. This thesis contributes to that approach by outlining a simple and flexible control optimization strategy for inert building systems, as an addition or even alternative to the efficiency first strategy.

1.3 Aim and Scientific Hypotheses

This research aims to explore the possibilities and constraints of a simple and robust weather and emission predictive control strategy for building technology to optimize the energy and CO_2 performance of an office building without compromising users' thermal comfort. The main outcome of the dissertation is a parametric study analyzing the potential of the selected control strategy in various climates and building scenarios while showcasing its limits and bottlenecks. These outcomes and findings intend to open up the debate about using buildings and their technologies as part of a design thinking process in the sense of a connected grid. They also aim to provide valuable insights for further research and product design in the building technology industry.

This research project aims to evaluate the following underlying hypothesis considered as the main driver behind exploiting the potentials and limits of this dissertation:

A simple weather-and CO_2-predictive-control improves the energy and emission performance of an office building without harming thermal comfort conditions.

Several sub-hypotheses and research questions are evaluated to elucidate the main hypothesis. This concept guides through the present dissertation and the individual chapters address the ensuing hypotheses and the connected research questions.

Chapter 3 – Validation

- Is it possible to validate a thermal model through the local weather and thermal data of the test facility according to the ASHRAE Guideline 14:2002, taking the parametric simulation tool TRNLizard into account?
- Which key parameters can be identified to fulfill the validation criteria according to the ASHRAE Guideline 14:2002?

Chapter 4 – CO_2 -predictive control

Using dynamic, hourly emission factors to calculate the CO_2 emissions for the building operation generates emission savings, which are not represented in the common calculation concept based on static, imprecise data.

- How does the consideration of a dynamic instead of a static emission factor impact the CO_2 balance of a building operation?
- What potential does an emission-optimized load control have?
- How does an increased storage capacity influence performance?
- How big is the impact of the dynamic emission factor calculation on the overall transformation of the German electricity grid?

Chapter 5 – Weather-predictive control

The energy demand and thermal comfort of a Munich-based office building can be optimized compared to a state-of-the-art control strategy by the simple approach of a weather predictive control of inert buildings.

- Is it possible to optimize the thermal comfort of a room with a WPC?
- Is it possible to generate energy savings with a WPC?

Chapter 6 – International comparison of weather and predictive control

The simple concept of weather and emission predictive control improves the overall energy performance and emission balance of a building without harming thermal comfort.

- What impact do insulation and thermal mass have on the performance of the WEPC?
- How does a photovoltaic system impact the emission balance using the WEPC with thermal and electrical storage?
- Does the WEPC improve a room's energy performance and CO_2 balance without compromising thermal comfort?
- How does the WEPC perform in 2050, considering future weather and emission data that account for an increased share of renewable energies?

1.4 Research Method and Strategy

Beyond the previously described research background and potential gap, as well as the aim, hypothesis, and linked research questions, this chapter describes the applied methodology and the research strategy of this dissertation. Digital thermodynamic simulations aim to represent the actual physical behavior of a system. This thesis uses thermodynamic models to analyze the effects of the weather and emission predictive control. To relate the simulation results to the built environment in the first step, the thermodynamic simulation model is validated according to ASHRAE Guideline 14:2002 with real building measured data [1-28]. Located on the roof of the main building of the TUM the Solarstation, a 1:1 test chamber, is used. The generated measurement data is compared with the simulation data to iteratively fulfill the defined thresholds of the validation. This forms the basis for the thermodynamic simulation model. The thermodynamic simulation is mainly performed using the TRNSYS 18 simulation engine [1-29], while it is fed by the parametric simulation tool TRNLizard. This is executed in the graphical programming campus of Grasshopper, a part of the multifunctional Software Rhinoceros 7. Grasshopper and its Add-In Honeybee, a tool for radiation analyses, use the weather and CO2 data to carry out further sub-simulations to generate the data predictive algorithm. With this simulation setup, the weather and emission predictive control can now be performed. The ensuing Figure 1-4 illustrates the methodology graphically.

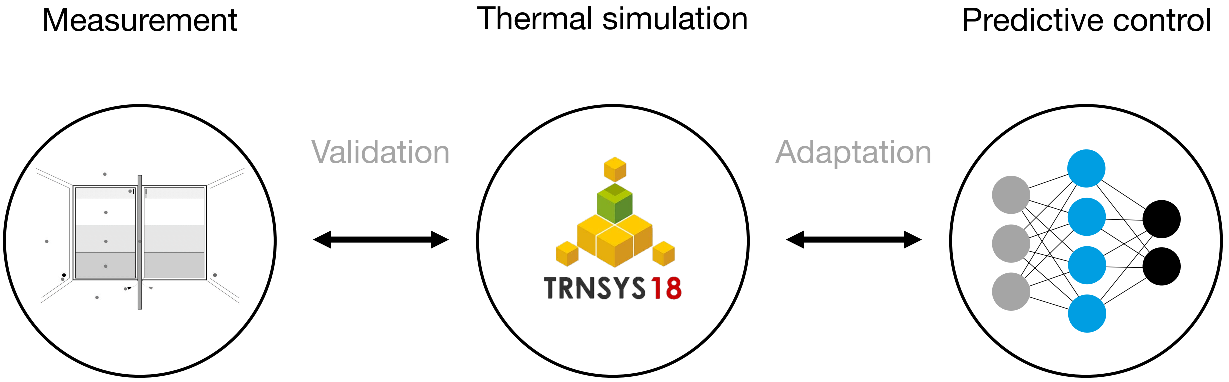


Figure 1-4: Graphical illustration of the methodology (own representation using the TRNSYS icon [1-29]

Corresponding to the research methodology above, the structure of this dissertation presents itself modularly in the following chapters. In general, this chapter is divided into three parts, starting with the present introduction and the fundamentals. The second part involves chapters three to six. Here every chapter outlines one peer-reviewed research paper. Overall, this represents the analysis part of the dissertation with its structure, background, analytical section, and result as well as discussion, and outlook. The third and last part comprises the overall conclusion. Here all previous chapters are summed up, and an overall evaluation as well as the answer to the underlying hypothesis are given. The following Figure 1-5 outlines the structure of this dissertation and at the same time functions as a guideline for this dissertation.

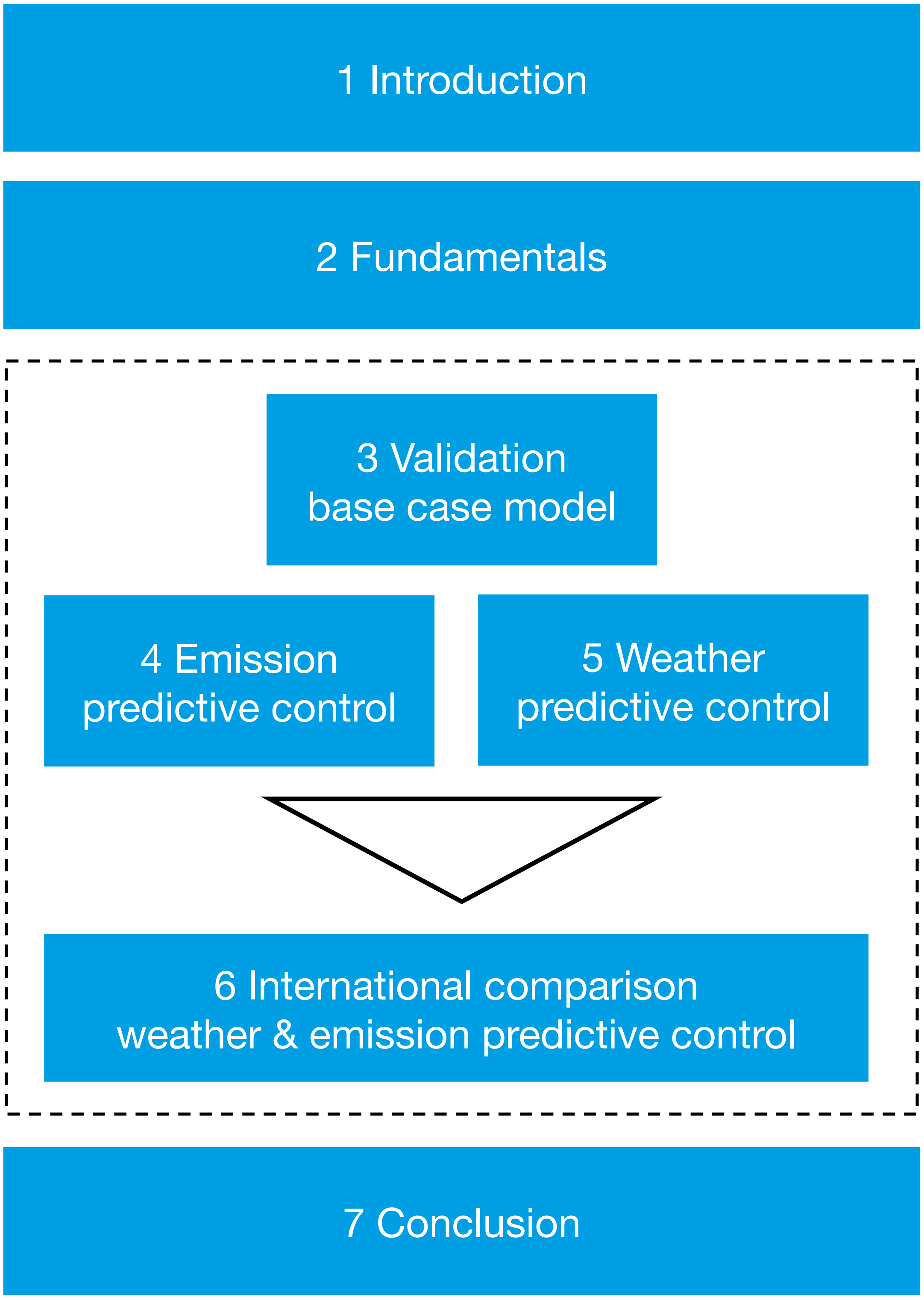


Figure 1-5: Graphical illustration of the structure of this dissertation (own representation)

The following paragraphs outline the milestones of the individual chapters:

Chapter 2 adds to the introduction and lays out the fundamentals of this study. Therefore, the state of the art, the state of literature, and the state of legislation outline the framework of the topic. Furthermore, the software structure and the description of the measurement room Solarstation, including the overall location, the geometry, and the measurement concept for the validation are pointed out. Consequently, this chapter prepares the ground for the following analytical part.

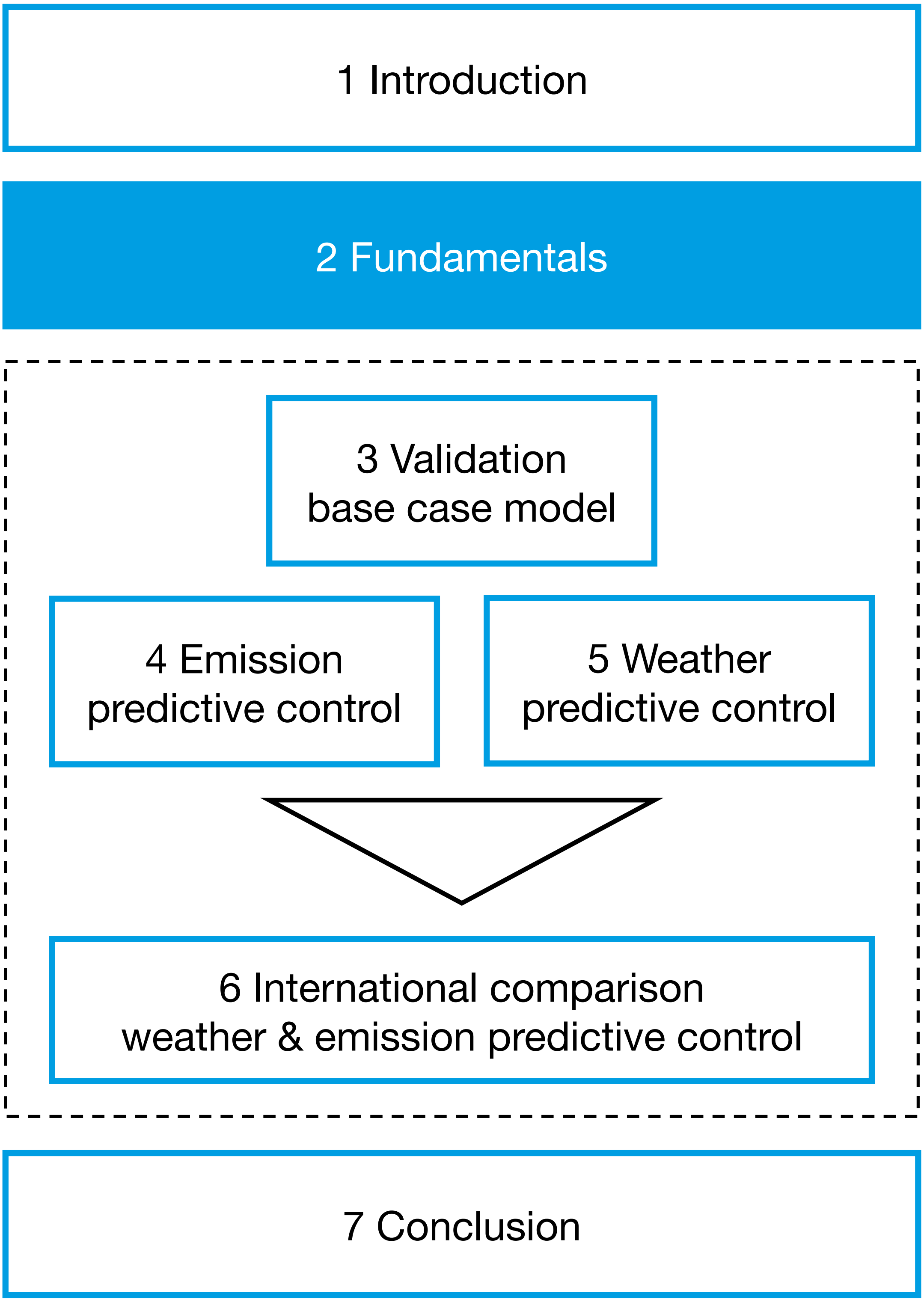
Chapter 3 presents the process of the generation of a suitable, validated thermal simulation model and therefore lays the basis for the following research studies. The validation compares the air temperature of the Solarstation, a measurement room, and the thermal simulation for four type weeks. Lastly, this chapter outlines the key parameters for the validation.

Chapter 4 introduces the concept of a dynamic emission factor that leads to the CO_2-predictive control. Current annually averaged emission factor calculations do not consider the fluctuation in the electric energy grid with the rising renewable energies. Further, this chapter reviews the state of research and outlines the potential for the CO_2-predictive control. The study further introduces the predictive approach and parametrically compares various control approaches considering energy prices and emissions. Finally, different building technology systems with inert thermal and electrical storage units are evaluated, considering current and future emission scenarios to wrap up the potentials of the CO_2-predictive control.

Chapter 5 utilizes the methodology to explore the effect of a weather-predictive control for thermally activated building systems. Starting with a literature review on smart control strategies the simple approach of the weather-predictive is further evaluated in this chapter. The control strategy considers the future ambient temperature and solar radiation to optimize the heating, cooling, ventilation, and sun protection system of a Munich-based office building. The thermal comfort and the energy demand evaluate the performance of the approach in which the thermal mass is parametrically varied to elucidate its effect on the approach. With an outlook on a future weather scenario in Munich, this chapter finally evaluates the potential of the weather-predictive control to contribute to the European roadmap goal of climate neutrality in 2050.

Chapter 6 combines the approaches of the three previous papers and presents a weather-and-emission-predictive control strategy. This approach is then applied to an international research study setup, using five climate and electric grid locations representing an arid, tropical, subtropical, moderate, and cold climate. The different climate locations each perform parametric studies varying the thermal mass, the quality of the thermal envelope, the storage system, and the future data sets, including data for 2050. With this parametric study, the energy, thermal comfort, and CO_2 performance of various building types can be evaluated in different climates of the world.

Chapter 7 summarizes the previous research segments, discusses the overall results, reflects the impact by outlining the limitations, and evaluates the potential for future research emphasis following this dissertation.


1 Introduction
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5 Weather predictive control
6 International comparison weather & emission predictive control
7 Conclusion

2 Fundamentals

Summary

The second chapter establishes the general assumptions and fundamentals of this thesis. The state of the art, the state of literature as well as the state of legislation, provide a holistic introduction to the field of academia, industry, and applicable norms and codes. Therefore, the keywords for the analysis of this thesis are energy efficiency, thermal comfort, and intelligent control. Further, an overview of the software structure used for thermodynamic simulations is given, and its parametric interconnectivity is explained. Finally, this chapter outlines the characteristics of the in-situ measurement room, the Solarstation, that form the simulation's geometrical basis: the overall location, the construction details, and the measurement concept, including weather and sensor data are demonstrated. The chapter Fundamentals rounds off the introduction part and prepares for the following chapters 3-6, which represent four research studies analyzing the energy and emission saving effect of the weather and emission predictive control.

2.1 State of the Art

With the increasing energy demand for buildings, the building industry also aims to optimize its building technology systems. The field of global HVAC (Heating, Ventilation, and Air Conditioning) providers is very broad. Various companies worldwide are developing new approaches to optimize their building energy systems towards a more efficient operation. With the rise of digitalization and artificial intelligence, building data is becoming increasingly available and holds great potential for optimization. This boosts the trend of optimization and leads to even more products in the market. Furthermore, the smart home development, which connects the building technology with the room conditions, is globally addressed. Particularly in Western countries – with a higher degree of technology companies – there is huge potential for energy savings for residential and office buildings by optimizing the operation of the building technology systems. Besides the big global corporations like Bosch Thermotechnik, Carrier Global, Siemens Group, Viessmann GmbH, Vaillant Group Field [2-1–5], and others, the following Table 2-1 exhibits a structured overview of companies and their services. It is to be noted that this market is changing rapidly and that this overview represents the current situation at the time of the publication of this thesis. Additionally, this overview mainly focuses on Europe and only represents the information shown online on the corresponding official homepages of the companies.

Table 2-1: Overview of companies and services in the field of intelligent control strategies of building technology

Company (markets)	Market value	Device Functions	Controlled Building Technology	Claimed Energy Savings Potential
Tado [2-6] (Europe)	Total funding 157.5 Mio $ 1 Mio. sold Smart devices 2020	Comfort control Occupancy Open window detection Weather prediction	HVAC single story heating Floor heating	Energy saving (no specific numbers)
Netatmo [2-7] (Europe)	No information	Comfort control Weather open window detection Auto-adapt function	Gas/Boiler Heat-pump Pellet-wood stove	Energy saving (no specific numbers)
Wiser [2-8] (Germany)	89 Mio. € revenue 2020	Eco-mode (weather & building data considered)	Heating Lighting Sun protection	Energy saving (no specific numbers)
Controme [2-9] (Europe)	No information	Weather Prediction Geolocation calendar function	Single story heating Floor heating Storage Solar system Heat pump	Energy saving (no specific numbers)
Nest Thermostat [2-10] (worldwide)	More than 11 Mio. sold devices, part of Google Group	Schedules Occupancy	Heating Forced air radiant Heat pump Oil, gas, electric hybrid systems	10-12% heating 15% cooling
Danfoss Leanheat [2-11] (Europe)	No information	AI learns the thermal behavior of the room	Heating, cooling, sun protection, and ventilation systems	30% of maintenance
Dabbel [2-12] (Europe)	3.6 mio € series A Funding	Holistic approach for overall building control with predictive control based on AI	Heating, cooling, sun protection, and ventilation systems	Up to 26% average energy saved per building”

2.2 State of the Literature

The research and practical efforts of optimize the heating and cooling processes of buildings are widely discussed topics and are connected to various aspects. To better understand the individual parts, the literature review is separated into smaller sections presented in the individual research papers in the following chapters 3-6. This provides an opportunity to delve deeper into the specific topics while maintaining a linear focus for the reader. This section briefly introduces the keywords that were identified in the individual literature reviews of the research papers. The keywords can be categorized into the topics: CO_2, Control, Weather, and Building. These topics also represent the overall topic of this dissertation and, at the same time, are addressed in the individual papers. The following Table 2-2 lists the keywords, but there is no weighting in their ranking, meaning the position of the keywords carries no specific significance.

Table 2-2: Overview keywords State of the Literature

CO_2	Calculation, hourly, annual, footprint, static, dynamic, compensation, air quality, plant, tree, environment, pollutant, diaxide, carbon, emission, equivalent, LCA, compensation, neutrality, storage,
Control	Smart, intelligent, strategy, model, dynamic, predictive, variable, parameter, measure, time, step, advanced, feedback, open, closed, loop, analog, prediciton, two-point, PID, forecast, algorithm, artificial intelligence, machine learning, deep learning, ANN, neural network
Weather	Sun, air, wind, speed, direction, rain, precipitation, humidity, temperature, dry bulb, surface, clouds, radiation, global, diffuse, absorption, transmission, anemometer, reflection, albedo IPCC; data, epw, tmy, scenario
Building	Wall, ceiling, floor, window, door, mass, materials, U-value, technology, active, passive, activated, cooling, unit, overcooling, heating, radiator, power, user, human, energy, demand, power, source, thermal, overheating, comfort, PPD, PMV, air, venitlation, natural, HVAC, automatic, shading, internal, external, blinds, lighting, artifical, monitoring, simulation

2.3 State of the Legislation

Nowadays norms, guidelines, and certificates for building design vary from country to country and state to state. The building industry is responsible for up to 40% of the total end energy consumption [2-13]. The following first section outlines a brief summary of how the European guidelines intend to address this significant challenge and how the transformation into the German code is envisioned. The focus here lies on the energy efficiency of buildings. To reach the goal of climate neutrality for Germany in 2050, energy consumption needs to be lowered by 80% in comparison to the level of 2008 [2-14].

In practice, designing an energy-efficient building means to match the energy performance and the environmental conditions of a building. However, this work does not take the life cycle of a building into account. The environmental conditions of a building are mainly defined by the visual, acoustical, hygienic, and thermal comfort of a building, indoors and outdoors. The energy performance is mainly influenced by the thermal comfort of a room. With climate change, especially in the summer, thermal insulation is becoming more and more important. This is also represented in the codes, as one of the main aspects is considering strategies to prevent indoor overheating. The second section of this chapter outlines the individual evaluation parameters and the current state of the legislation in Germany regarding thermal comfort.

2.3.1 Energy efficiency

To boost the energy performance of buildings, the European Union has established a framework to achieve the major environmental goal of carbon neutrality within the EU by 2050. This includes the goal to "*achieve*

- a highly energy-efficient and decarbonized building stock by 2050
- create a stable environment for investment decisions and to
- *enable consumers and businesses to make more informed choices to save energy and money.*" [2-15]

To attain these goals the EU introduced the *Energy Performance of Buildings Directive* (EPBD) in 2002 and the *Energy Efficiency Directive* in 2012 with a revised version in 2018, as part of the *Clean Energy for All Europeans* package. The EU countries were hereby forced to include the revised actions of the EPBD into their national laws until March 2020 [2-15]. In Germany, this led to the 2020-published and integrated *Gebäudeenergiengesetz* (*GeG*) – a follow-up of the 2002 invented *Energieeinsparverordnung* (*EnEV*) and the *Energieeinspargesetzt* (*EnEG*) and to an update of the DIN V 18599 for non-residential buildings in Germany [2-16].

This legislative background forms the basis of the adapted goals of the EU and transforms the focus of the guideline from the prevention of energy losses of a building to a building-integrated production of electricity and heat. Further, the *GeG* unites the *EnEG* which is responsible for the construction of buildings and the *EnEV* with its building physics and building technology requirements in a single guideline [2-17].

For residential buildings, the 1959 introduced *DIN 4108* tackles the prevention of energy loss. Although the prevention of overheating in summer periods draws the main attention in the design process of a building nowadays, the *DIN 4108* still forms the basis for the calculation of energy losses as follows in Equation 2-1 [2-18].

$$Q_H = Q_t + Q_V - \eta\ (Q_S + Q_i) \tag{2-1}$$

Symbol	Description	Unit
Q_H	Heating demand	[-]
Q_t	Transmission heat losses	[-]
Q_V	Ventilation heat losses	[-]
η	Utilization factor of thermal mass	[-]
Q_S	Solar gains	[-]
Q_i	Internal gains	

2.3.2 Thermal comfort

In Germany, two codes (DIN 1946-2-1994-01 and DIN EN ISO 7730:2003) are addressing and defining the topic of thermal comfort. Here, thermal comfort describes "*the condition of the mind that expresses thermal satisfaction with the thermal environment*" [2-19].To evaluate thermal comfort in a building one could focus on the indoor temperatures or the comfort parameters PPD (Predicted Percentage of Dissatisfied) and PMV (Predicted Mean Vote), introduced by the Danish scientist Ole Fanger. In his work, he defined an energy balance for the human body for thermal comfort depending on the following variables, illustrated in Figure 2-2 below [2-20]:

- Air temperature
- Mean radiation temperatures
- Air speed
- Humidity
- Metabolic rate
- Closing Insulation

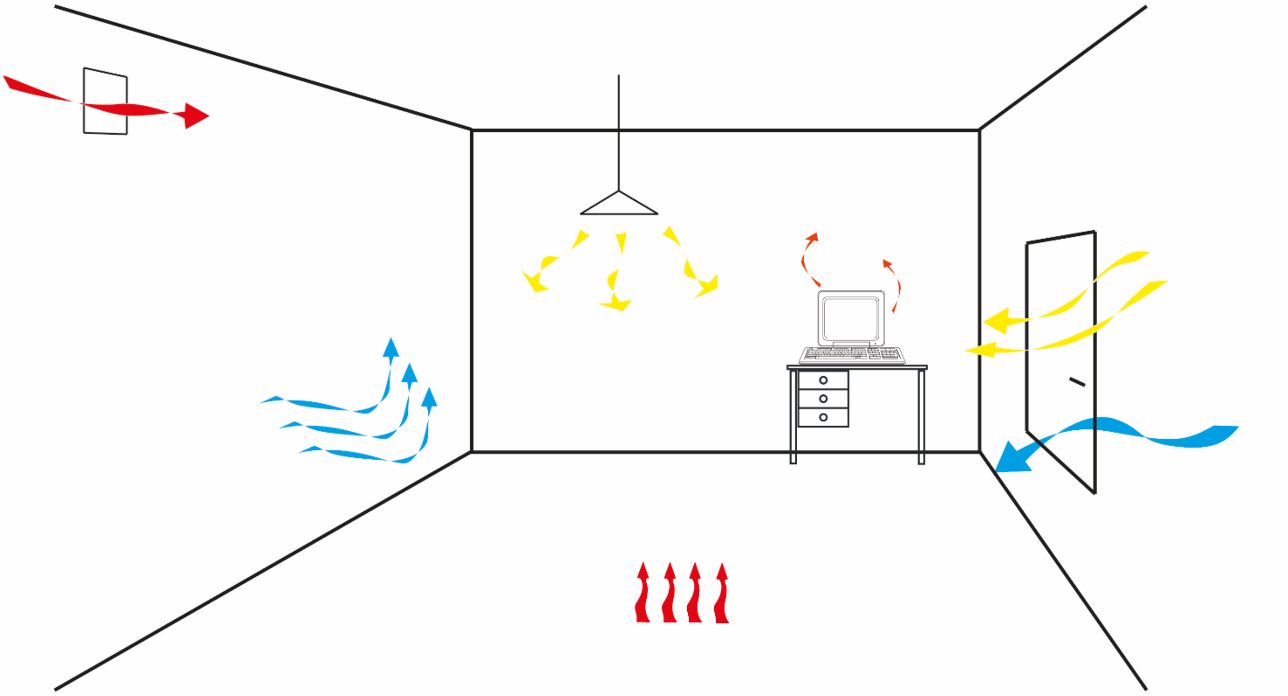


Figure 2-1: Thermal comfort parameters (own representation following [2-21])

Based on these parameters, Ole Fanger defined the numerical parameter PMV. The PMV can vary from 3 (hot) over 0 (neutral) to -3 (cold), representing the thermal conditions in a room. Based on empiric studies, he further developed a curve describing the correlation between PMV and PPD to address the individual senses of comfort of humans [2-20]. The following Figure 2-3 shows the PMV and PPD and its interconnection. According to the code DIN EN ISO 7730:2003, a PMV from -0.5 to 0.5 and a PPD of 10% should not be exceeded to provide thermal conditions in a room. [2-22, 2-23]

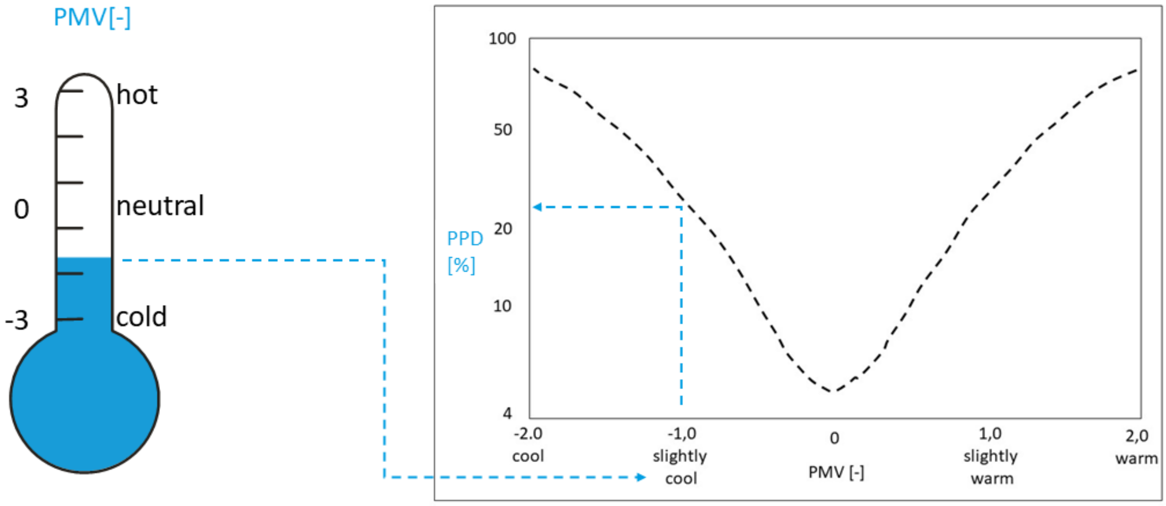


Figure 2-2: Thermal comfort parameters PMV and PPD (own representation based on DIN EN ISO 7730:2003 [2-19])

Another approach to evaluate comfort is to address the temperatures in a room. In addition to that, the *DIN EN 15251* from 2002 followed and replaced by the *DIN EN 16798* in 2019 defines the thermal conditions for indoor environments under the concept of energy efficiency with a focus on the prevention of overheating in summer periods. Here, thermal comfort is defined as the operative temperature. The operative temperature includes the air and mean radiation temperatures of all surrounding surfaces of a room.

Depending on the ventilation system and the adaptation opportunity of the user, the comfort boundary conditions change. To fulfill the requirements of a category the temperatures have to be within the boundary conditions. Here a maximum of 3% (up to 5%) of the usage hours of the room are allowed to be outside the boundary conditions. With a mechanical ventilation system, the indoor temperatures according to the ambient temperature are shown in the following left graph of Figure 2-4. The comfort categories from I to III are equivalent to the international categories A, B, and C of the DIN EN ISO 7730. [2-19, 2-22, 2-23] For a natural ventilation system and with the opportunity for the users to adapt to the indoor environment conditions, the comfort band depends on the average ambient temperature over the last 24 hours Θ_{rm} illustrated on the right of Figure 2-4. [2-22, 2-23]

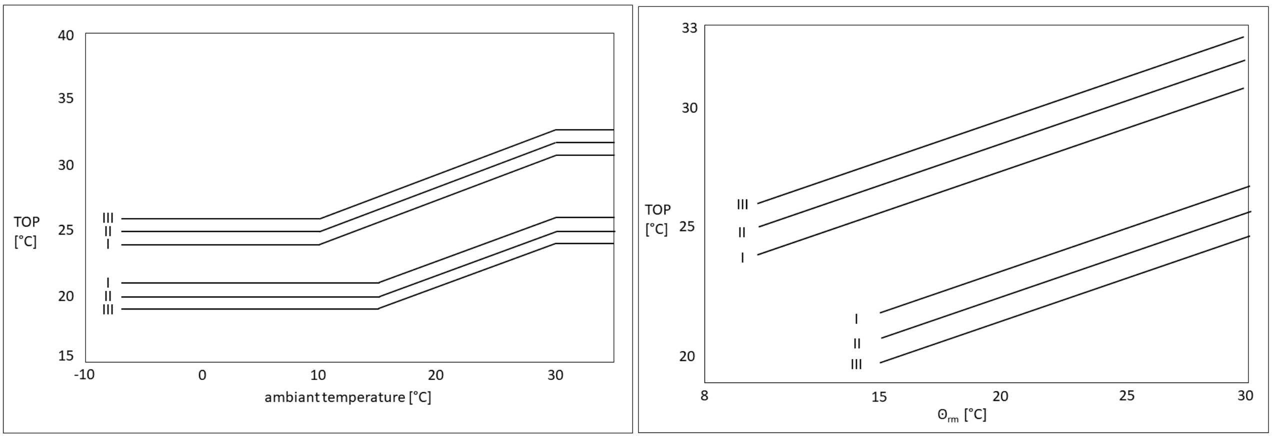


Figure 2-3: Indoor temperatures for the design of a building with (left) and without (right) mechanical ventilation according to DIN 15251 (own representation following DIN EN 15251 & DIN EN 16798 [2-22, 2-23])

2.4 Software Structure

In order to analyze the saving potential of the weather and emission predictive control and to answer the initial research questions a thermal simulation is executed. A dynamic thermal simulation is an appropriate tool to evaluate multi-dynamic behavior, as it is the case with the building physicals of rooms. This section points out the general functions of the thermal simulation tool TRNSYS and the mathematical engine behind it. Further, the advanced evaluation tool of TRNLizard and its serial connection to the CAD software Rhino with the parametric, visual programming surface Grasshopper are outlined. As the simulation concept grows from chapters 3 to 6, this section only presents the general information and structure of the software. The additional tools and boundary conditions of the individual parts of the simulation approaches are explained in detail within each chapter. In this thesis, the fundamental thermodynamic simulation software used is TRaNsient SYstems Simulation (TRNSYS) developed by the University of Wisconsin and first released in 1981. TRNSYS is a simulation software to calculate energy concepts for multi-zone buildings and to perform energy simulations on small and large scales, from domestic water systems up to complex multi-zone building simulations. It can simulate dynamic solar systems, HVAC systems, renewable energy systems, cogeneration plants, or geothermal heat pump systems all in connection with a thermal building simulation. [2-24] The modular software works with a variety of more than 150 components. These components are called types. The simulation studio with its core type TRNbuild manages the wide range of types and concentrates all the necessary building information for the calculation into a text file called .b18-file. All data regarding the simulation process as well as the further boundary conditions are collected in the .d18-file and transferred to the simulation engine. This time-step-based equation is dynamically solved by the simulation engine. The ensuing Figure 2-5 illustrates the conceptual structure of the software TRNSYS used in this work.

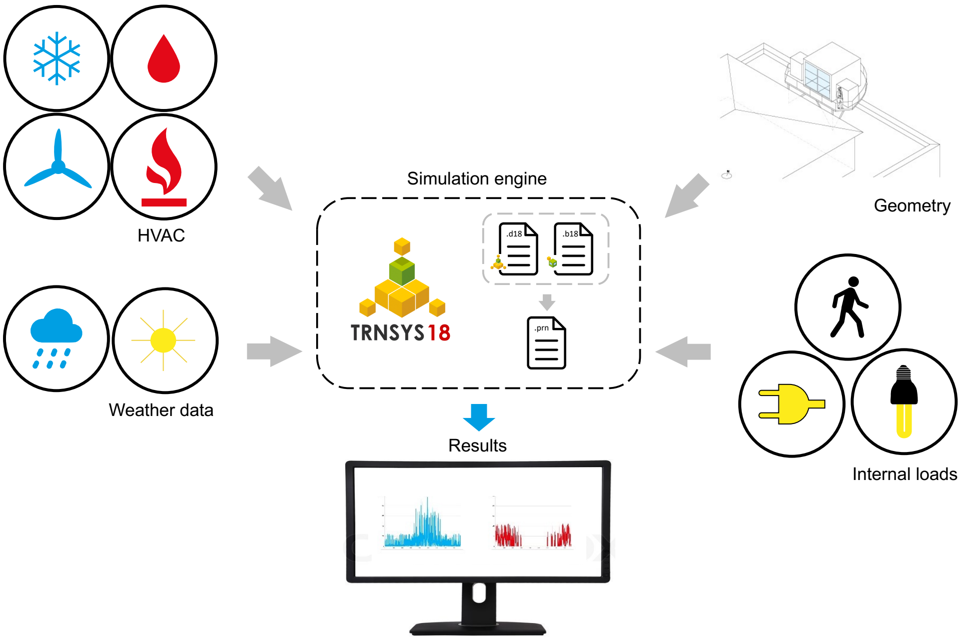


Figure 2-4: Conception structure of TRNSYS (own representation, icon from [2-24])

The simulation process is separated into three main parts: thermal simulation, radiation simulation, and system simulation. These individual simulation parts are split up in the following chapters and cover parts of the workflow to finally connect all simulation steps and perform the overall simulation. The individual simulation approaches are outlined separately. In the thermal simulation, TRNLizard a Plug-In for the visual programming environment Grasshopper of the 3D modeling software Rhinoceros 3D (Rhino) is used [2-25]. Grasshopper is primarily used to build generative algorithms and allows the user to create own programs by dragging components onto a canvas. TRNLizard is one of many free Plug-ins that combines the powerful parametric modeling tool Rhino/Grasshopper with the previously described features of the thermal simulation software TRNSYS to enable advanced thermal simulations. The Plug-In HoneyBee for Grasshopper performs the radiation simulation. This way, the weather data sets are here analyzed in every time-step to create hourly radiation data. To perform the system simulation and to analyze the building technology and its emissions, this simulation approach again uses the Grasshopper interface in combination with the connection to the programming language Python. Thereby, the hourly values of the emissions as well as the thermal and radiation data are considered to calculate the annual emission performance for a building simulation variant. Overall, with this workflow, the energy, comfort, and emission performance for various simulation variants can be calculated parametrically. Figure 2-6 provides a conceptual overview of the simulation workflow.

Figure 2-5: Conceptual workflow of the simulation approach (Own representation, icon from [2-24, 2-25])

2.5 Solarstation

The base case of the thermal simulation model forms an in-situ measurement room located on the roof of the main campus building of the Technical University of Munich, the so-called Solarstation. The following sections lay out the structure and design of the Solarstation. Further, its technical equipment and measurement concept that will form the basis of the following chapter 3 will be outlined, scrutinizing the validation of the thermal simulation model. Figure 2-7 shows the Solarstation on the roof.

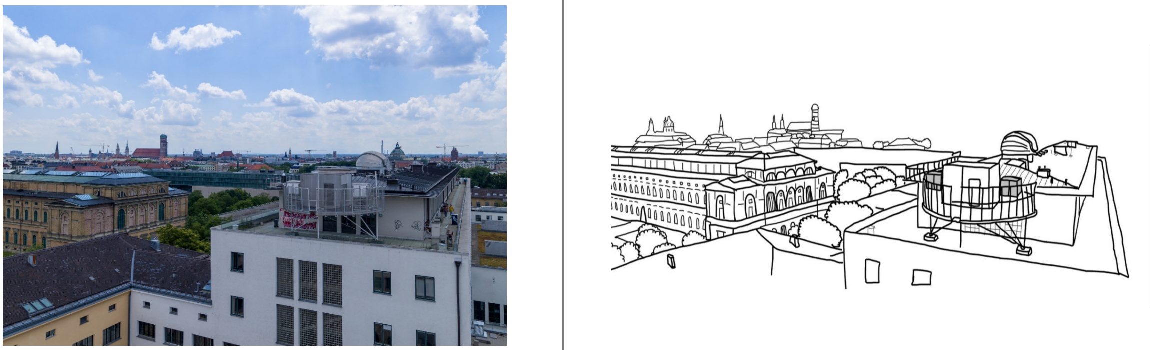


Figure 2-6: Location of Solarstation on the roof of the main building of TUM (Picture: Own representation; drawing: Michelle Pierburg [2-26])

2.5.1 Location, Orientation, and Construction

At the exposed location on the roof of TUM at a height of approximately 28 meters above the ground (3.8 meters above the 5th floor), the Solarstation is mainly influenced by the urban weather of Munich Arcisstraße 21 (48°08‘20“, 11°34‘30“). The station consists of three cuboids that stand on a steel frame of the northern terrace of the main building. One cube represents a 1:1 simulation of a test chamber oriented southwest. The two cubes to the east and west of the large body encompass on a scale of 1:5 and can be rotated in biaxial to investigate various sun positions. Figure 2-8 below presents the location and orientation of the Solarstation in the urban context of Munich.

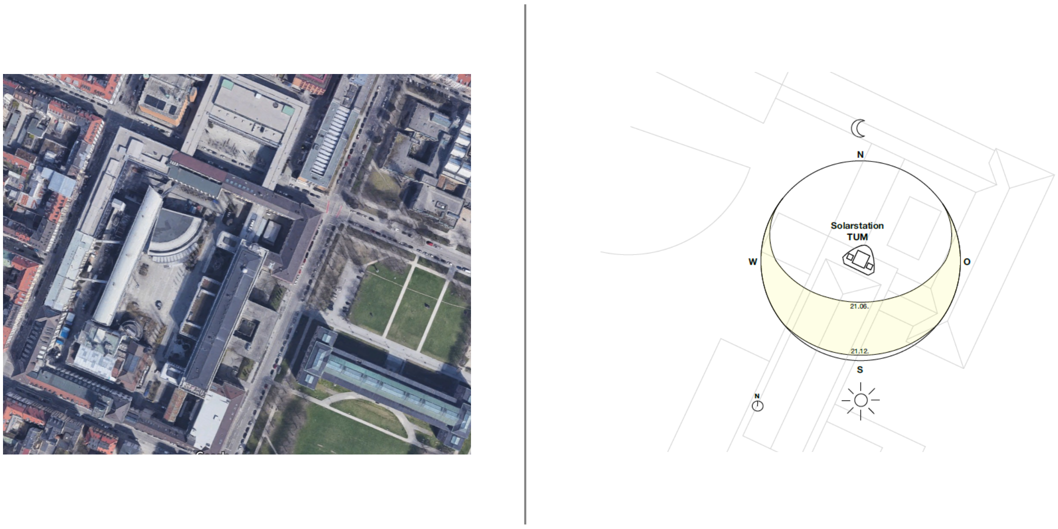


Figure 2-7: Aerial view of the location of the Solarstation in Munich (Picture: Google Street View; drawing: Christian Zang [2-27])

The measruement is performed in the main cube with a length of 4.30 meters, a width of 4.30 meters, and a height of 3.3 meters, illustrated in Figure 2-9. The main orientation, including the big glass façade (window-to-wall ratio 90%), faces 23° southwest. Over the year, the sun changes its position, so the sun's azimuth angle varies, with lower angles in the winter and steeper angles but longer exposure in the summer. Solar radiation with lower angles transmits deeper into the room in winter, helping to heat the inner surfaces passively.

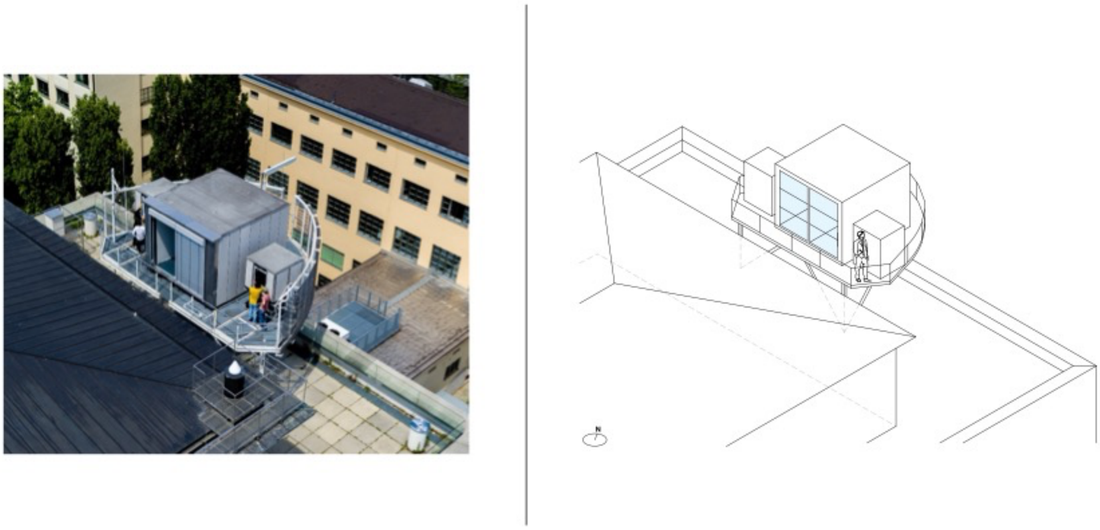


Figure 2-8: Perspective view of the Solarstation at TUM (Picture: own representation; drawing: Christian Zang [2-27])

As Figure 2-10 shows, the main cube of the Solarstation comprises three rooms. The anteroom is equipped with the technical and measurement equipment that supplies the two test chambers. It further allows physical access to the test chambers. With a width of 1.55 and depth of 2.87 meters, the two measurement rooms are structurally identical and are used to provide simultaneously identical conditions for the measurements. As this thesis does not focus on a specific façade and uses the Solarstation mainly to validate the simulation model, for the validation only one single test room is considered.

Figure 2-9: Top view of the Solarstation at TUM (Picture: own representation; drawing: Dissertation Philipp Molter [2-28])

The window-to-wall ratio accounts for 90% of the south-facing façade. During the measurements, the main façade is equipped with a special window. The double-glazed window consists of five electrochromic layers as well as a heat-mirror foil which together result in a very well insulated and non-transmitting window. Typically, the electrochromic layer can adapt its transmittance (a chemical process to darken the color of the window) to regulate the overall transmittance of the glass thus affecting the visual and thermal interior conditions. This effect was not active over the validation period of the simulation model, as the focus of this thesis does not lie on the high-performant window that is illustrated in Figure 2-11 below. For the thermal simulation, a comparable window represents the electrochromic window. The simulation window is a triple-glazed window with a U-value of 0.68 W/(m²K), a τ-value of 0.43, and a g-value of 0.3. The window frame covers 10% of the window area and has a U-value of 1.5 W/(m²K).

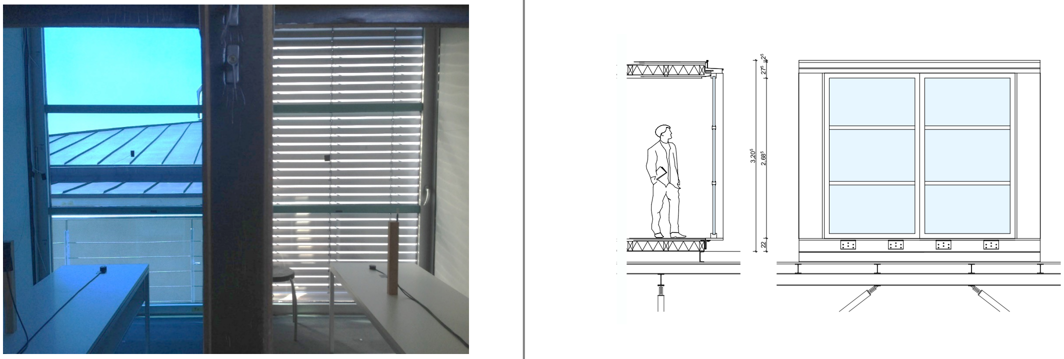


Figure 2-10: Facade/Section view of the Solarstation at TUM (Picture: own representation; drawing: Dissertation Philipp Molter [2-28])

To not affect the individual measurements, the thermal envelope and the interior wall between the two test chambers are very well insulated to generate high-quality measurement results. The U-values are as follows: External wall 0.175 W/(m²K), Internal wall 0.437 W/(m²K); roof 0.222 W/(m²K), floor 0.266 W/(m²K). The infiltration of the room is 1 1/h, and the thermal bridges are 0.1 W/(m²K). A detailed overview of the single layers of the building constructions, as well as the thicknesses, the density, and the heat capacity, are given in Table 2-2 at the end of this section.

2.5.2 Measurement concept

This section describes the measurement concept in the Solarstation. This measurement concept rests upon the manufacturer *Ahlborn Mess- und Regelungstechnik GmbH* which provides a modular multifunctional tool set including measuring instruments, a data logger, sensors, and software [2-29]. In general, three categories of measurements are performed at the Solarstation: Recording weather data, tracking thermal data, and capturing visual situations in the cubes. As this thesis focuses on thermal and energy performances, the visual data is excluded from the analyses, as shown in the following concept Figure 2-12.

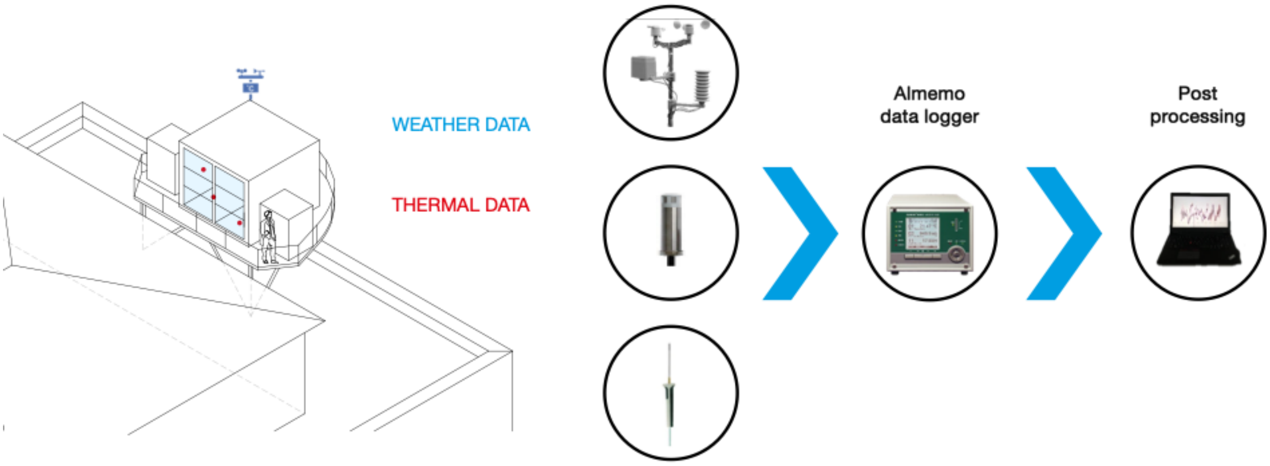


Figure 2-11: Measurement concept at the Solarstation (drawing: own representation; pictures: Ahlborn catalog [2-29])

Weather data

The weather station at the Solarstation comprises six different sensor types dynamically recording the air temperature, the relative humidity, the air pressure, the precipitation, and the wind direction and speed. A case surrounding each sensor protects them from the sun's radiation and the overall weather. Four ultrasound sensors orientated in four different directions measure the wind conditions. By calculating the time differences in the wind speed [m/s] as well as the wind direction [°] are determined. A double radar sensor measures the drop velocity of the precipitation to track the overall rainfall [mm]. In winter, the ultrasound system and the radar sensors are heated to create consistent conditions for the measurement. The air temperature [°C], by means of a NTC-resistance sensor, and the relative humidity [%] using a capacitive humidity sensor are also tracked inside the case [29]. Further, the weather station comprises a pyranometer tracking the radiation [kW/m^2]. The pyranometer opens up a half-space on a horizontal surface to measure the overall absorbed radiation, the so-called global radiation. Combined with a second measurement instrument, global radiation can be separated into direct (directly hitting the surface) and diffuse radiation (reduced through air molecules and particles). This weather data can later be implemented in the simulation tool to get precise simulation results. [2-29]

Thermal data

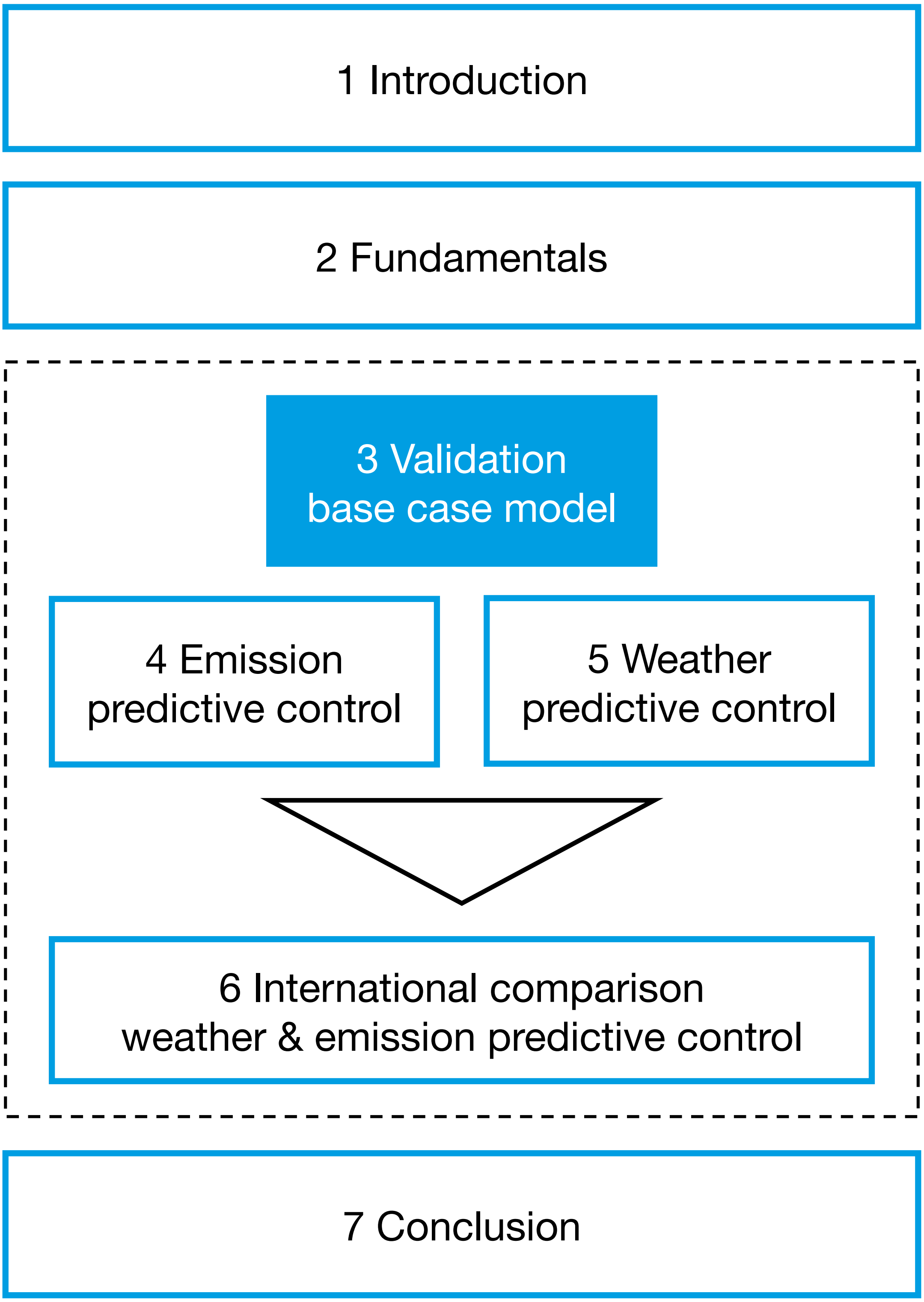
The thermal data inside the cubes focuses on the temperatures. The operative temperature consists of the surfaces' mean radiant temperatures and the room's air temperature. The *Almemo FHAD 46-C2-sensor* in the middle of the room measures the general air temperature of the room with an accuracy of +- 0.2 K and a temperature range of -100 to 170°C. The six individual inner surfaces of the measurement room (ceiling, floor, walls, and window) are equipped with PT-100 sensors to track the individual mean surface temperatures. Using the individual inner surface areas as well as the temperature values, the operative temperature is calculated dynamically in every time step to fulfill the validation with the thermal model. [2-29]

Data processing

The data processing does not follow a specific concept but focuses on data safety and data accessibility. Cables from the sensors to the anteroom of the Solarstation connect all sensors to a main measurement device, the ALMEMO® data logger. The ALMEMO® data logger collects, stores, and processes the measurement and weather data for the first time for every time step. The ALMEMO® data logger is connected to a local computer in the anteroom of the Solarstation that saves the data. The computer can be controlled remotely to have wireless access to the data at all times of the day. For safety in the third step, an ethernet connection transfers the data onto an internal server to finally store the data one last time. These processes repeat every minute to ensure a safe data structure and prevent data losses. This also enables the dynamic request of the measurement data and allows further remote control of the technology of the Solarstation (potential heating or cooling element), which was not performed in this work.

Table 2-3: Construction elements and thermal properties of the Solarstation (Dissertation Philipp Molter [28])

Building element Construction [from outside to inside]	U-value [W/(m^{2}K)]		
	Thickness [mm]	Density [kg/m^3]	Specific Heat Capacity [kJ/(kgK)]
External wall	0.175		
Ethernit board	8	1650	1
Wooden batten	30/60	59	1,063
Foil	-	-	-
EPS board	30	100	0.9
Mineral wool	120	100	0.9
Wooden stand	60/120	136	0.956
Wooden composite Board + Foil	16	550	1.063
Air layer	60	-	-
Wooden composite board	16	550	1.6
Internal wall	0.437		
Wooden stand wall	53/35	550	160
vacuum insulation + pyrogenic silica	-	221	0.849
Roof	0.222		
Sealing + wooden framework + Foil	19	660	2.1
Mineral wool	160	100	0.9
Rafter layer with foil	80/160	136	0.956
Wooden framework	19	550	1.6
Wooden batten	30/50	45	1.048
Wooden composite board	16	550	1.6
Floor	0.266		
Wooden framework	19	550	1.6
Wooden rafters with foil	80/160	136	0.956
Core: Mineral wool	130	100	0.9
Timber formwork	19	550	1.6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3 Validation of a thermodynamic building model based on weather and thermal measurement data

Summary

The inertia of massive buildings harbors enormous potential for energy savings. In order to address these potentials, the objective of this paper is to present a suitable, validated thermal model. The validation compares the air temperature of a test facility with a thermodynamic model in four type-weeks. The main finding is that the validation according to ASHRAE guideline can be performed using a parametric simulation tool. The key parameters to adapt the model are the infiltration rate and the window and construction properties, particularly the thermal mass. This supports the initial concept of addressing the thermal mass of a building.

Author Contributions

Conceptualization, C.H., T.S., F.B. and T.A.; methodology, C.H. and T.S.; software, C.H. and F.B.; validation, C.H. and T.A.; formal analysis, C.H.; investigation, C.H.; resources, C.H., T.S. and T.A.; data curation, C.H. and F.B.; writing—original draft preparation, C.H.; writing—review and editing, C.H., T.S., F.B. and T.A.; visualization, C.H., F.B.; supervision, T.A.; project administration, C.H.

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3.1 Introduction

At the Paris Climate Agreement in December 2015, almost 190 parties consent to the agreement to limit global warming to 1.5°C [3-1]. The main cause of this are greenhouse gas emissions. If these remain too high, this will lead to irreversible environmental tipping points, resulting in the severe limitation of (human) life on earth. The European Union has thus committed itself to reduce its greenhouse gas emissions by at least 40% compared to 1990 levels by the year 2030 [3-2].

The building sector accounts for around 13.6% of total direct greenhouse gas emissions in Germany, though this can rise to 26% if embodied carbon are considered too. The 2019 Climate Report of the German Federal Ministry for the Environment states that the contribution of the building sector is essential to achieve the set energy and climate goals. With its climate protection plan, the German government aims to become climate neutral by 2045. One component of this plan is climate-friendly buildings and housing. This includes, among other things, long-term strategies for the renovation of existing buildings, high standards for new constructions, and a gradual shift towards renewable energies in the area of building technology. [3-3]

The German Building Energy Law (GEG) sets out requirements for the building envelope and its systems technology in order to promote an increase in energy efficiency in the building sector and a switch to renewable energies [3-4]. These challenges are addressed in the scientific field of building technology, where thermal models are commonly used to analyse the effects on the energy efficiency of buildings e.g. evaluating intelligent control strategies.

Therefore, one fundamental step to generate reliable approximations that describe the real circumstances of a building is the validation of a thermal model, comparing the simulated model with measured data. This paper deals with the process of such a validation to create a base case model for future research.

3.2 Objective

The objective of this paper therefore, is to provide a validated thermodynamic simulation model according to the ASHRAE Guideline 14:2002. By changing the individual parameters of the parametric simulation model, it gradually approaches the measured values of the test facility. This leads to the following two research questions of this paper: Research questions

- Is it possible to validate a thermal model through the local weather and thermal data of the test facility according to the ASHRAE Guideline 14:2002 taking the parametric simulation tool TRNLizard into account?
- Which key parameters can be identified to fulfill the validation criteria according to the ASHRAE Guideline 14:2002?

3.3 Methodology

The methodology used is summarised in the following with regard to the previously described research background as well as the outlined research questions. Numerical thermodynamic simulations try to represent the actual physical behaviour of a system. As TRNSYS is validated according to ANSI/ASHRAE Standard 140, the correctness of the simulation engine is proven for various test cases [3-5]. In order to link the simulation results to the built environment, the thermodynamic simulation model is initially validated against measured data according to the ASHRAE Guideline 14:2002. To this end, a test facility was set up at roof level with measurement equipment to track thermal and weather data. This data further is compared with the simulation data to iteratively adapt the thermal model to fulfil the defined thresholds for the validation.

This forms the foundation for the thermal simulation model in TRNSYS 18, which is fed by the parametric simulation tool TRNLizard performed in the graphic programming interface Grasshopper, a plug-in for the CAD-software Rhinoceros 7. The thermal simulation model can now be adapted parametrically and evaluated dynamically within the simulation environment to analyse the individual effects of a WPC (e.g. thermal inertia, different climates, and key parameters).

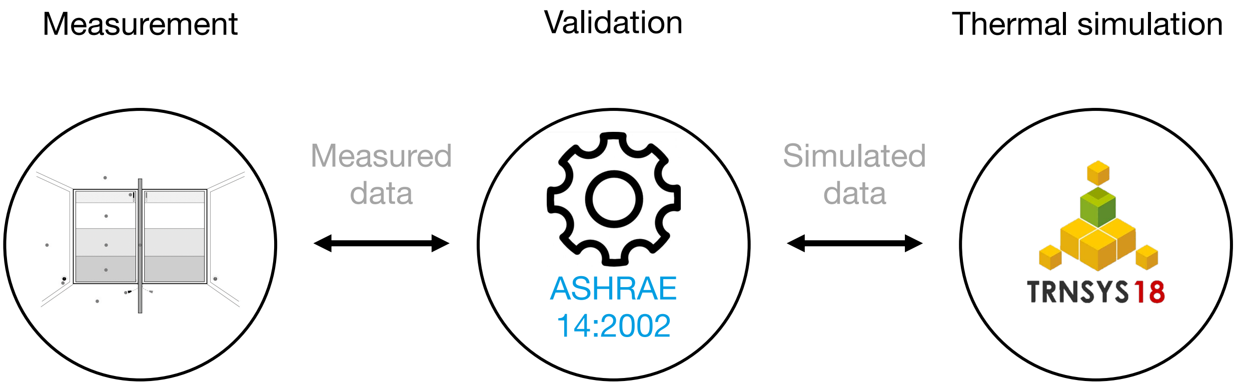


Figure 3-1: Graphic illustration of the methodology (own representation)

3.4 Fundamentals

The validation process according to the ASHRAE Guideline 14:2002, the structure of the simulation, the measurement room, and its measurement equipment are outlined in the following sections.

3.4.1 ASHRAE Guideline 14:2002

The scope of the ASHRAE Guideline 14:2002 is to provide a standard for “pre-retrofit and post-retrofit data to quantify the billing determinants (e.g., kWh, kW, MCF, etc.) used for calculation of energy and demand savings in payments to energy service companies, utilities, or others” [3-6]. A major step is to validate the model with measured data so as to form a valid foundation for the analysis and respective statements. By adjusting single assumptions of the simulation model and comparing them with the measured parameters, a simulation can be adapted better to reality. This process is called calibration and leads to the question: when is a calibration of the model precise enough to represent reality? The ASHRAE Guideline 14:2002 introduces two mandatory terms (and one optional term) to prove the validation that is outlined below.

The Normalized Mean Bias Error (NMBE) describes the mean percentage of deviation of the simulation values from the measured ones. To keep the values comparable, the mean deviation is normalized with the average measured values. This outlines the regression line of the sample. The NNBE must be within ± 10% to fulfill the requirement. When considering the NMBE, positive and negative differences could outweigh each other and the threshold would be met overall despite large individual deviations. [3-6]

$$\mathrm{NMBE} = \frac{1}{\bar{m}} \cdot \frac{\sum_i^n (m_i - s_i)}{n - p} \cdot 100\ (\%) \qquad (3\text{-}1\ )$$

The Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) describes the error deviation between the simulated and measured data and provides feedback on the significance of the model. By squaring and further assigning the square root of the values, the negative effect of the NMBE is compensated and a more adequate evaluation can be carried out. In general, the CV(RMSE) shows the variability of the error between the measured and simulated values, which must be smaller than 30%. [3-6]

$$\mathrm{CV(RMSE)} = \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_i^n (m_i - s_i)^2}{n - 1}} \cdot 100\ (\%) \qquad (3\text{-}2\ )$$

In addition, the Coefficient of Determination (R^2) can be added to the process of validation but is not mandatory according to the ASHRAE Guideline 14:2002. It is recommended that this be greater than or equal to 0.75. It describes the proximity of the simulation to the regression line of the sample. The absolute ideal would be 1. [3-6]

$$R^2 = \left(\frac{n \cdot \sum_i^n (m_i - s_i) - \sum_i^n m_i \cdot \sum_i^n s_i}{\sqrt{n \cdot \sum_i^n {m_i}^2 - \left(\sum_i^n m_i\right)^2 \cdot \left(n \cdot \sum_i^n {s_i}^2 - \left(\sum_i^n s_i\right)^2\right)}} \right)^2 \qquad (3\text{-}3\ )$$

Table 3-1: List of Symbols

Symbol	Description	Unit
m_i	Measured value	[-]
s_i	Transmission heat losses	[-]
η	n° of measured data points	[-]
$\bar{m}$	Mean of the measured values	[-]

3.4.2 Software – structure of the simulation

A thermal simulation is performed for the validation and further thermal simulations. A dynamic thermal simulation is an appropriated tool to analyse and evaluate multi-dynamic behavior, as is the case in the building physics of a room. The general functions of the thermal simulation tool TRNSYS will be explained below. Further, TRNLizard and its serial connection to the CAD-software Rhino, including the parametric, visual programming interface Grasshopper, are outlined.

The software used for thermal simulations in this paper is called TRaNsient SYstems Simulation (TRNSYS). TRNSYS is a simulation software to calculate energy concepts for multi-zone buildings. TRNSYS is able to perform energy simulations on a small and large scale, from domestic water systems up to complex, multi-zone building simulations. It can simulate solar systems, HVAC systems, renewable energy systems, cogeneration plants or geothermal heat-pump systems. [3-5]

TRNLizard is a plugin for the visual programming environment Grasshopper of the 3D modeling software Rhinoceros 3D (Rhino). Grasshopper is primarily used to build generative algorithms and allows the user to create their own scripts by dragging components onto a canvas or via code. TRNLizard is one of many free plugins that combines the powerful parametric modeling tool Rhino/Grasshopper with the previously described features of the thermal simulation software TRNSYS to enable advanced, parametric thermal simulations. The thermal model with its building properties is set up according to the following test facility.

3.4.3 Test Facility

The base case model of the thermal simulation model forms an in-situ measurement test facility located on a rooftop in an urban environment. The structure and design of the test facility as well as its technical equipment and underlying measurement concept is examined in the following so as to perform the validation of the thermal simulation model.

At the exposed location on the rooftop at a height of approximately 28 meters above the ground floor (3.8 meters above the 5th floor), the test facility is mainly influenced by the urban weather conditions (48°08‘20“, 11°34‘30“). The central main cube is a full-scale test room facing south-west. This analysis described in this paper was carried out in the main cube with a length of 4.30, a width of 4.30, and a height of 3.30 meters. The main orientation, including a large glass façade (window-to-wall ratio 90%), faces 23° southwest. The sun's position changes during the year so that its azimuth angle varies with lower angles in the wintertime and steeper angles but longer periods in summer.

Figure 3-2: Perspective view of the test facility (Picture: own representation 2021)

As Figure 3-2 shows, the main cube comprises three rooms. The anteroom houses the technical and measurement equipment which supplies the two test chambers. It also grants physical access to the test chambers. With a width of 1.55 and a depth of 2.87 meters, the two test rooms are structurally identical and offer almost identical physical conditions. Since this paper does not focus on a specific façade and uses the measurement rooms mainly to validate the simulation model, only the test room facing southeast is considered for the validation.

At the time of the analysis, the main façade is equipped with a special window. The double-glazed window consists of five electrochromic layers as well as a heat-mirror foil which together result in a very well insulated and low-transmitting window. Typically, the electrochromic layer can adapt its transmittance (a chemical process to darken the color of the window) to regulate the overall transmittance of the glass, thus affecting the interior visual and thermal conditions. This effect was not active during the validation period for the simulation model, since this paper does not focus on the high-performance window. Figure 3-3 shows the internal visual conditions of the tinted window compared with an external shading system, even though the sun shading systems are not activated during the validation measurement periods.

Figure 3-3: Facade/section view of the test facility (Picture: own representation 2021)

So as not to affect the individual measurements, both the thermal envelope as well as the interior wall between the two test chambers are very well insulated to generate high-quality measurement results. Further, no building technology is activated during the measurements and the room is unoccupied and without internal loads. Table 3-2 shows the construction details from the outside to the inside as well as the individual u-values of the thermal envelope.

Table 3-2: Overview of the individual construction layers and the building envelope (Source: [3-7] & [3-8])

External wall U-value 0.175 W/(m^{2}K)	Ethernit board 8 mm Air layer 30 mm Wooden batten + foil 30/60 mm EPS board 30 mm Mineral wool 120 mm Wooden stand + foil 60/120 mm Wooden composite board 16 mm Air layer 60 mm Wooden composite board 16 mm	**Roof** U-value 0.222 W/(m^{2}K)	Sealing membrane + wooden framework Mineral wool 160 mm Rafter layer with foil 80/160 mm Wooden framework 19 mm Air layer 30 mm Wooden batten 30/50 mm Wooden composite board 16 mm
Floor U-value 0.266 W/(m^{2}K)	Wooden framework 19 mm Wooden rafters + foil Core: mineral wool 80/160 mm Timber formwork. 19 mm Carpet 5 mm	**Internal wall** U-value 0.437 W/(m^{2}K)	Wooden stand wall 50/35 mm Core: vacuum insulation with pyrogenic silica

In general, three categories of measurements are performed at the test facility: the recording of weather and thermal data as well as visual measurements in the cubes. As this paper focuses on thermal and energy performances, the visual data is excluded from the analysis, as shown in the following concept figure. The weather data is recorded by the nearby weather station. It is roughly 400 m away and at 28 meters, it has a comparable height to the test facility.

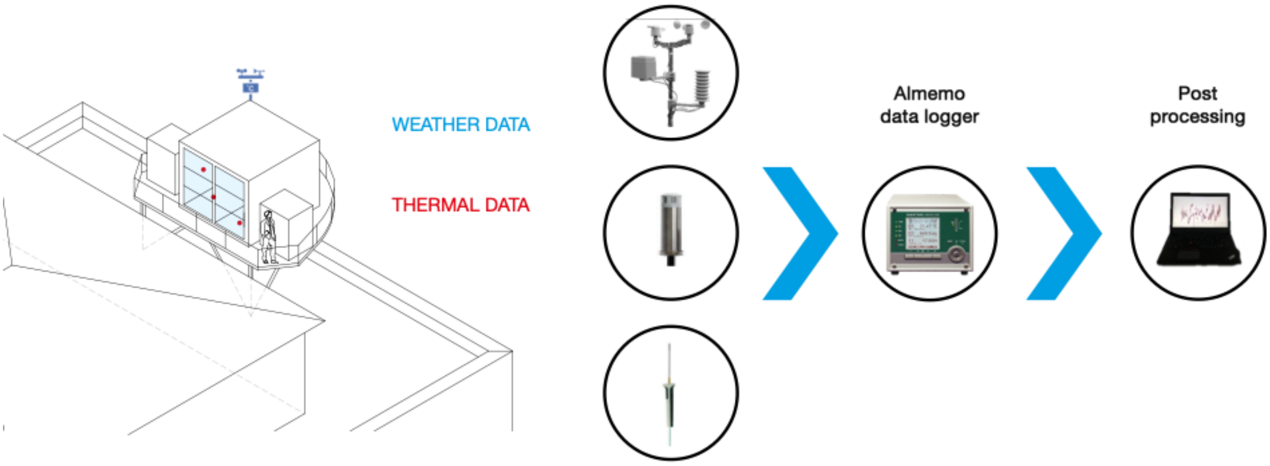


Figure 3-4: Measurement concept at the test facility (drawing: own representation; source pictures: [3-9])

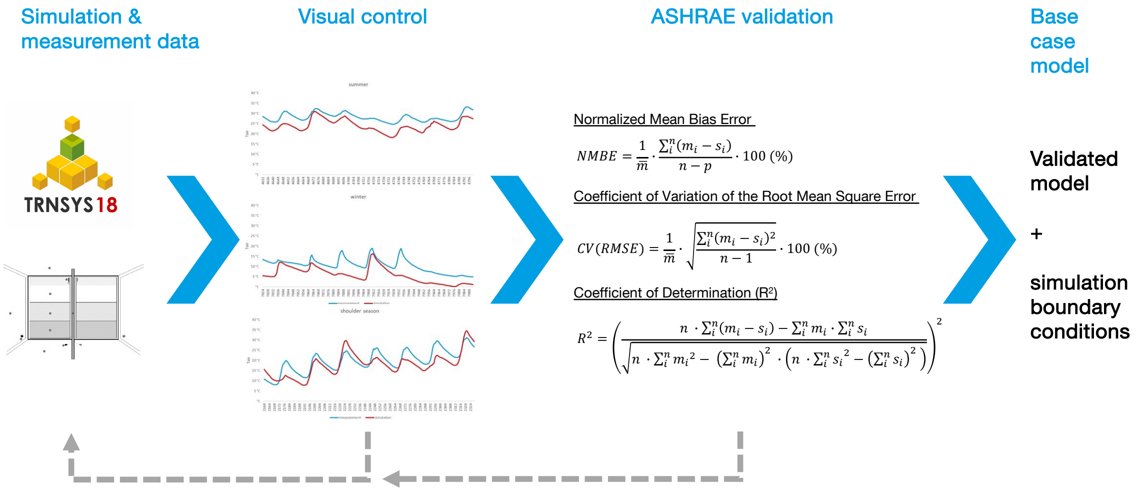
The weather station comprises different sensors to dynamically record dry-bulb and wet-bulb air temperature, each at a height of 2 and 28 meters, the wind direction, the wind velocity, as well as the horizontal global and diffuse radiation.

The thermal data inside the test cubes focuses on the temperature. The operative temperature consists of the mean surface temperatures and the air temperature in a room. An Almemo FHAD 46-C2-sensor in the middle of the room measures the air temperature of the room. The six individual inner surfaces (ceiling, floor, walls and window) are equipped with PT-100 sensors to track the individual mean surface temperatures. Using the individual inner surface areas as well as the temperature values, the operative temperature is calculated in every time step. [3-9]

The thermal data is collected by a data logger in the anteroom of the test facility and is then stored and processed for the first time for every time step. The ALMEMO data logger in turn is connected to a local computer in the anteroom that saves the data once more and can be controlled remotely. In a third phase, an ethernet connection transfers the data to an internal server to finally store the data one last time. These processes repeat every minute to ensure a safe data structure and to prevent data losses.

3.5 Validation

This chapter first examines the calibration process for the weather data with a nearby meteorological weather station. The second section describes the calibration and validation of the thermal simulation model with the dynamic measurements. The following figure outlines the iterative process of the validation. The simulation and measurement data are initially processed and converted into graphs for visual control. If the curves of the graphs do not match, an initial calibration process begins in which the model settings are adapted by an iterative process. Following the visual control, the aforementioned normalized mean bias error, the coefficient of variation of the root mean square error, and the coefficient of determination are calculated. Once again, the model's results are evaluated in an iterative process and it is adapted to finally generate a validated simulation model.



Normalized Mean Bias Error

$$NMBE = \frac{1}{\overline{m}} \cdot \frac{\sum_i^n (m_i - s_i)}{n - p} \cdot 100\ (\%)$$

Coefficient of Variation of the Root Mean Square Error

$$CV(RMSE) = \frac{1}{\overline{m}} \cdot \sqrt{\frac{\sum_i^n (m_i - s_i)^2}{n - 1}} \cdot 100\ (\%)$$

Coefficient of Determination (R²)

$$R^2 = \left(\frac{n \cdot \sum_i^n (m_i - s_i) - \sum_i^n m_i \cdot \sum_i^n s_i}{\sqrt{n \cdot \sum_i^n {m_i}^2 - \left(\sum_i^n m_i\right)^2 \cdot \left(n \cdot \sum_i^n {s_i}^2 - \left(\sum_i^n s_i\right)^2\right)}} \right)^2$$

Figure 3-5: Methodology of the validation process of the simulation model with final base case model (own representation)

3.5.1 Weather Data

The weather has a major impact on the performance of a building as it influences the energy balance in various ways, such as solar radiation or pressure differences. The exposed location of the measurement rooms means they experience more extreme weather conditions than a normal urban environment, which leads to the need for accurate and correct weather data.

Even though there is a weather station at the test facility itself, the weather station at the accompanying meteorological facility was found to supply more reliable data. The weather data from this station still has a high locality and is sufficient to evaluate the simulation variants. The recorded data is then prepared for implementation in the thermal simulation software. This process is concluded by a conversion into hourly values by calculating the arithmetic mean for each weather parameter per hour. Further, these parameters are extracted and transformed into a weather data file in the EPW-format to comply with the international common standards for various thermal simulation tools.

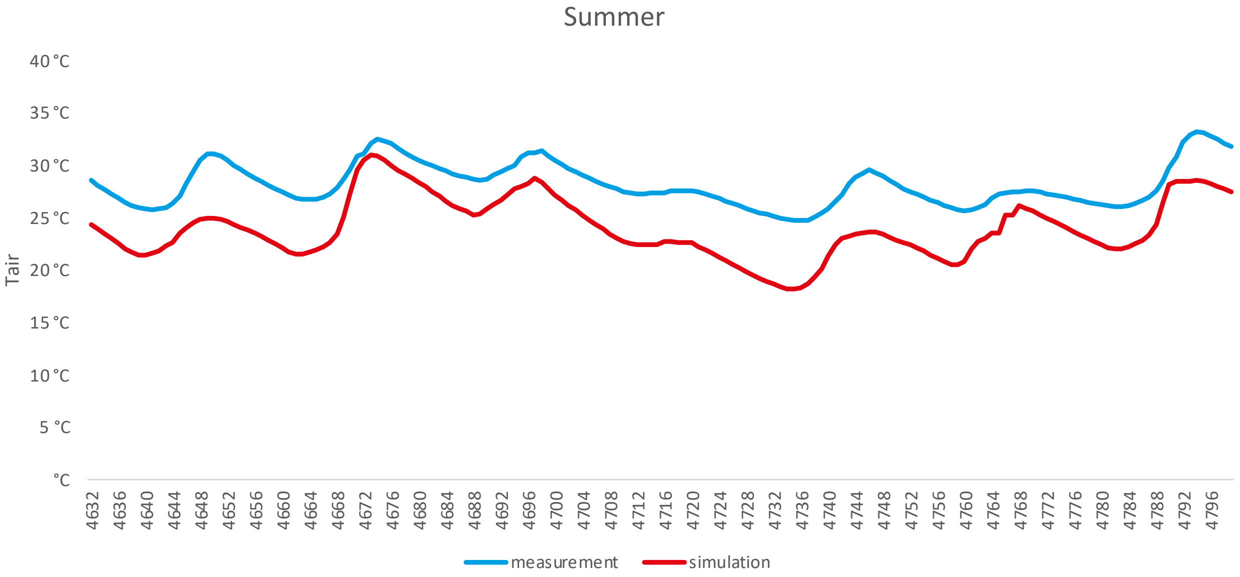
As regards the validation, a consideration of a whole year is seen as unnecessary and may even mean that the validation itself cannot be completed. Smaller time frames representing the different seasons are more suitable and are not dominated by data losses and unpredictable disturbances while generating the same outcomes. Therefore, four type-weeks are chosen since they represent the typical weather conditions in winter, summer, spring and fall season in the moderate climate of Munich.

• Shoulder week 1	16.03.2020 – 22.03.2020
• Shoulder week 2	01.04.2020 – 07.04.2020
• Summer week	13.07.2020 – 19.07.2020
• Winter week	23.11.2020 – 29.11.2020

3.5.2 Results – Validation Simulation Model

The simulation model is validated according to the parameters of the measured and simulated indoor air temperature. As outlined previously, the validation is performed according to the NMBE, CV(RMSE) and R^2 for the time step of one hour in the defined time periods. The individual steps to adapt the simulation model are not explained (in line with the focus of this paper) but the simulated model generally shows more comfortable conditions in all periods (shown exemplarily for summer in Figure 3-6). This formed the basis for the iterative process to address the thermal envelope of the building model and to make it more airtight so as to increase the simulated temperatures in summer and reduce the indoor air temperatures in winter, as it the case in the measurement test facility.

After an iterative process of adaptation, the thermal model is finalized with the window properties with a G value of 0.3 and a U-value of 0.68 W/(m²K). This is due to the fact that the electrochromic windows with a heat mirror foil perform better than the initial assumptions for the base case model. Further, the thermal bridges are set to 0.1 W/m²K and the infiltration is lowered to 0.25. The combination of the very well insulated windows and the very airtight thermal envelope again led to this assumption. These adapted parameters and the individual calibration steps are outlined in the master thesis of Brunet 2021. The updated simulation model's graph course as well as the overall NMBE, CV(RMSE) and the R^2 are shown in Figure 3-6 and Table 3-3.



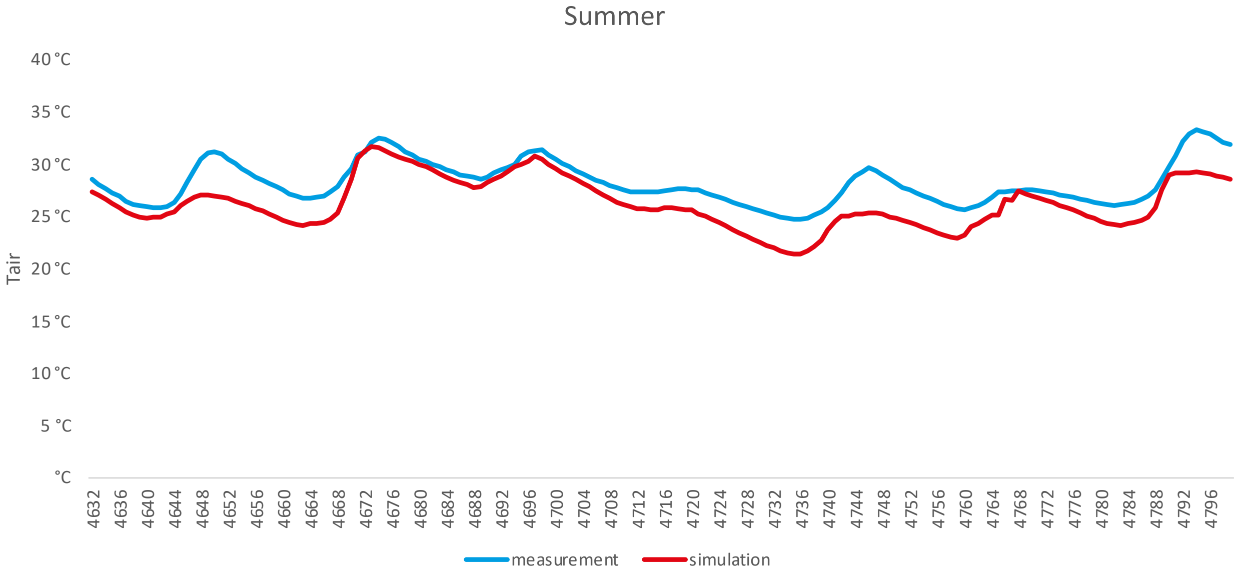


Figure 3-6: Curve for the simulated (red) and the measured (blue) air temperature for the summer before (top) and after (low) validation (own representation based on calculations acc. to [3-10])

Table 3-3: Validation results: Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and the Coefficient of Determination (R^2) (source: calculations acc. to [3-10])

Index	3 week period	4 week period	Criteria
NMBE	7.9%	0.7%	± 10%
CV(RMSE)	20.5%	25.9%	< 30%
R^2	0.82	0.69	> 0.75

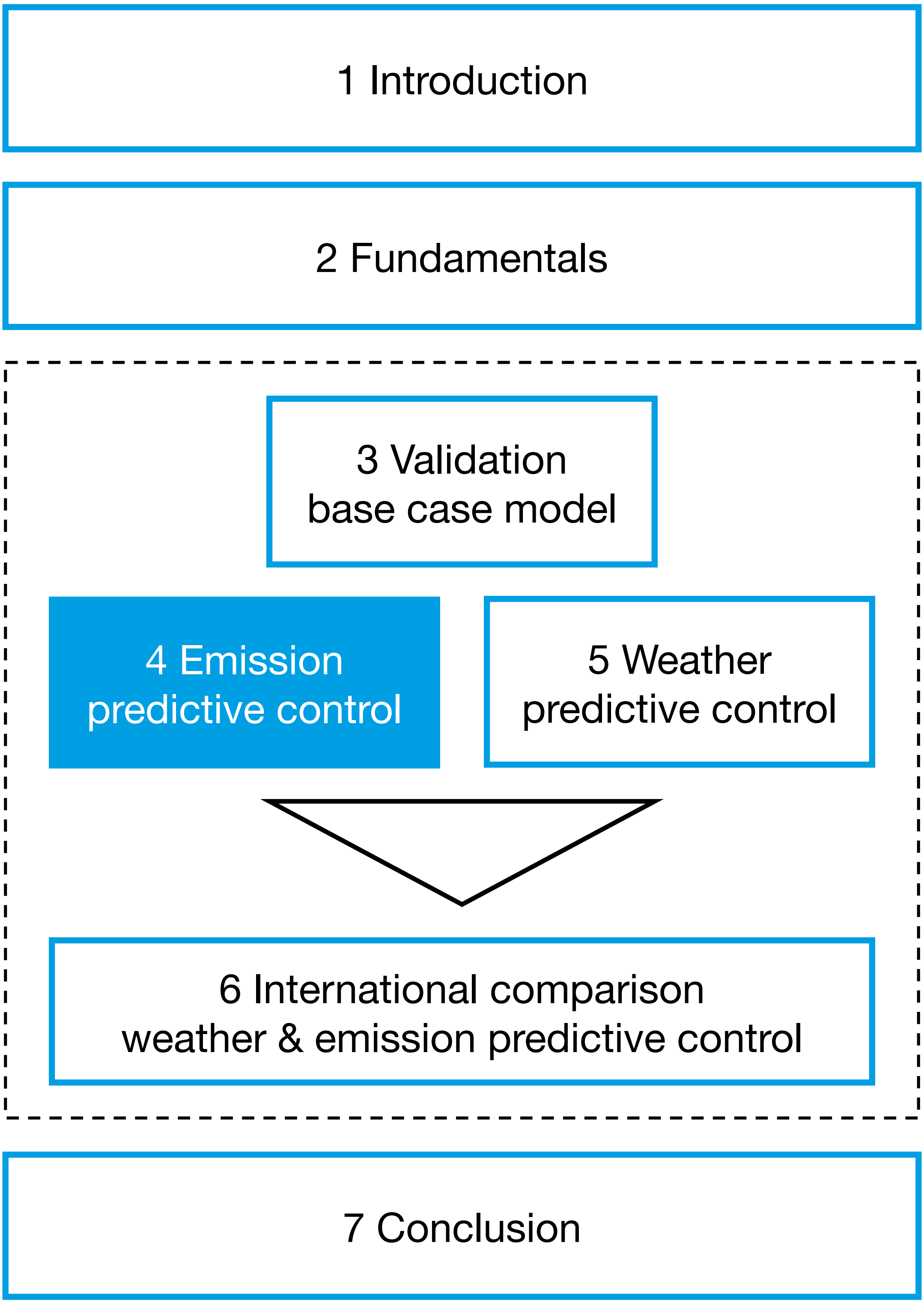
3.6 Conclusion

Even though the weather data came from a weather station 400 m away, a validation with this weather data is conclusive. Thus, the first research question as to whether it is possible to validate a thermal model with local weather and thermal data using a parametric simulation tool like TRNLizard can be answered in the affirmative. A validation using the parameter of air temperature is possible following several adaptions of the simulation model. This also satisfies the limitation criteria of the ASHRAE Guideline 14:2002. The values for the 3-week and 4-week time slots lie well within the NMBE range of ± 10% and the CV(RMSE) is within the upper limit of 30%. Only the lower limit of the Coefficient of Determination (R^2) at 0.75 can be complied with in the 3-week period, though this is not a criterion that has to be fulfilled.

To answer the second research question: the two main parameters that enable this validation are the infiltration rate and the thermal bridges. Lowering these parameters leads to an optimized thermal behavior for the summer and winter weeks. The indoor temperatures can thereby be raised to a level at which they almost coincide with the measured temperatures. However, this adaptation affects the results for the shoulder week, particularly the first week, in a slightly negative way, so that the criteria values change unfavorably. In the authors' opinion, this may be due to the rather light construction and fast thermal responses of the test facility which needs to be examined in further studies.

3.7 Outlook

Since the validation was proven to be successful, a validated thermal simulation model of the test facility is now ready for further thermal simulations. This can be used as a basis for testing various control strategies, such as weather predictive control strategy (WPC). These strategies may then conversely be performed at the test facility with the goal of reviewing the thermal model. In addition, adaptations to the model itself can be carried out, such as changing the envelope and usage, which can then be revalidated. Furthermore, this model may be adapted, so that a WPC can be examined in other locations (e.g. different climates) and various building typologies or types of usage to identify energy savings from a more global perspective.


1 Introduction
2 Fundamentals
3 Validation base case model
4 Emission predictive control
5 Weather predictive control
6 International comparison weather & emission predictive control
7 Conclusion

4 Impact of dynamic emission factors of the German electricity mix on the greenhouse gas balance in building operation

Summary

Due to climate change, emission balancing is a relevant tool to quantify the environmental impact of a building system. The electrification of energy production at a national level, as well as energy supply at a building level, shifts the focus to the emission factor (EF) of the electricity grid. Currently, static EFs are used for calculating the emission balance. However, the electricity grid already shows fluctuations in power generation and EF due to renewable energies. The paper reviews recent literature outlining the research gap and presents the development of a simulation setup and concept, in which the emission balance of the building operation changes, using dynamic EFs that map fluctuations at an hourly resolution. In the first step, we simulate the thermal building and radiance performance. The data are then used in a second step to conduct a system simulation, which analyzes the effects of the dynamic EFs. The results show that the dynamic balance approach for different building system variants deviates considerably from the static approach. By comparing different concepts for the loading strategy, the predictive strategy outperforms a common control strategy, when considering the energy prices and/or the emissions. This is especially true for systems with inert storage units, where charging times significantly influence the balance, as well as for systems with PV integration. This paper outlines the potential of the EFs-optimized control increases when evaluating a potential scenario for the year 2040, factoring in increased seasonal and daily fluctuations in electricity generation.

Author Contributions

Conceptualization, C.H., K.B., L.L., S.C.K. and T.A.; methodology, C.H., K.B. and L.L.; software, C.H., K.B. and L.L.; validation, C.H., K.B. and L.L.; formal analysis, C.H., K.B., L.L. and S.C.K.; investigation, C.H., K.B. and L.L.; resources, C.H., K.B., L.L., S.C.K. and T.A.; data curation, C.H., K.B. and L.L.; writing—original draft preparation, C.H. and K.B.; writing—review and editing, C.H., K.B., L.L., S.C.K. and T.A.; visualization, C.H., K.B. and L.L.; supervision, T.A.; project administration, C.H.

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4.1 Introduction

At the Paris Climate Agreement in December 2015, almost 190 parties signed the agreement to limit global warming to 1.5 °C [4-1]. The main causes of global warming are manmade greenhouse gas emissions. According to the United Nations Environment Programme (UNEP), the overall amount of carbon emissions related to the building sector adds up to 38% [4-2]. This share not only comprises the building operation (28%) but also includes the emissions from the building industry caused during the production of the building materials, especially concrete and steel. This outlines the potential and, furthermore, demands the urgent need for action to decrease emissions.

Within the existing norms and codes for buildings, the constant, annual static emission factor plays a key role as a parameter for the evaluation of the emission balance. However, it is due not only to climate change and the rise of electrical, renewable energy sources such as photovoltaic (PV) or wind energy, but also, according to the Fraunhofer Institute for Solar Energy Systems, to the electrification of building technology, which changes the circumstances on the supply and demand side [4-3]. This leads to daily and seasonal variability in the price and emissions of the German power grid.

Under these circumstances, especially with the system of emission balance boundaries of the building operation, the common concept of a static emission factor should be criticized. This, consequently, leads to the necessity of the examination of the dynamic emission factor.

4.1.1 Objective

With its climate protection plan, the German government aims to be climate-neutral by 2045 [4-4]. One component of this plan is a climate-neutral building sector. National and international legislations, such as the German Building Energy Code (GeG), have set out requirements for the buildings and the technologies contained in them in order to promote an increase in the energy efficiency of the building sector and a transition to renewable energies [4-5]. The research field of building technology addresses these challenges with thermal simulation models to analyze the effects on the energy efficiency of buildings (e.g., load management). Within the evaluation of these processes, the emission factor plays a key role, with climate neutrality becoming the overarching goal of modern building projects. In addition to the development of a concept and simulation process, the effects of a dynamic emission factor were analyzed, under the general hypothesis of this paper:

Using dynamic, hourly emission factors to calculate the CO_2 emissions for the building operation generates emission savings, which are not represented in the common calculation concept based on static, imprecise data.

To evaluate this hypothesis and to facilitate a deeper understanding of the concept of the dynamic emission factor and its impact, this paper explores the following research questions:

- How does the consideration of a dynamic instead of a static emission factor impact the CO_2 balance of a building operation?
- What potential does an emission-optimized load control have?
- How does an increased storage capacity influence performance?
- How big is the impact of the dynamic emission factor calculation on the overall transformation of the German electricity grid?

4.1.2 Methodology

This paper proposes the concept of using the dynamic emission factor in thermal building simulations to more accurately depict the emission balance of a building. After an initial literature review establishing the current state of the research and defining the research gap, this paper presents the weather and electrical power-grid data and outlines the simulation setup (as displayed in Figure 4-1), which also defines the concept for the analysis of a dynamic emission factor.

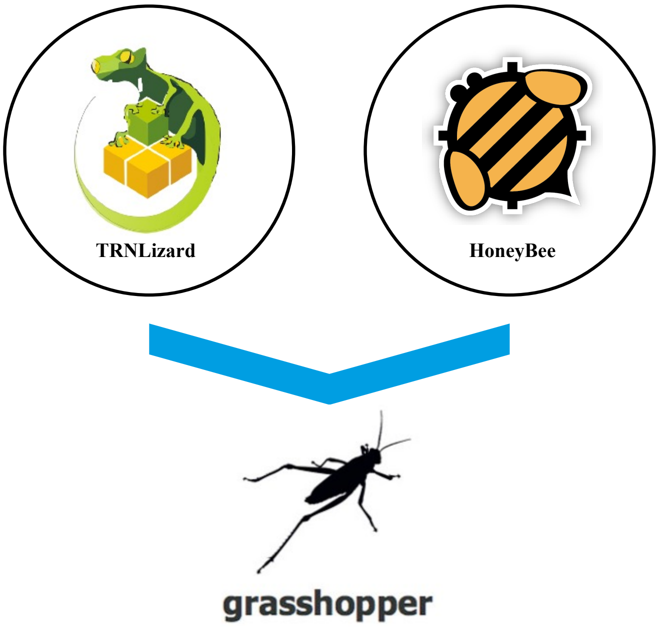


Figure 4-1: Graphic illustration of the simulation methodology (own representation)

For this purpose, the dynamic thermal simulation (Plug-In TRNLizard for Rhino 7) and the radiance simulation (Plug-In HoneyBee for Rhino 7) form the basis of feeding a system model simulation (Grasshopper/Python) to evaluate the emission balance in a second step. After introducing the concept and the simulation model, the potentials of this strategy are presented and further outlined in the final outlook through potential future research projects with the aim to achieve the previously mentioned climate neutrality.

4.1.3 Literature Review

Within this research field, a couple of studies have already taken into account the hourly emission-factor profile of the German power grid. They comprise first studies that were conducted to detect the energy- and emission-saving potential [4-6–9]. These studies all focus on the concept of the average-emission factor. A second approach to dealing with a dynamic emission factor is using the marginal emissions method, but this approach is not considered in this paper nor in this literature review. The following gives a quick overview of the aforementioned studies and defines the research gap of this paper.

Regett and Heller, in 2015, showed that there is a notable variation between static and dynamic emission factors in the power grid. The effect is very easily detectable in the mid-day hours in the summer months with the increase in the photovoltaic energy, as well as a general increase in the winter months with aggrandized wind speeds and, thus, an increase in the wind energy. According to the authors, a CO_2-optimized approach with dynamic emission factors is very suitable [4-6].

In their work “Dynamic Prospective Average and Marginal GHG Emission Factors—Scenario-Based method for the German Power System until 2050”, Seckinger and Radgen developed a method to generate an hourly emission factor based on the German power grid. They also outlined the day and night variances in the summertime, as well as the seasonal variability and the advantage in the winter months. Furthermore, they outlined the advantages of these high-resolution analyses [4-7].

Wörner et al. also demonstrated a method for the dynamic electrical emission factor. In their work, they analyzed the effects of a CO_2-emission-optimized control compared to a customary control strategy of the building technology of a residential building with a heat pump. According to their study, this CO_2-optimized operation opened up huge energy- and emission-saving potentials, with these potentials further increasing with bigger buffer storage in the building technology system [4-8].

In 2019, Müller and Wörner presented a second paper: “Impact of dynamic CO_2 emission factors for the public electricity supply on the life-cycle assessment of energy efficient residential buildings”, in which they used the CO_2-optimized control in a thermal building simulation to calculate the emission balance for a residential house with a heat-pump system. They could also detect a deviation within the single-digit percentage range, as the dynamic version performed worse considering the emission balance. This is based on the fact that power consumption mainly takes place in the winter months when there is no PV yield. They further analyzed the system for the years 2030 and 2050, under the assumption of an expansion of renewable energies, which reduces the CO_2 emissions and increases the difference between the static and dynamic approaches [4-9].

Overall, all authors agree on the need for a dynamic, hourly emission factor. Only through this can the real effects and potentials of single-efficiency measures be quantified, and only with this information can the regulation of the load management of the electric power grid be represented correctly. [4-7] These studies only focused on a residential building with a heating system. The authors highlight the necessity of considering further areas of consumption to better evaluate the effects and to differentiate building usages and locations, such as hot-water power consumption, or a cooling system in the summertime [4-9].

4.2 Fundamental Data

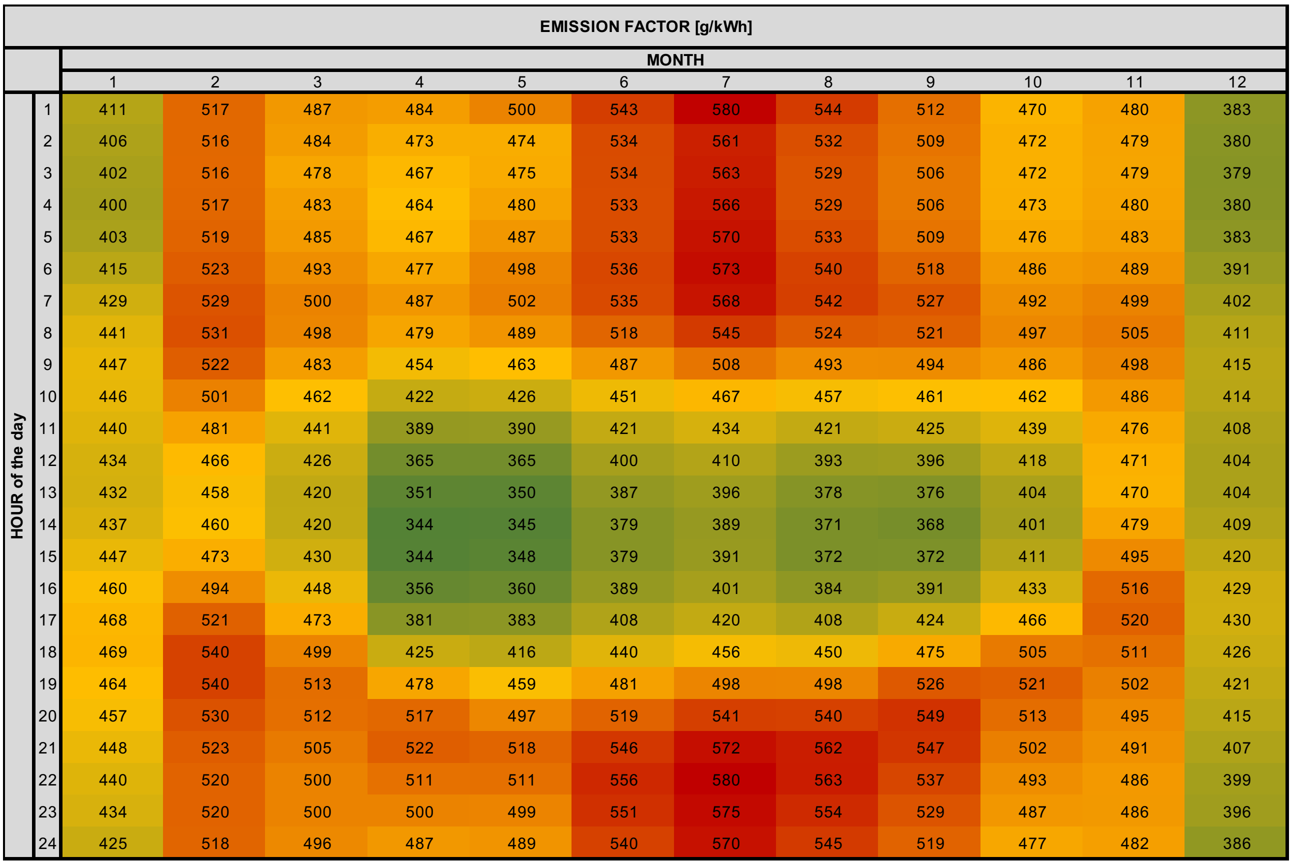
To represent the correct, local metrological and energy circumstances and to connect the data in the right manner, this paper uses the hourly data for the weather and the power grid of the year 2018. In the following, this chapter first describes the weather data, and the data of the electrical power grid, displayed in detail, to generate a general insight for the following analyses.

4.2.1 Weather Data

The weather data have an influence on the performance of a building and its energy balance. As of the year 2018, according to the DWD (Deutscher Wetter Dienst; In Englsch: German Weather Forecast Services), 10.5 °C represents the highest average temperature of the year since data recording started for the location of Munich [4-10]. For the simulation, the weather station closest to the location of the building was chosen. In general, a validation of the weather data was carried out to prevent uncertainties [4-11]. The DWD already provides a validated data set that includes air temperature, dew point temperature, relative humidity, air pressure, atmospheric radiation, horizontal radiation, direct normal radiation, wind velocity, and wind direction.

4.2.2 Power Grid Data

The data set for the dynamic emission factor is provided by the think tank Agora Energiewende. The data set comprises the production capacity, level of consumption, electricity import and export, and the electricity price of the German power grid for the years 2011 to 2020. From these values, the Agora Energiewende calculates an hourly value for an emission factor, as presented in Figure 4-2 [4-12].



		EMISSION FACTOR [g/kWh]											
		MONTH											
		1	2	3	4	5	6	7	8	9	10	11	12
HOUR of the day	1	411	517	487	484	500	543	580	544	512	470	480	383
	2	406	516	484	473	474	534	561	532	509	472	479	380
	3	402	516	478	467	475	534	563	529	506	472	479	379
	4	400	517	483	464	480	533	566	529	506	473	480	380
	5	403	519	485	467	487	533	570	533	509	476	483	383
	6	415	523	493	477	498	536	573	540	518	486	489	391
	7	429	529	500	487	502	535	568	542	527	492	499	402
	8	441	531	498	479	489	518	545	524	521	497	505	411
	9	447	522	483	454	463	487	508	493	494	486	498	415
	10	446	501	462	422	426	451	467	457	461	462	486	414
	11	440	481	441	389	390	421	434	421	425	439	476	408
	12	434	466	426	365	365	400	410	393	396	418	471	404
	13	432	458	420	351	350	387	396	378	376	404	470	404
	14	437	460	420	344	345	379	389	371	368	401	479	409
	15	447	473	430	344	348	379	391	372	372	411	495	420
	16	460	494	448	356	360	389	401	384	391	433	516	429
	17	468	521	473	381	383	408	420	408	424	466	520	430
	18	469	540	499	425	416	440	456	450	475	505	511	426
	19	464	540	513	478	459	481	498	498	526	521	502	421
	20	457	530	512	517	497	519	541	540	549	513	495	415
	21	448	523	505	522	518	546	572	562	547	502	491	407
	22	440	520	500	511	511	556	580	563	537	493	486	399
	23	434	520	500	500	499	551	575	554	529	487	486	396
	24	425	518	496	487	489	540	570	545	519	477	482	386

Figure 4-2: The average value of the emission factor g/kWh for 2018 according to the hours per day and month over the year (own representation, data from [4-12])

The figure illustrates the fundamental daily and seasonal characteristics of the emission factor. In general, the values in the noon times, especially in the summer, are lower than those at night times. Further, in the winter months, particularly December and January, the values are lower over the course of the day. Both characteristics are related to the higher share of renewable energies in the summer with the photovoltaic and in winter with the wind energy.

The second approach used in this paper considers the energy price. For consumers, one of the main motivations to save energy is the costs, and as the energy price is at least partly linked to the emission factor, an economic approach is also targeted. An in-depth look into the data depicts that the electrical energy price on the market varies frequently over the course of a day, while performance remains steady over the course of a year. The energy price not only depends on the related emissions but also considers aspects such as the import, export, and availability of certain energy resources. In general, the overall price contains a variety of fixed shares, which leads to a very low fluctuation.

The different characteristics of the emission factor and the electricity price approaches will be analyzed to save energy and/or CO_2. In addition, a future scenario for 2040, also provided by Agora Energiewende, will evaluate the potential development of these strategies. The individual assumptions are the phase-out of conventional energies, the extension of renewable energies, the increase in the electrical energy demand (E-Mobility, heat pumps, hydrogen production, etc.), and the flexibility in the industrial energy demand. These assumptions are based on the study of 2021: Klimaneutrales Deutschland 2045 (Climate Neutral Germany 2045) [4-12].

According to these boundary conditions, the share of renewable energies increases significantly, which in most cases leads to a significantly lowered emission factor. The daily variation in the emission factor is conspicuous and occurs mostly in summer times.

4.3 Thermal and Radiance Simulation

This chapter outlines the fundamental models and assumptions of the dynamic thermal and radiance simulation. To evaluate the influence of the dynamic emission factor, a thermal and radiance simulation was performed. This chapter describes the principles and the baseline model for this analysis. To calculate the energy demands on an hourly basis, a thermal building simulation was performed. The software used to perform such stationary processes is TRNSYS (Version 18) [4-13]. With its Plug-In TRNLizard for Rhino 7, this software environment provides a modular base for thermal analyses and forms the connection to the Plug-In Ladybug Tools. Within this additional tool kit, further investigations can be performed. The Plug-In HoneyBee focuses on the radiant performance of a building. Based on the hourly solar radiation on a building's PV collectors, the overall solar yield can be determined [4-14].

4.3.1 Thermal Simulation

The inputs for the thermal simulation are the information about the building, the construction details, and the usage, which are used to calculate the energy demand.

To keep the focus of this paper on the dynamic emission factor, the thermal simulation is only described briefly. The north–south-oriented office building for the base case model is located in the city of Munich and is partly supplied with natural and mechanical ventilation. The heat energy is provided by a geothermal heat pump with buffer storage and floor heating to transfer the heat to the rooms. The COPs for the heating, domestic hot water, and ventilation are assumed to be 5.24, 3.30, and 4.20. The office areas with mechanical ventilation are supplied with cooling ceilings using groundwater. The natural ventilation also includes nighttime flushing. Venetian blinds, with an fc-value of 0.2, are included to prevent overheating in the summer period. The shading system is controlled according to the solar radiation.

The usage and device profiles of the rooms are simulated according to the “Raumpilot Grundlagen” [4-15]. The U-values are connected to the German reference values according to the GeG (Gebäudeenergiegesetz; German building energy code) (external wall 0.167 W/(m^{2}K), internal wall 0.556 W/(m^{2}K); roof 0.177 W/(m^{2}K); window 0.923 W/(m^{2}K), floor slab 0.182 W/(m^{2}K)), and the thermal bridges are considered with 0.05 W/(m^{2}K) [4-5]. The heat capacity varies between 50 and 130 Wh/(m^{2}K), which represents a medium-duty de-sign according to DIN 4108-2 [4-16].

Further, the usage of the building determines the internal loads. This includes the internal gains considering people, devices, domestic hot water, and the power for lighting. These assumptions are connected to the reference values of the DIN V 18599 [4-17].

Based on these factors, information zones are formed. These zones interact with the adjacent zones as well as with the outdoors to calculate the annual energy demand. In total, the office building is 1690 m^2. The standard arrangement of the rooms according to Jochen and Loch (illustrated in the following Figure 4-3) is used in all five stories of the building.

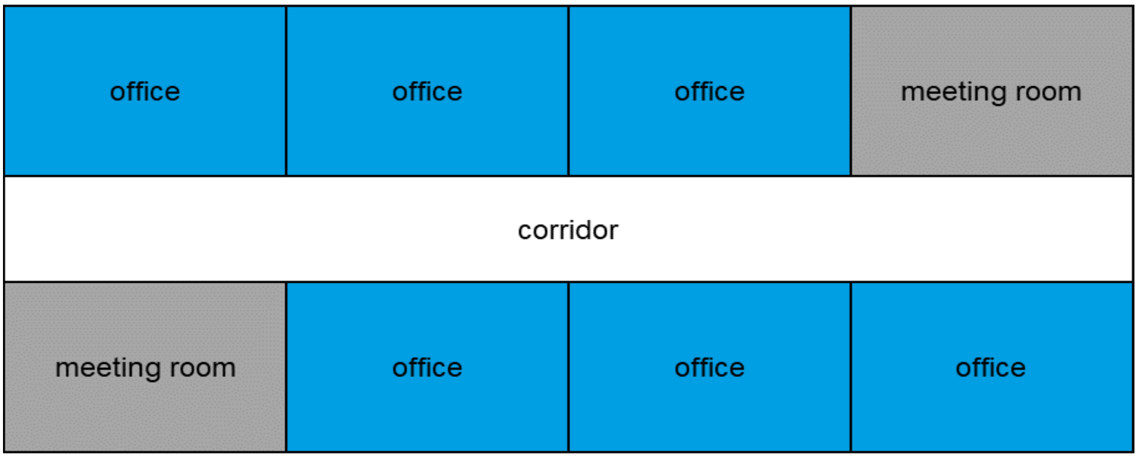


Figure 4-3: Standard ground floor of the office building (own representation, data from [4-15])

The results of the thermal simulation are evaluated according to the energy demand, thermal comfort represented by the specific energy demand in kWh/(m^{2}a), and the operative temperatures of a south-oriented office room. Figure 4-4 illustrates the high energy demand mainly responsible for the north-oriented office rooms. A cooling demand for the variant with active conditioning occurs during the middle of the day during the summer. The nighttime ventilation and the Venetian blinds can cover this cooling demand in the variant with natural ventilation, which, on the downside, causes an increase in the heating demand in the colder seasons.

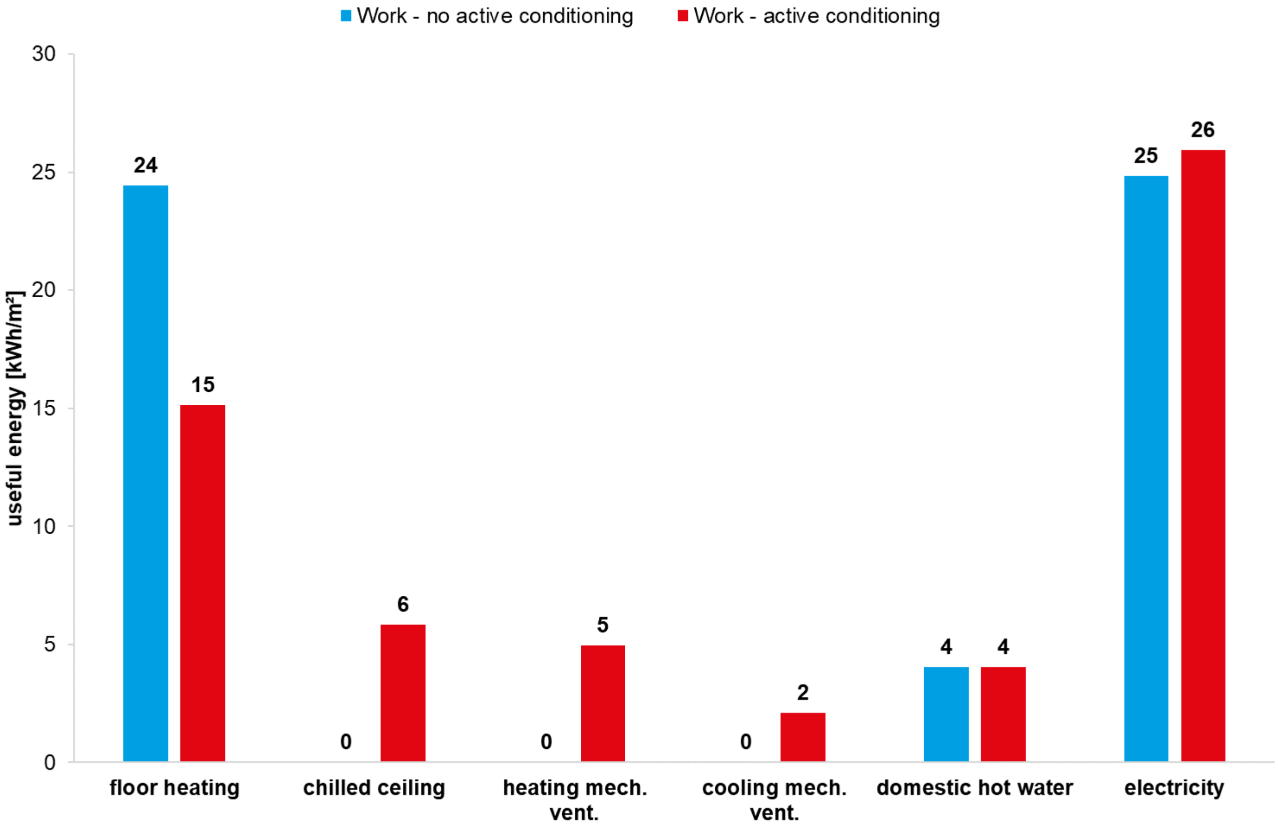


Figure 4-4: Energy demand per m^2 of different areas with (red) and without (blue) active conditioning (own representation)

Subsequently, in Figure 4-5, the operative temperatures of areas with natural ventilation are illustrated. The comfort boundaries of 20 and 26 °C were set based on the DIN EN 16798-1 for the analysis. It should be recognized that there is no cooling energy needed, but especially in the winter times, the ventilation causes below-comfort-temperature hours (own translation, from German: Untertemperaturgradstunden). There are no over-comfort-temperature hours (own translation, from German: Übertemperaturgradstunden) but 79 hours below a comfortable temperature, which is still acceptable according to the norm [4-18].

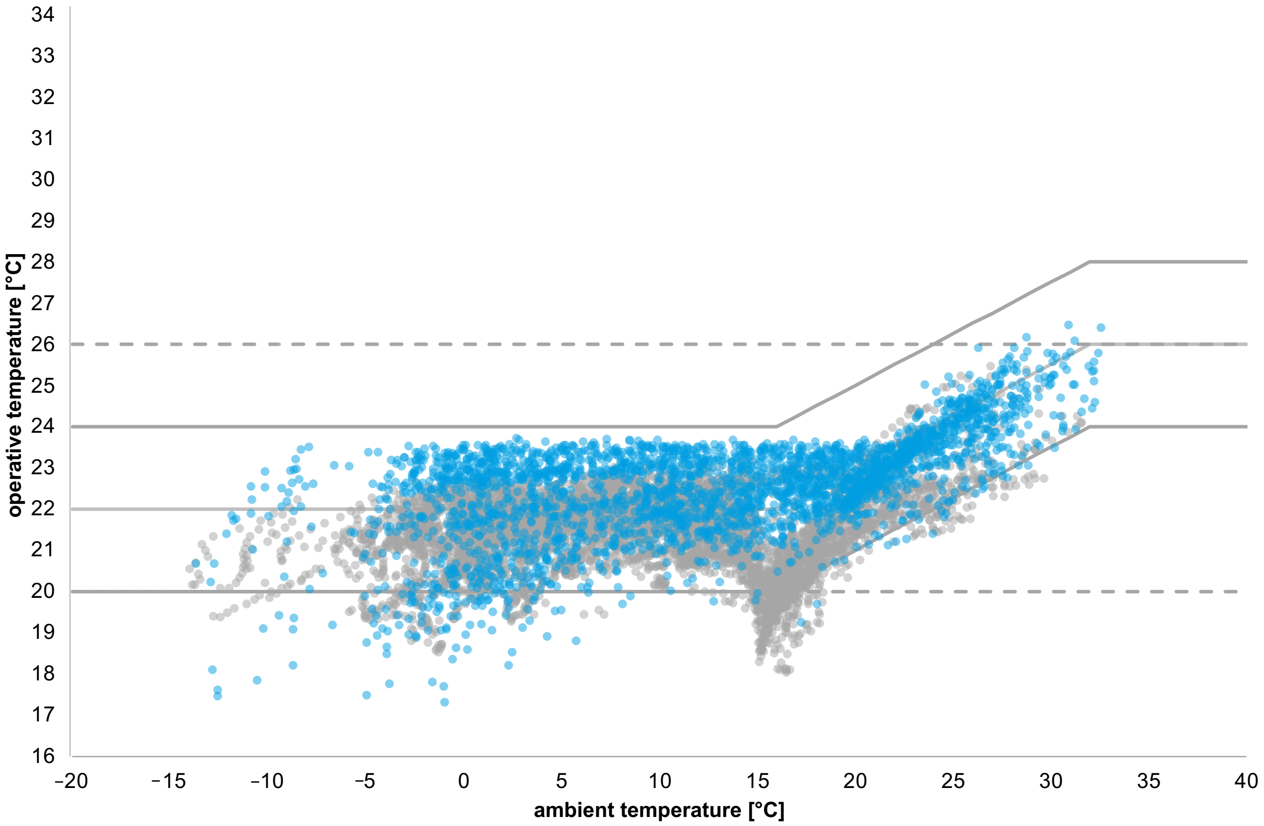


Figure 4-5: Annual operative temperature over the outdoor temperature without active conditioning during occupancy (blue) and all year (grey) (own representation)

4.3.2 Radiance Simulation

Besides the local weather data, the software Plug-In HoneyBee for Rhino 7 needs a couple of further inputs to calculate the solar yield. To increase the solar collection, the solar panels on the flat roof are oriented east and west, with a tilt of 12.5° to avoid the self-shading of the modules. This orientation collects more sunlight in the morning and evening hours and increases the share of the usage of electricity. The distance to the fascia is set to 0.5 m, where the distance between the models amounts to 0.3 m. This adds up to a total area of 214 m^2 of solar panels.

To calculate the solar yield, a detailed model according to Heydenreich et al. (2008) was used. His concept considers the fluctuation of the solar panel temperature and the solar radiation to calculate an hourly coefficient of performance [4-19]. The efficiency of the panel and the increase in the power of the system can be calculated as represented in the following equations. The individual parameters of the equations are selected according to the implemented system components:

$$\eta_{\mathrm{mod},25} = a \cdot G_{\mathrm{mod}} + b \cdot \ln(G_{\mathrm{mod}} + 1) + c \cdot \frac{\ln^2(G_{\mathrm{mod}} + e)}{(G_{\mathrm{mod}} + 1) - 1} \tag{4-1}$$

$$\eta_{\mathrm{mod}} = \eta_{\mathrm{mod},25} \cdot (1 + \gamma \cdot (T_{\mathrm{mod}} - 25)) \tag{4-2}$$

$$P_{\mathrm{mod}} = G_{\mathrm{mod}} \cdot A_{\mathrm{mod}} \cdot \eta_{\mathrm{mod}} \cdot \eta_{\mathrm{WR}} \cdot \eta_{\mathrm{MM}} \cdot \eta_{\mathrm{K}} \cdot \eta_{\mathrm{s}} \tag{4-3}$$

Via Microsoft Excel and the programming language Python, these equations are implemented into the software to calculate the solar yield. The solar yield of the whole system amounts to 29 kWh/m^2 which adds up to 49 MWh per year. With a closer look at the data, the seasonality of the photovoltaic system can be observed.

4.4 System Model Simulation

Inputs flowing into the building system model are the results of the thermal and radiance simulation, as well as the emission data. The main output is the emission balance considering various storage models. The balance boundary for these analyses is the operation of the building. Explicitly excluded in this paper are all the phases of the process connected to the production, transportation, and disposal of the components. The main goal is to evaluate the dynamic emission factor, taking various system setups and load-control strategies into account. The following sections of this chapter outline the fundamentals concerning the storage models, the system configurations, the evaluation indicators, and the load-control strategies.

4.4.1 Storage Models

The building system model displays thermal (heating and hot water) and electrical battery storage. This means there has to be enough charging capacity within the storage. or else, in the case of empty storage, additional energy charging occurs (e.g., using a heat pump). The fundamental parameters and variables for the model are storage capacity, rated charging capacity, unloading capacity, control strategy for charging, limit temperature for charging, storage losses, and storage efficiency. The discharging capacity is equivalent to the simulated energy demand of the building simulation without losses of transportation (e.g., cables or ducts). The general outputs of the storage model are the reservoir storage level, the loading capacity, and the auxiliary power. The system configurations, including photovoltaic systems with battery storage, supplement the inputs with the PV productions. The additional outputs are the PV effective output and the rest of the PV effective output. In general, the electrical power of the PV system is used to load the storage. The thermal storage in that case uses the heat pump to charge up. The next section outlines the system configurations in detail.

4.4.2 System Configurations

This paper analyses four system configurations. The system configurations represent state-of-the-art system configurations to transfer, store, and reuse photovoltaic energy and can be implemented in various building configurations or usages:

- SC1: Thermal storage
- SC2: Thermal storage + battery storage
- SC3: Thermal storage + PV
- SC4: Thermal storage + battery storage + PV

The thermal storage is divided into two storage areas for heating and hot water. The battery storage provides energy for the user electricity requirements and the power for the circulation pump and the heat pump. The capacity of the thermal storage is designed for a 1-day period. According to the day with the highest energy demand, this leads to a capacity of 550 kWh for heating and 25 kWh for hot water storage. The capacity for the battery is 90 kWh, following Weniger et al. who showed that, above 2 kWh capacity per kWp, the level of self-sufficiency does not rise anymore [4-20].

SC1: In the basic system configuration, two thermal storage areas are loaded according to the simulated energy demands. The grid fully covers the electrical energy.

SC2: The second variant operates identically except for the battery storage areas. This capacity is used to buffer the electrical energy demand.

SC3: In the third scenario, power from the installed PV system is integrated into the system. Whenever possible, the PV power is used for direct usage (user electricity and electricity for the pumps and the heat pump). Beyond that, the storage for heating is utilized and the storage for hot water is filled. Only after those steps is the surplus power fed into the grid.

SC4: The last system configuration is similar to SC3 besides the integration of battery storage. The usage is prioritized as follows:

1. Direct electrical usage
2. Feeding into heating storage
3. Feeding into hot water storage
4. Feeding into battery storage
5. Feeding into the electrical grid

4.4.3 Indicators

To evaluate the balance of the various system configurations, the emission in kg CO_2, the cost for electricity in EUR, and the network load in kWh are used as indicators. This section outlines the general calculation processes of the individual indicators. Exceeding the focus of this paper, the detailed calculation processes are not displayed.

The emissions are summed up over the year according to the energy demand and the corresponding emission factor. With a PV system, a specific CO_2 credit is calculated for the surplus power, which is fed into the grid. To evaluate the effect of the dynamic calculation, the static and dynamic calculation process is presented in the following equations.

$$\mathrm{E_{dyn}} = \sum_{\mathrm{t}=1}^{8760} \left(\mathrm{p_{net}(t)} \cdot \frac{\mathrm{ef(t)}}{1000} \right) \tag{4-2}$$

$$\mathrm{E_{stat}} = \sum_{\mathrm{t}=1}^{8760} \mathrm{p_{net}(t)} \cdot \frac{\mathrm{EF}}{1000} \tag{4-3}$$

The costs for electricity are identified according to the domestic electricity price. Within this value, the trading price only holds a small share, which leads to no notable difference between a static or dynamic calculation. A credit for the integrated electricity is calculated but not displayed in the following equation:

$$\mathrm{C} = \sum_{\mathrm{t}=1}^{8760} \left(\mathrm{p_{net}(t)} \cdot \frac{\mathrm{sp(t)}}{100} \right) \tag{4-4}$$

Besides the emission factor and the domestic energy price, the data of Agora Energiewende also provides the consumption and the production within the grid. Their ratio represents the self-defined indicator net load. The data display a surplus of energy in the early morning and late evening hours in the summer period. In the winter months, no correlation between the emission factor and the net load can be seen. The following equation represents the calculation process for the net load:

$$\mathrm{NB} = \sum_{\mathrm{t}=1}^{8760} (\mathrm{p_{net}(t)} \cdot \ \mathrm{nb(t)}) \tag{4-5}$$

4.4.4 Load Control Strategies

The load control strategy defines the points in time when to fill up the storage. This paper analyses four different control strategies that can be divided into two categories and thereby address either the energy price or the emission factor. The first category comprises a simple, constant period control strategy, whereas the second category uses a predictive method to determine the minimum of a parameter. In this paper, the parameter is represented by the energy price or the emission factor:

- Energy price simple (EPs)
- Energy price predictive (EPp)
- Emission factor simple (EFs)
- Emission factor predictive (EFp)

The simple control strategies found in the previously outlined data analyses. Thereby daily constant load periods are defined to make use of the low periods of the energy price and the emission factor. For the energy price, this results in a 6 h loading period between 00:00 and 06:00 a.m. when the trading energy prices are low. Considering the emission factor for the simple control strategy, the loading periods shift to 10:00 a.m. to 04:00 p.m. to use the PV energy production during the daytime.

The predictive control strategy in that sense does not represent a real, data-driven prediction. It uses the annual net data and searches for a minimum within the next 24 h at each time step. Based on this process, a 5 h loading period is then implemented to fill up the storage. This concept uses the data to define the minima for the energy price as well as for the emission factor.

Figure 4-6 illustrates the overall annual CO_2 emissions of the four control strategies in comparison to the average baseline, indicating the potential of the emission-based control strategies. The black dots represent the overall, annual energy price, where the energy-price-optimized controls consequently show the lowest values.

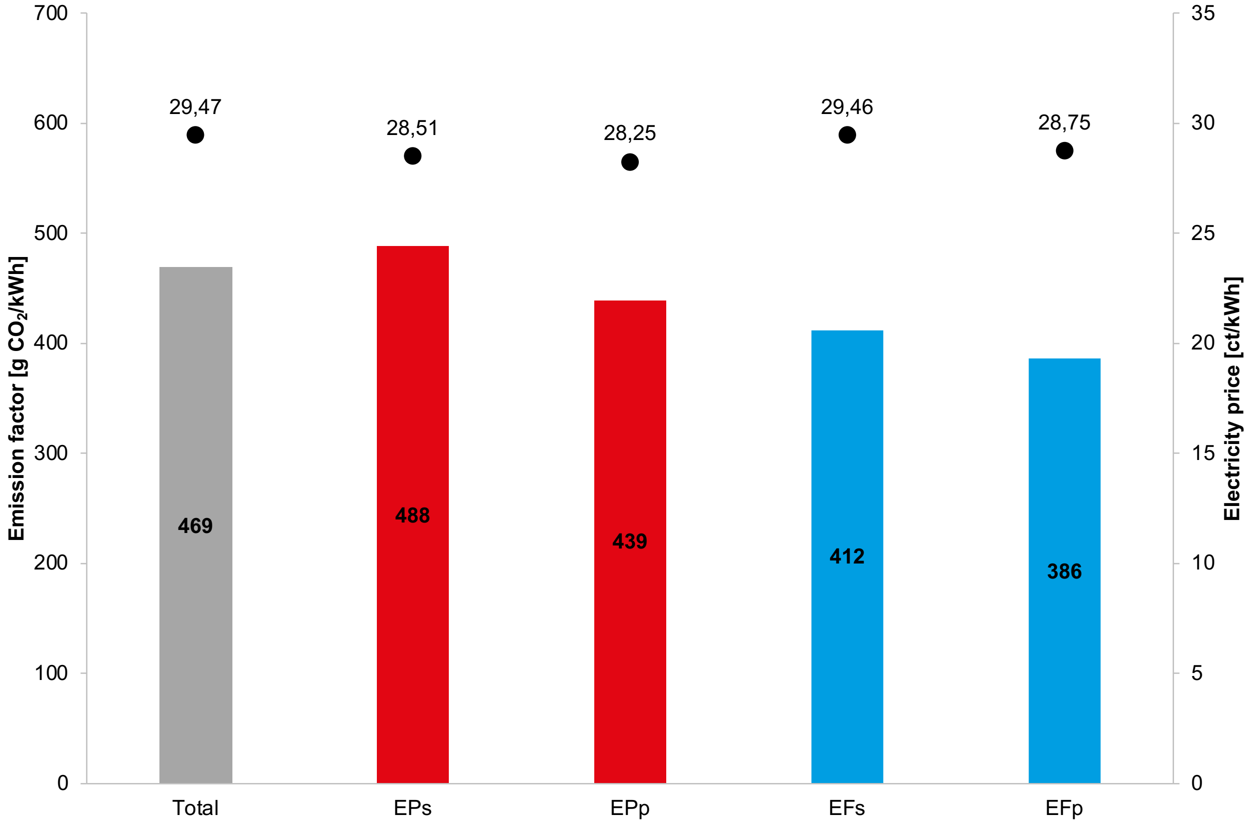


Figure 4-6: Annual CO_2 emissions (red EP and blue EF) and energy price (black dot) for all control strategies compared with average (grey) (own representation)

4.5 Results and Evaluation

This chapter presents the results and their evaluation. The following sections outline the individual research questions and evaluate the results.

4.5.2 Difference in CO_2 balance between dynamic and static calculation

The following results are based on the load control strategy EPs, taking the energy price into account. The disparities between the four load strategies are addressed by the next research question. Figure 4-7 shows a variety of data addressing the CO_2 emissions on the y-axis and the different system configurations for an office building with natural and mechanical ventilation, calculated with a dynamic and static emission factor. It further shows the differences between the two calculation approaches. If the energy source is a heat pump, the emissions are mainly influenced by the user power demand. If there is no battery (SC1), a significant difference between the static and dynamic approach can be observed. For both variants—with and without mechanical heating—the emissions for the dynamic approach are lower because the main electrical demand occurs around noon. Furthermore, it can be seen that the emissions increase when implementing a battery storage. This is mainly caused by the energy-price-oriented control strategies, besides the general storage losses. Integrating a PV system reduces overall emissions significantly. This is due to the efficient usage of PV electricity (SC3 and SC4), as well as the electricity for the heat pump. However, again, the overall static emissions are lower based on the credit note in the calculation process.

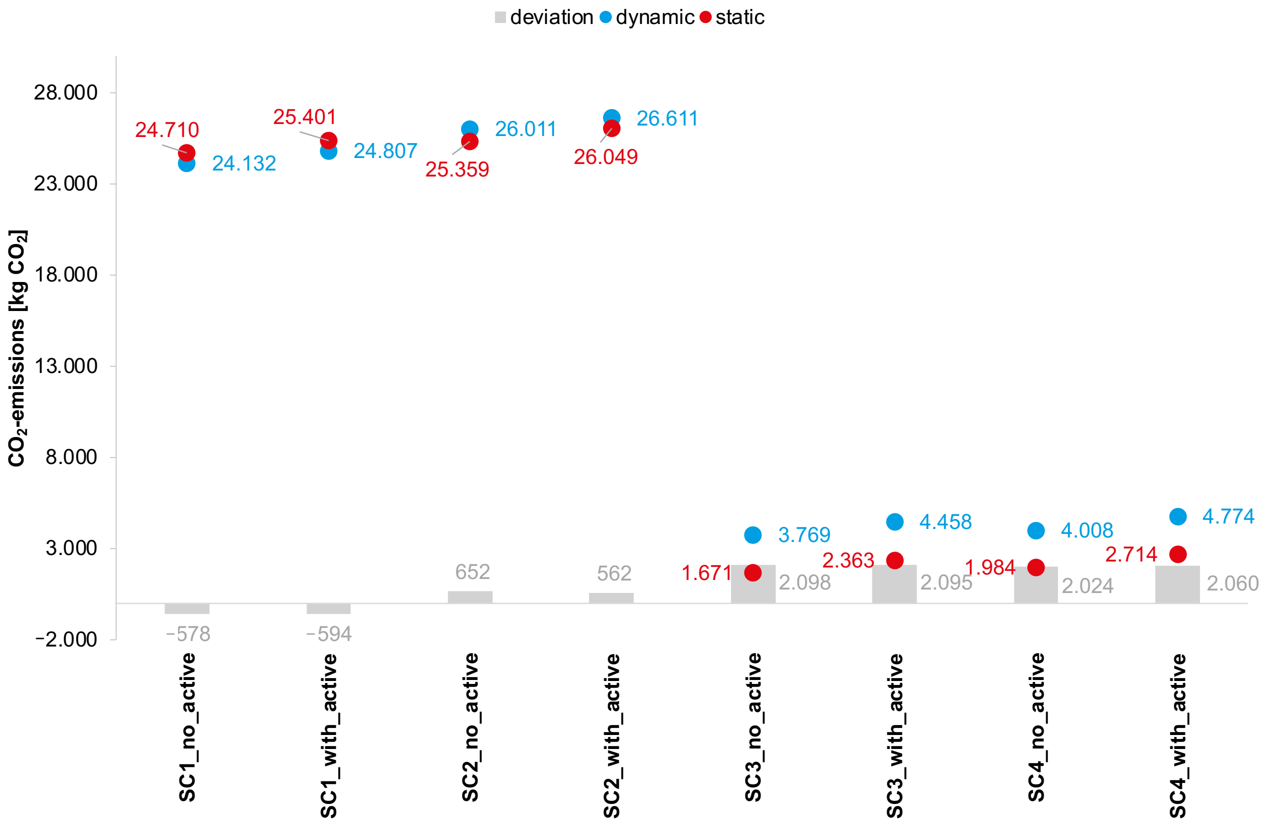


Figure 4-7: Overall annual CO_2 emissions in kg for SC1 to SC4 with and without active conditioning for the static (red) and dynamic (blue) calculation approach and the deviation (grey) (own representation)

In a heat-pump-based building configuration, the user's electricity dominates the overall consumption. With no storage or too-small storage, the emissions are mainly dependent on the user's electricity demand. The answer to the question presented initially can be divided into two. With a non-emission-optimized control strategy and without a PV system, the difference between a dynamic and static approach is negligible. With a PV system, significant differences can be identified. This again leads back to the credit effect of the calculation method. Going beyond the focus of the analyses, the following sections will only present the simulation results with mechanical ventilation, as both variants produce similar results, as confirmed in the first research question.

4.5.2 Potential of an emission-optimized load control

This section answers the previous research question. All storage load strategies, as well as all three indicators, were used for the analyses. Based on the huge number of variants and data, not all the results are visualized in this paper.

To evaluate the emissions, Figure 4-8 displays the percentage deviation between the individual variants and the previously outlined results, considering the simple energy price approach. This deviation is outlined for all four control strategies of the mechanical ventilation system.

All system configurations result in a reduction in emissions based on the advanced load periods. In the case of the SC1 the reductions are minor (max. 3.5%). In this case, only the thermal storage uses the optimized approach. The system configurations with battery storage show large saving potentials, especially with an emission-optimized control, which is due to the high share of user electricity demand. This is true for both variants (EFs ~ 8% and EFp ~ 11%), with or without mechanical ventilation, while Figure 4-8 only illustrates the variants with active conditioning.

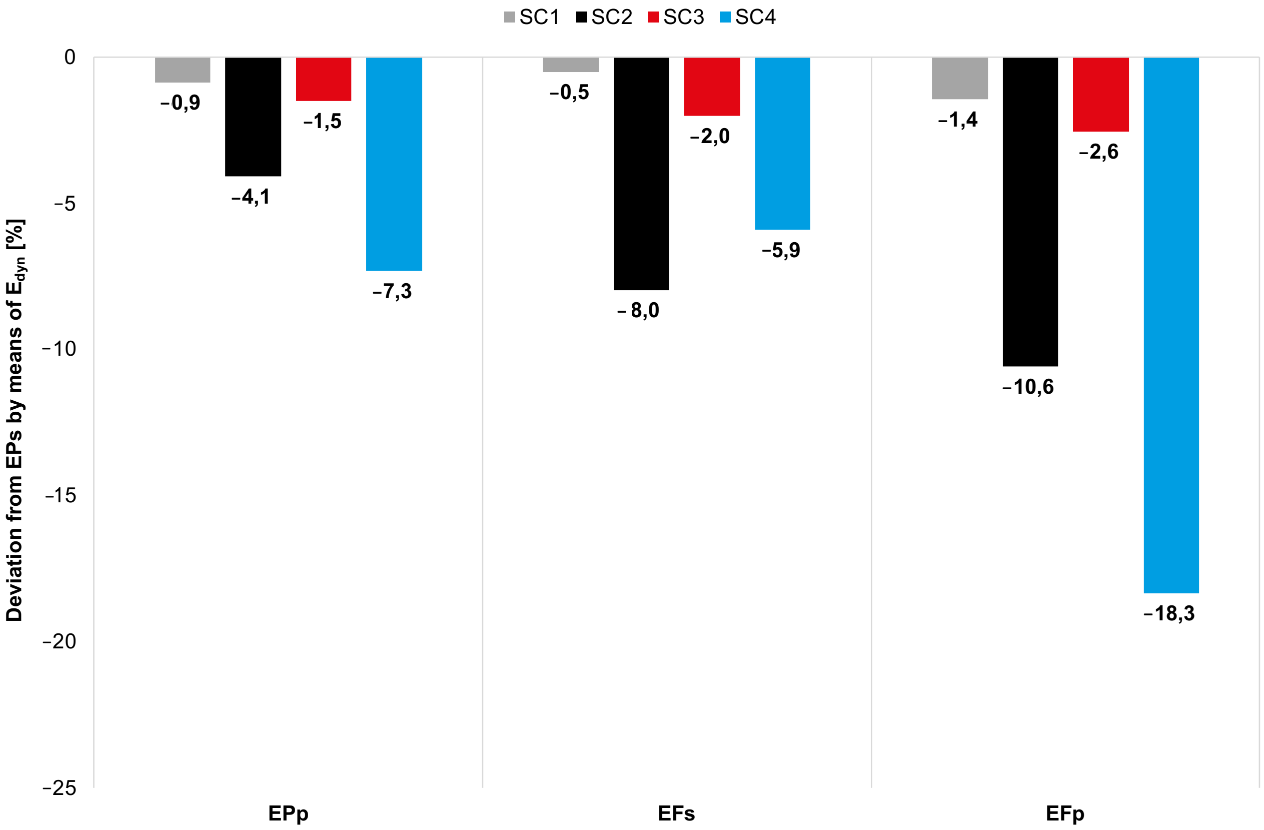


Figure 4-8: The deviation between the individual variants and the simple energy price approach as a percentage for SC1 to SC4 (own representation)

In general, the predictive energy price approach also shows emission reductions, caused by the energy price being partly connected to the availability of renewable energies. Considering SC4, EFs show lower savings and the potential of two predictive approaches increases. This is because of the seasonality factor. In the summer periods, with a high, constant onset of low emission phases, the simple control strategy can perform very well, whereas the predictive control strategies also anticipate the low emission phases in an inconstant occurrence, e.g., in the winter months.

Besides the comparison of the emissions of the various control strategies for all variants, the difference between the static and dynamic approaches is calculated. The data show that for the emission-optimized approach, the characteristics change. The differences increase, and for a system with battery storage, the emissions decrease. The opposite effect takes place when a PV system is implemented. Here, from the variants EPs to EFp, the deviation between the two approaches decreases due to the disadvantage of the credit effect in the calculation process.

The differences in the overall energy costs are minor. This is also explained by the small share of the dynamic price in the domestic energy prices. Only the variants with battery storage show minor deviations. With SC1 and SC2, the energy prices are the highest with the EFp load strategy. This is based on the fact that in summer and winter times, the energy prices are lower at night that are not considered with an emission-optimized control. This is not the case with SC3 and SC4 where the energy prices of EFp are similar to the EPp approach. With the EPp variant, the storage is filled at night at low prices, but then the solar energy is not used during the day as much as with the EFp approach.

Even lower than the differences in the energy price are differences considering the net load. The authors cannot determine a real trend. Based on an overlap of different effects and rebound effects, there is no tendency concerning which system configuration or which load strategy performs best. The fourth research question addresses the topic of the net load where a future electricity net exhibits other supply and demand characteristics.

The answer to the second question is that emission-optimized controls create significant emission savings when combined with battery storage and in fluctuating periods. The simple control strategy already shows good emission-saving potentials in the summer periods, and the predictive control strategies do not increase these savings significantly. In the winter and shoulder seasons, the predictive control strategy notably outperforms the simple ones.

4.5.3 Influence of an increased storage capacity

To evaluate this effect, an additional variant with an increased storage capacity is outlined. The capacity of the thermal storage is raised to 2-day storage, and further, the capacity of the battery is doubled. To use the full potential, the load capacity is also doubled, and the period of prediction is set to two days. This section answers the research question only considering the emissions, as the fundamental findings of the two previous research questions remain the same.

The additional storage variant for the simple load strategy does not show significant differences. The differences between the static and dynamic approach for the simple load strategies show only marginal differences in comparison to the basic approach with smaller storage capacities (differences smaller than 1%).

If we compare the averages of the emissions with the initial approach, the results for the simple control strategies can be confirmed (Eps from 488 to 483 g CO_2/kWh and EFs from 412 to 414 g CO_2/kWh). In contrast, the emissions of the predictive control strategies differ by up to 40 g CO_2/kWh for EPp from 439 to 403 g CO_2/kWh and for EFp from 386 to 354 g CO_2/kWh. This already outlines the fundamental potential of this approach. A consequence is the deviation between the static and dynamic approach between the smaller and larger storage capacity. Figure 4-9 outlines these differences for SC2 and SC4 with a thermal and an electrical storage and an option PV system. System variant 1 (_SV1) represents the approach with the bigger capacity.

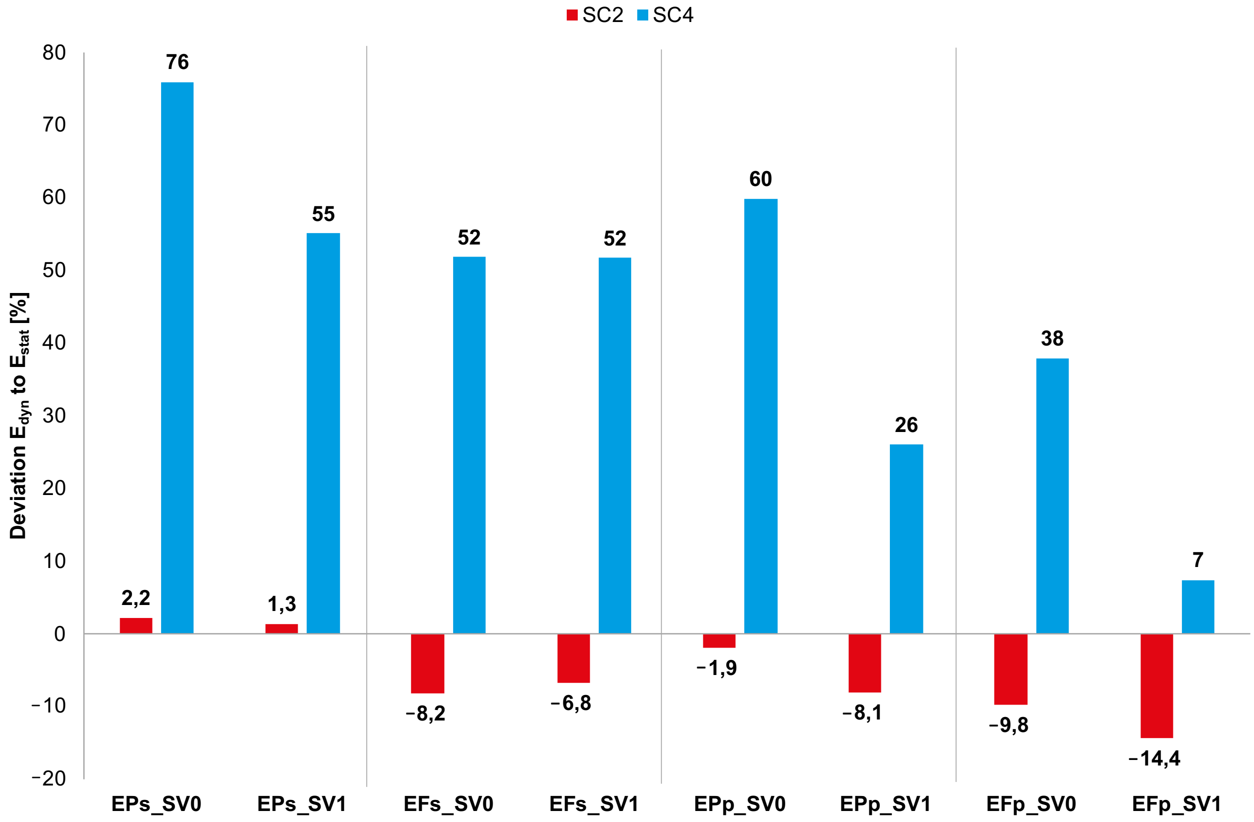


Figure 4-9: Deviation between the static and dynamic approach for SC2 (red) and SC4 (blue) for all control strategies in comparison with a 2-day storage capacity (_SV1) (own representation)

The answer to the third research question can be answered in two parts. First, the change in the storage characteristics only shows marginal effects on the emission balance using a simple load strategy. Secondly, there is a substantial impact on the energy balance when choosing a bigger storage capacity and a predictive load strategy. With extended loading periods, more advantageous load times can be used, which results in lower emissions.

4.5.4 Impact of the dynamic emission calculation for the transformation of the German electricity grid

To evaluate the impact on the German electricity grid, a future scenario is analyzed that takes future electricity data into account. Thereby, only the effects on the emissions and the net load are analyzed, as a prediction of the future energy prices would be very imprecise.

The future scenario considers a huge expansion in the PV and wind energy that leads to a major reduction in the emission factor. Overall, the average emission of 2018 will be reduced from 469 to 62 g CO_2/kWh in 2040. Within a 48 h prediction period, and in the future electricity grid, multiple minima often exist. To use these periods effectively, the concept of the centered moving average was applied. The detection of the minimum based on this concept, according to a self-defined threshold, was set to 50 g CO_2/kWh. If the value of the considered period is higher than the threshold, the minimum is the center of the period. If the value is smaller than the threshold, the minima is set to noon.

The high reduction potential based on the lower emission factors is also represented in the deviation between the static and the dynamic approach. All deviations for all sys-tem configurations are bigger. Figure 4-10 shows the difference between the static and the dynamic approach for the simple and predictive emission factor approach for SC1 to SC4. In SC1 and SC2, the simple approach shows slightly smaller negative deviations. For SC3, the deviations are bigger, whereas in SC4, the simple approach shows smaller differences. This leads back to the storage characteristics of the system and, with bigger storage, the advantages of the predictive approach would show these potentials (results not presented in this paper).

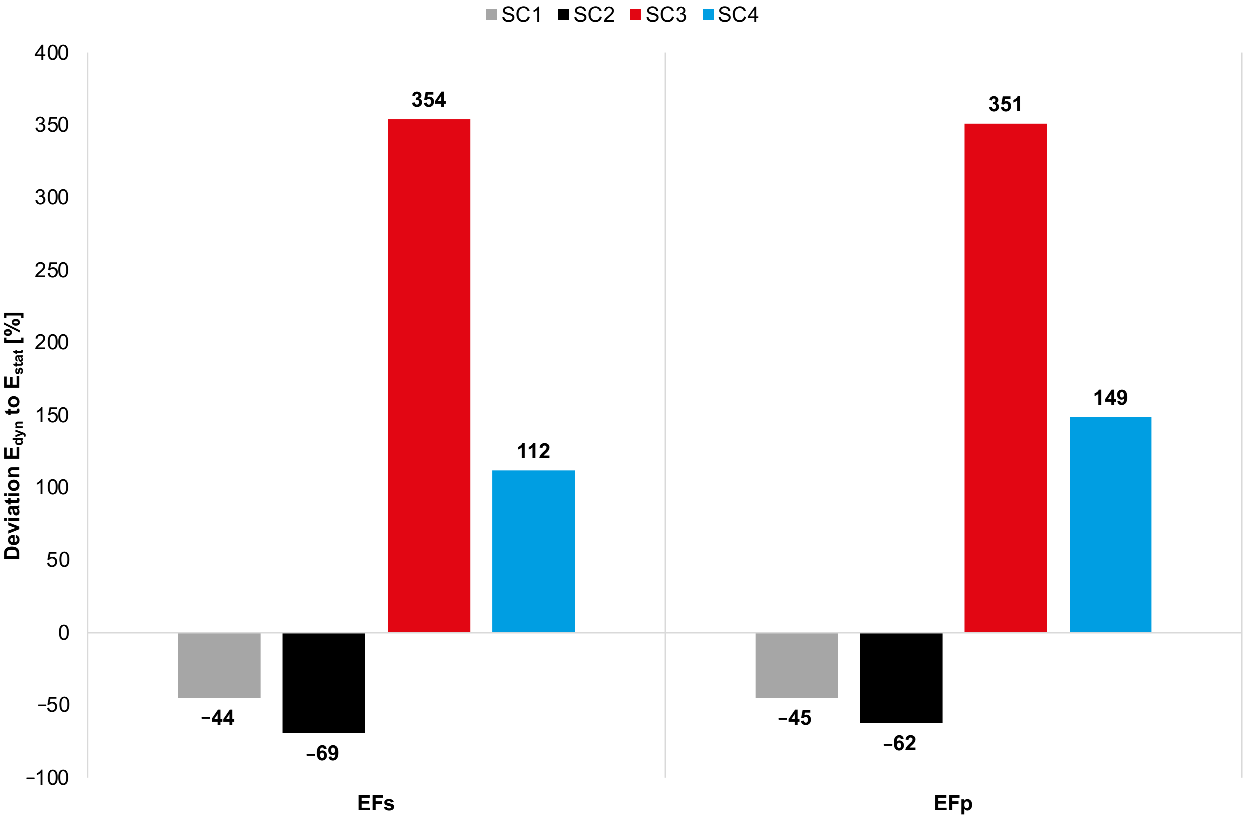


Figure 4-10: Deviation between the static and dynamic approach for SC1 to SC4 for the year 2040 for the emission-optimized control strategies EFs and EFp (own representation)

Even more so than with the emission balance, the net load mainly depends on the PV characteristics of the grid. The net load is defined as the ratio between consumption and production within the net. Overall, with predictive control in 2040, the net load is reduced by 18% in comparison to the average control, where this reduction in 2018 amounts to just 4%. The differences in the net load between the two predictive control strategies are marginal.

The answer to the fourth research question is divided into the impact on the emissions and the net load. In a future electricity grid with more renewable energies, an emission-factor-based control can result in bigger savings. This is due to the huge daily fluctuation. It also results in bigger deviations between the static and dynamic approach for system configurations with PV. Already, simple-emission-based control strategies create emission savings in the summer period. To use the winter periods efficiently, predictive control is more suitable. Based on the dominance of PV in the future scenario, the indicator net load correlates with the emission-optimized controls. The differences between the individual control strategies are minor. Based on these findings, the authors suggest further research be performed focusing on a net-load-optimized control.

4.6 Discussion

The following provides a summarizing discussion of the most relevant outcomes of this study. The authors outline the main findings of the research questions and reprise the hypothesis. This chapter is divided into sections dealing with the localization, utilization, and transformation of the potentials of the dynamic emission factor. Finally, the limitations of this paper are outlined before giving an outlook.

The results of this paper attest to the statements of the hypothesis. The outcomes of the individual research questions prove this assertion. The potentials of the hourly dynamic emission factor are classified in the next three sections.

4.6.1 Location of the Potentials

Nowadays, emission factors play a key role in the evaluation of the sustainability of buildings. As of now and for reasons of convenience, only a static emission factor is considered for the energy balance. For certain system configurations, this can deliver comparable results to a dynamic approach. This is not the case for building systems with a PV system, a distinct storage system, or fluctuating user demands and emission factors. A PV system leads to higher overall balances, as the dynamic credit system is significantly smaller than the constant static one. Storage systems, especially with a heat pump or battery storage in combination with intelligent control strategies, open up huge potential to shift loads. In general, in an office environment, with or without mechanical ventilation, the dynamic approach can lead to emission savings due to the demand concentration in the midday hours.

4.6.2 Utilization of the Potential

Using a predictive control strategy with storage systems creates significant emission savings. In the summer periods, simple load strategies already generate good results. In winter times, with fluctuating and irregular low-emission periods, predictive control strategies outperform simple ones. The increasing seasonality in renewable productions, as well as the increasing fluctuating demands also in future scenarios, demands predictive control strategies to lower emissions in the best possible way.

This demand for predictive control strategies is also represented when extending the shifting periods with bigger storage systems. The results of this paper show that bigger storage systems only perform suitably with an emission-optimized predictive control strategy that leads to further emission savings.

4.6.3 Transformation of the Potential

The forecast scenario data of Agora Energiewende for the German electricity grid predicts a substantial increase in renewable energy, especially in photovoltaics. This leads to a general deviation between the static and dynamic approaches for all the system configurations. Furthermore, the emission savings due to the predictive control strategies and the increased storage systems go hand in hand with the demand concentration in the winter periods. In future summer periods, these advanced control strategies and the bigger storage do not result in a surplus of emission savings, as there are daily long periods of low emissions. In a future emission-neutral electricity grid, this rather demands an effective way to handle the topic of the net load.

4.6.4 Limitations

The characteristic data of the emission factor only correlate partially with the real energy price and the net load of Germany's electricity grid, and thus no full conclusions can be drawn. This further leads to the fact that the simulation variants with the lowest emissions are not necessarily linked to the lowest costs.

As outlined previously, the balance boundaries of this paper comprise the operation of a building. This means that this paper only outlines statements regarding various system configurations and does not evaluate the overall emission balance of a building. The findings of this paper only present tendencies when comparing the operation of different building technology systems.

Furthermore, the results are presumed with an efficient groundwater heat pump that uses electricity as the main energy source. Indeed, these systems are trendsetting but the outcomes of this paper are not necessarily applicable to other building technology systems.

The indicator net load in this paper only covers the ratio between net consumption and net production. With the increase in the fluctuation and the low-emission phases, the topic of timing the demand and supply is becoming essential but was not considered in this paper.

4.7 Conclusion

The complex topic of this paper results in a variety of assumptions and limitations that give rise to a multitude of further research topics. As the results present a promising outlook overall, the topic of a dynamic emission factor should be included in the process of thermal simulation in general, to evaluate the emission balance more precisely. This leads back to the previously mentioned topic of a holistic emission balance beyond the building operation and the impact of the dynamic emission factor. This also comprises the building technology components of, e.g., a heat pump, storage, or a PV system, and should be evaluated for the whole life cycle of a building.

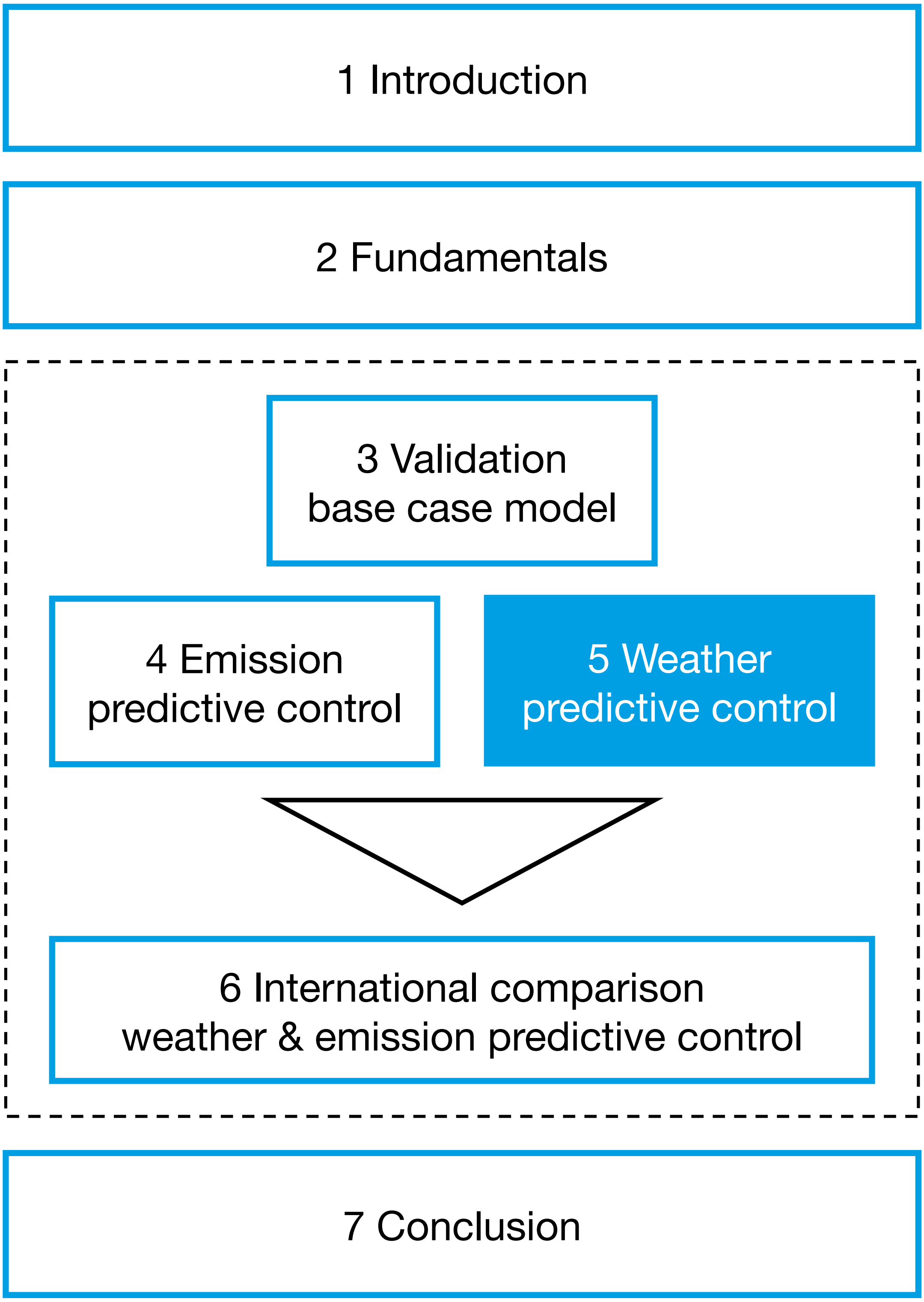
To better represent the seasonality of the demand side, the daily profiles of the devices and the user should also vary over the course of the year. This would extend the fluctuation on the demand side and could increase the need for intelligent control strategies to balance the electricity grid.

The electrical energy generated by the photovoltaic system in this paper is directly transferred into the grid when no local consumers are available. In the case of battery storage, the concept of the immediate supply could be rethought to optimize the concept of a credit note.

This paper focuses on the German net and the location of Munich. Further research should include other national and international locations with different electricity grids and weather conditions. With these analyses, the concept of a dynamic emission factor could be brought in a broader discussion.

The practical significances of this paper is twofold. First, it shows that the general concept of analyze an emission balance needs to be revaluated, and a dynamic emission factor should be mandatory for such analyses. Secondly, the developed control strategy should be used and implemented in existing buildings to reduce their emissions.

The results of this paper are based on a variety of assumptions, taking into account building characteristics, especially user and device profiles, as constant. These assumptions are based on conventional norms and codes, especially for lighting, heating, and ventilation. A broader view, such as the predictive control of these variables with the focus on energy efficiency and thermal comfort, could result in new possibilities. This has al-ready been shown in initial research approaches using the building mass and its inert technology itself as energy storage with a further research approach looking into trans-forming buildings into short-term emission storage.


1 Introduction
2 Fundamentals
3 Validation base case model
4 Emission predictive control
5 Weather predictive control
6 International comparison weather & emission predictive control
7 Conclusion

5 Impact of a weather predictive control strategy for inert building technology on thermal comfort and energy demand

Summary

The sun's total radiation alone exceeds the world population's entire energy consumption by 7.500 times and ignites secondary renewable energy sources. The end energy consumption buildings use for heating amounts to 28% of Germany's total energy consumption. With the ongoing trend of digitalization and the transition of the German energy supply away from fossil fuels and the consequent political dependency, electric heat pumps and photovoltaic (PV) systems have become increasingly important to the discussion. This has led to an increasing demand for smart control strategies, especially for inert systems such as thermally activated building systems (TABS). This paper presents and analyses a weather predictive control (WPC) strategy using a validated thermodynamic simulation model. The literature review of this paper outlines that the current common control strategies are data-intensive and complex in their implementation into the built environment. The simple approach of the WPC uses future ambient temperature and solar radiation to optimize the control of the heating, cooling, ventilation, and sun protection system. The thermal comfort and energy demand evaluate the concept. We show that with a WPC for TABS, thermal comfort can improve without increasing the energy demand for the office building in the moderate climate of Munich. Furthermore, this paper concludes that the WPC works more effectively with more thermal mass. This simplified building control strategy promotes the European roadmap goal of climate neutrality in 2050, as it bridges the phenomenon of the performance gap.

Author Contributions

Conceptualization, C.H., L.O., S.C.K., M.G., D.B. and T.A.; methodology, C.H. and L.O.; software, C.H., L.O. and D.B.; validation, C.H., L.O., M.G. and D.B.; formal analysis, C.H., S.C.K., M.G. and D.B.; investigation, C.H., L.O., S.C.K., M.G. and D.B.; resources, C.H., L.O., S.C.K., M.G., D.B. and T.A.; data curation, C.H. and L.O.; writing—original draft preparation, C.H., writing—review and editing, C.H., L.O., S.C.K., M.G. and D.B.; visualization, C.H., L.O., S.C.K., M.G. and D.B., supervision, T.A.; project administration, C.H.

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5.1 Introduction

Significant changes are required to meet the EU's 2050 climate goals, as the building sector globally accounts for over 40% of energy-related carbon emissions and more than one third of energy consumption throughout the construction and operational phases [5-1]. The new climate protection law, which came into effect in August 2021, increased the targets for climate protection in Germany. The law aims to attain carbon neutrality by 2045 [5-2]. By 2030, greenhouse gas emissions from the building sector must be 67% lower than they were in 1990. The building sector should therefore emit no more than 72 million tons of CO_2 annually by that time [5-2]. To accomplish this, buildings must undergo energetic renovations [5-3], which are subsidized by the Federal Government of Germany [5-2]. In addition to the need for renovation of the building envelope [5-4&5-5] and the exchange of oil and gas heating systems, intelligent predictive control strategies for building technology show great potential in terms of energy savings and comfort enhancement [5-6]. When paired with weather forecast data, model predictive control (MPC) strategies using state-of-the-art or newly introduced artificial neural networks (ANN) can reduce the energy demand while ensuring thermal comfort [5-7&5-8]. Both are promising approaches, but they have drawbacks such as the need for sophisticated control software or even digital twins of the buildings, which limits their applicability to high-tech building technology. Nevertheless, these control strategies are optimized to the building's location and offer a promising approach to reducing energy use and increasing thermal comfort, particularly when implementation is decentralized [5-9]. Moreover, buildings can be converted into thermal storage for load management using predictive control strategies, which can then be used to offset fluctuations in the electrical energy grid [5-7&5-8, 5-10–12]. Focusing on inert buildings and their technology, this paper proposes a trade-off between an optimized, intelligent, yet fairly simple approach for universal applicability.

This paper begins by outlining the goal and demonstrating the core possibilities of the concept while accounting for weather information, thermal inertia, and thermal comfort. The methodology also includes a description of the hypothesis and any associated research questions. A comprehensive literature analysis is used to classify the methodology. The idea of weather prediction control is then thoroughly presented, leading to an explanation of the fundamentals and outcomes of the thermal simulation. In order to prepare for a perspective to expand on the potential of the concept, the results are examined, the initial hypothesis is addressed, and the related research issues are clarified.

5.1.1 Objective

Three categories of research potential—weather data, thermal inertia, and thermal comfort—form the basis for this study. The characteristics of each topic are briefly discussed in the following subsections, which also reveal each category's potential for energy savings.

Potential – Weather Data

Along with the increasing occurrence of extreme weather, the world's temperatures are shifting as a result of ongoing climate change. The primary goal of creating a good architectural concept, according to Hausladen et al., is to adapt the building to the local climate [5-13]. This procedure of adaptation can be achieved through changes in the thermal envelope, the internal gains or, especially when the building has already been constructed, the implemented building technology. This link to the building technology is necessary to meet the building's potential energy performance in tandem with the continually changing local weather conditions.

The use of local weather conditions is essential when developing a climate-friendly energy design for a building, not only because of the expanding attention given to these topics due to climate change and the rising cost of energy but also because of the burgeoning trend of digitization. The gathering of weather data dates back to the early phases of human data generation and is the cornerstone of the complex type of life we have on this planet. With increasingly precise sensors and a very dense global data grid (see Figure 5-1), it is imperative to use these data sets intelligently to reduce energy use and improve thermal comfort in buildings.

The German Weather Forecasting Agency now uses numerical algorithms to better estimate and interpolate the local weather conditions while taking into account external weather occurrences, which adds to the quality of the already dense grid of weather data [5-14]. These prediction algorithms give a local weather forecast with a very high probability using various grid sizes and scales. With the aid of these data sets, it is feasible to forecast the local weather for the foreseeable future and to determine the prospective thermal conditions in our structures. This paper assesses if we can reduce energy use and improve thermal comfort by using this data to potentially adapt the buildings' technology to the location.

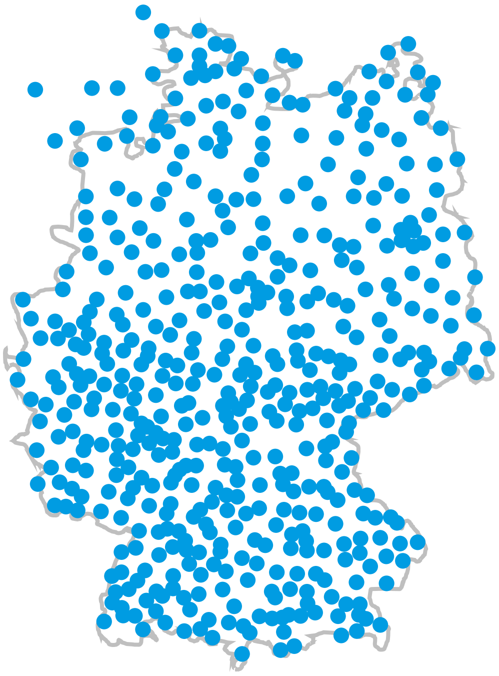


Figure 5-1: Availability of 537 weather stations in Germany (own representation)

Potential – Thermal Inertia

In the wake of the burgeoning building turnaround, especially in Germany, many Western countries are looking for funding opportunities to improve the thermal building envelope. As a result, the government is making significant investments into highly insulated building constructions, through broader access to funding opportunities. In the short term, this results in energy savings in the operation of the building, but in the long term, based on the embodied carbon of the materials, it can negatively impact a building's energy and CO_2 performance [5-15]. The reaction time needed to adjust the building, also known as thermal mass or time-related thermal inertia, seems to be another important factor in the process of building adaptation. As evidenced by numerous studies, this strategy not only reduces energy use and increases thermal comfort in the environment, but it may also enable load control and turn the building into a component of a larger energy network [5-7&5-8, 5-10–12].

Thermal mass or effective heat capacity describes the ability of materials to absorb/desorb heat based on temperature changes in a room [5-16]. As defined in the German Code DIN 4108, thermal mass has a significant impact on the energy consumption of a building. The various construction types are divided into three categories: heavy-, middle- and lightweight constructions. This classification establishes the effective heat capacity in accordance with the net floor area. Constructions are classified as being light if they are less than 50 Wh/(K m^2), medium if they are less than 130 Wh/(K m^2), and heavy if they are more than 130 Wh/(K m^2) [5-17]. The phrase thermal inertia refers to the rate at which a mass absorbs or loses heat. A building's thermal inertia can be utilized to reduce energy use and improve thermal comfort in a space [5-12]. The accompanying Figure 5-2 illustrates how time-delayed heating and cooling of the material's surface can create a more balanced and comfortable environment, particularly under conditions of fluctuating temperature in a space. With impending climate change, support for the prevention of overheating in the summer is becoming more and more crucial. This effect can aid in the storage of heat during wintertime.

According to prior research, a building's thermal mass can be transferred into a component for demand-side management, in addition to being used to save energy and provide thermal comfort [5-7&5-8, 5-10–12]. Here, the authors not only explain how the building's performance is greatly influenced by the local weather but also how people interact with the structure, which makes it possible to use a demand-side management method. With the emerging concept of using heat pump systems in combination with active layers for heating and cooling, especially in temperate/cold climates, the thermal mass of a building can serve as local storage, to convert surplus renewable electrical energy and support the energy revolution [5-18]. These studies usually claim to develop smart control strategies for building technology so as to exploit the potential of thermal inertia.

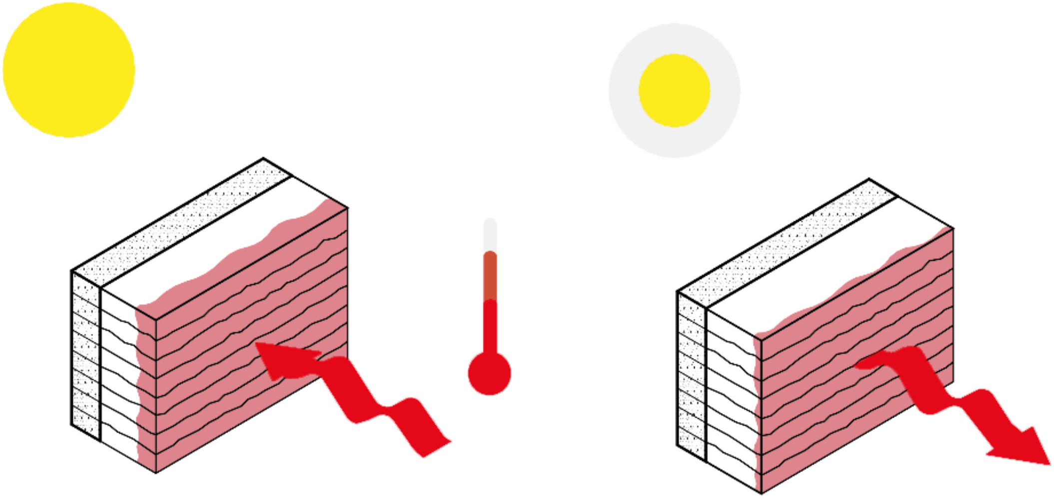


Figure 5-2: Effect of heating and cooling through thermal mass (own representation)

Potential – Thermal Comfort

With the ongoing energy crises in Europe and the overall transition away from fossil fuels, reducing the heating energy demand has become a key question in the building industry. Since 70% of the net energy consumed in households is used for heating [5-19], the question as to which temperature profiles and ranges are sufficient has become not only a focal point of research but a political debate.

National and international building codes consist of various parameters and methods to evaluate thermal comfort in a room, most of which rely on either the predicted mean vote (PMV) and percentage of people dissatisfied (PPD), or more simply, on the operative temperature in accordance with the running mean outdoor air temperature (adaptive method). While the PMV/PPD method performs particularly well in static, controlled environments, the adaptive method has been shown to be more accurate in real-world, dynamic environments and when observing human adaptation and expectations [5-20&5-21]. This paper therefore utilizes this adaptive method. The operative temperature (Top) is a mathematical temperature that best describes a human’s experience in a room. It is calculated as the equal distribution between the air temperature and the sum of the temperatures of the surrounding surfaces that effect the point of measurement through radiation. The adaptive comfort band of DIN EN 16798-1, with the upper and lower acceptable Top according to three categories of predicted discomfort (Figure 5-3), graphically illustrates the range for energy savings [5-22]. It depicts the methodology of evaluating comfort within a range and not only relying on one temperature set point to provide comfortable conditions in an environment. Consequently, as we recognize this flexibility in thermal comfort, we can argue a potential for energy saving by using the built environment as storage and therefore bridge phases from renewable energy excess times to times where there is little to no renewable energy availability.

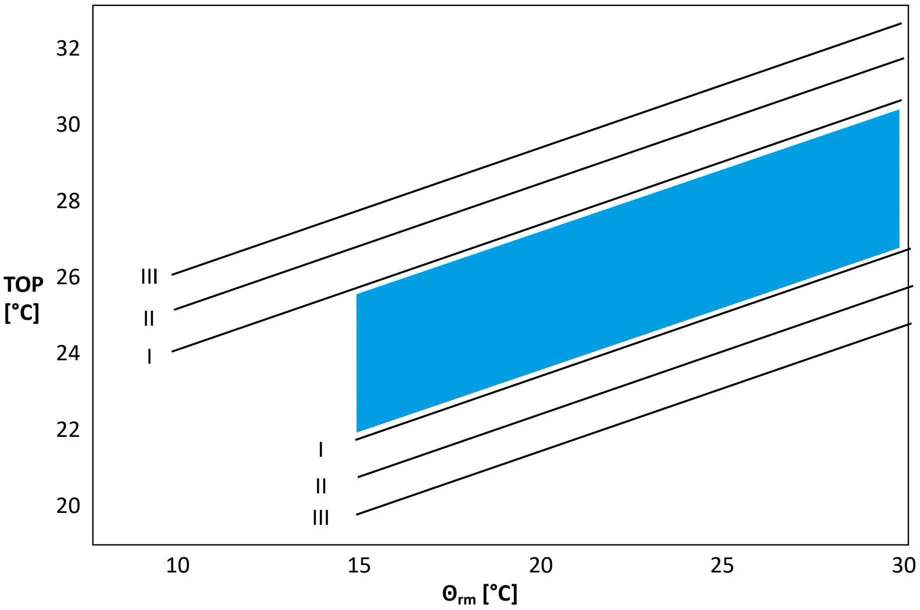


Figure 5-3: Energy saving potential within the adaptive thermal comfort band (own representation based on DIN EN 16798-1 [5-22])

Side note by the authors: While this paper investigates thermal flexibility and potential of weather predictive control within the thermal comfort ranges given by the established adaptive method, it should be noted that these category ranges are currently debated in their validity. In such, recent literature assumes wider comfort ranges and more personal flexibility in thermal adaptation to be perceived as more comfortable and potentially healthier in the long run [5-23–27]. This greater flexibility would also yield a wider range for energy harvesting and would strengthen the concept of a weather predictive control. This is also shown in various studies that question the static and tight conditioning of indoor environments [5-28–30].

5.1.2 Methodology

This section describes the methodology used with regard to the aforementioned research potentials, as well as the hypotheses that arise and the subsequent research questions. Digital, thermodynamic simulations try to represent the actual physical behaviour of a system. An energy improvement of a building system is virtually always attainable with a highly realistic digital duplicate [5-31]. To analyze the effects of a WPC this paper uses a validated thermal simulation model to evaluate the impact of a WPC on the thermal comfort and the energy demand of an office building in the moderate climate of Munich. The validated simulation model with its building characteristics is based on the Solarstation, a two-room test facility on the roof of the Technical University of Munich. This serves as the foundation for the thermal simulation model in TRNSYS 18, which is powered by the parametric simulation tool TRNLizard and carried out in the graphical programming environment Grasshopper in the software Rhinoceros 7. The thermal simulation model is parametrically adjusted to analyze the specific effects of the WPC.

After the setup and evaluation of the base case models, the WPC strategies developed for heating, cooling, ventilation, and sun protection are implemented in the software system using Python, taking into account the future ambient temperatures and future incoming solar radiation. The following hypothesis and the related research problems are addressed by the simulation setup used in this paper:

The energy demand and thermal comfort of a Munich-based office building can be optimized compared to a state-of-the-art control strategy by the simple approach of a weather predictive control of inert buildings.

- Is it possible to optimize the thermal comfort of a room with a WPC?
- Is it possible to generate energy savings with a WPC?

5.1.3 Literature Review

The current state of research into control methods for thermally activated building structures (TABS) is presented in this section. Many publications have defined various methods to govern inert building technology such as TABS, ranging from the early pioneers to the modern advanced control systems. The building structure can be integrated with TABS to serve as energy storage, but there is still room for improvement in the control. The system's mass flow and supply temperature can both be managed. In general, other building technology systems, such as radiators, are also capable of using an intelligent control strategy, although Amato et al. point out that the hydraulics of radiator systems severely restrict the performance of an intelligent control strategy [5-32]. The concept of a simple ON/OFF control, a proportional integral derivative control (PID), a weather-dependent control, a model predictive control (MPC), and other intelligent control strategies are introduced in this literature review. The authors also provide a brief overview of the benefits and drawbacks of each individual approach at the end of each subsection.

ON/OFF Control

The ON/OFF controller, which is the most widely used and basic control technology, typically determines when to switch merely based on temperature. The discontinuous room temperature control using a three-position controller is an easy way to operate the TABS. The controlled variable with two established limit values for heating and cooling is typically the room temperature. Hence, the system functions either in the heating mode, with the greatest possible supply temperature, or the cooling mode with the lowest possible supply temperature. A hysteresis is commonly used to avoid any immediate change between switching on and off [5-33].

This control strategy's simplicity and minimal data point requirement are advantages. This guarantees a straightforward implementation in practice. According to Tödtli et al. [5-34], this control method relies on the self-regulation impact of the thermal mass of the building, and many examples demonstrate a discomfort in the thermal zones without taking into account the heat gains in a room or an overall feedback variable from the thermal zones. Additionally, the impact of the building's location does not affect the thermal performance and can result in excessive energy demands and overheating/overcooling.

Proportional Integral Differential Control

The continuous control strategy is represented by the proportional integral differential controller (PID). It is frequently used for industrial applications due to its ability to take the history and the future behavior of the system into account. In contrast to the three-position controller, the PID controller is a closed-loop system that considers the output as feedback for the following input signal [5-17]. The tuning of the coefficients plays a key role in determining the performance of the controller.

Studies show that a PID controller outperforms standard ON/OFF controls in terms of the energy demand, but also leads to thermal discomfort [5-35]. Due to the complexity of the simulated model, it is impossible for the model to be abstracted into a mathematical model, which could be calculated and tuned with the classic control theory. Nevertheless, studies show that neither PID mechanisms nor three-position controllers offer a suitable strategy for controlling TABS [5-7]. This is because heating and cooling might occur on the same day, which causes a large increase in energy demand. Another issue is that these mechanisms cannot deal with dynamic effects caused by disturbances such as changes in solar radiation, losses through ventilation, and internal loads. Furthermore, tuning PID coefficients is already a complex matter in the digital context of a thermal simulation, and becomes even more complex if transferred to the built environment. This is why PID controllers are very expensive to implement and therefore are only suitable for large-scale building technology systems that are not representative of the majority of the market.

Weather-Dependent Control

A commonly used control strategy for TABS is the weather-dependent control. In this case, the supply temperatures are chosen depending on the ambient temperatures. The heating or cooling curve is the function that depicts this relationship between supply and ambient temperatures [5-33]. Figure 5-4 shows an exemplary heating and cooling curve with the ambient temperature on the x-axis and the target supply temperature on the y-axis. Within a defined neutral zone (here between 12 °C and 15 °C), heating and cooling are deactivated. Apart from the ambient temperature, the supply temperature is further regulated by the room temperature [5-12]. Another possibility is to control the return temperature depending on the ambient temperature. Functions for the target return temperatures that depend on the outside temperature are set up, similar to how the target supply temperatures are calculated. By taking into account the difference between supply and return temperatures, the main benefit of controlling the return temperature is the inclusion of the thermal conditions of the room (such as internal loads, solar radiation, etc.). The drawback is that when the system is turned off, the return temperature and energy transfer to the zone are unknown [5-12].

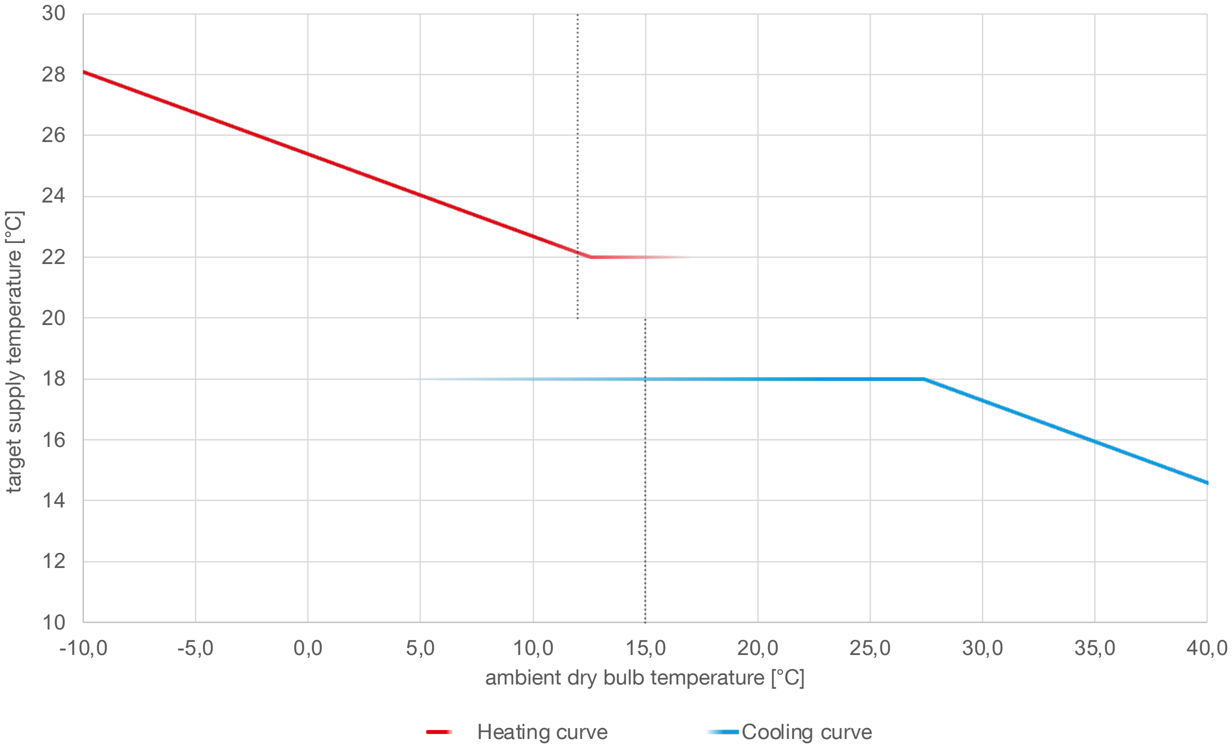


Figure 5-4: Exemplary heating and cooling curve for TABS (own representation)

As Bollin and Schmelas [5-33] and others point out, the main problem with a weather-dependent control is its adaptation to the local weather conditions. The set temperatures are based on experience and outlined in general national guidelines such as the Handbuch der Gebäudetechnologie (English: Guideline for building technology) in Germany [5-36]. The concept is regional and not customizable because the set point temperature needs to be adjusted for local conditions in various climates. A second system to evaluate the thermal comfort conditions of the zones is necessary to guarantee suitable conditions, as there is only indirect feedback about the thermal conditions of a room.

Model Predictive Control

Model predictive control, as a supervisory strategy, considers future disturbances to predict the system's behavior and to calculate an appropriate reaction of the system to minimize or maximize an objective function [5-37]. The new state of the system, including the relevant disturbances, is fed back to the MPC as input to optimize the next time step. In the context of building technology, the MPC usually aims to minimize energy demand and costs or enhance thermal comfort. Therefore, weather forecasts and predicted internal gains are taken into account. To achieve an efficient load management while maintaining thermal comfort, a suitable control strategy for energy systems is required. MPC holds potential for controlling it efficiently through prediction of loads, renewable energy generation, and weather forecasts [5-37].

The research project opticontrol [5-7&5-38, 5-39] investigated the effectiveness of a practical application of an MPC strategy using weather forecast data. As a result, the project forms a strategy based on weather forecasts to choose the variables for the subsequent hours. The optimization issue can take into account predictions for internal gains, changeable energy prices, or comfort levels. By implementing the designed MPC strategy in a building, the demand for renewable primary energy is reduced by 17%, and financial costs are also reduced by 17% [5-0-7]. Furthermore, they concluded that the investigated buildings were particularly sensitive to the forecast of incident radiation. According to the authors, MPC can also contribute to making buildings more efficient as energy storage systems. Nevertheless, one disadvantage of MPCs is the high computational costs and the great effort needed to model the building and its technology.

Other research projects, including the opticontrol project, have also pointed out that an advanced digital model of the building as well as a data-intensive simulation algorithm must be connected to the control strategy with an MPC. To implement this idea into practice, qualified technical experts and cutting-edge building control systems are needed. This narrows the application of this concept down to large, modern building technology systems and excludes the majority of customers on the market. Furthermore, this high complexity of data and science makes it hard to understand and increases the risk of discomfort or the phenomenon of the performance gap (the gap between the actual real and initially intended design of a building system) [5-40&5-41].

Intelligent Control Strategies

Due to the outlined disadvantages of the MPC, researchers around the world are developing alternative control approaches to find the right balance for TABS. One such approach is intelligent control strategies using artificial neural networks (ANN), which enable automatic adaptations to building properties. J.Y.-Lee et al. [5-42] investigated the potential for improved performance of ANN-based control strategies for radiant floor heating. Predictive control with an ANN avoids overheating the room temperature, while non-predictive control strategies exceed temperature limits [5-42]. The high adaptability of the neural network offers the possibility of applying it with different boundary conditions. This adaptability is also demonstrated through experiments in real applications.

M. Schmelas developed a self-learning algorithm to control TABS in his dissertation [5-7]. His AMLR algorithm (adaptive multi-level routing algorithm) calculates the amount of energy required by the TABS zone within the next day. The system also makes use of predictions for the daily mean outdoor temperature and global irradiation in addition to the schedule of occupancy. The advantages of the ALMR algorithms are validated with the help of simulation and measurement data from a pilot plant. Compared to standard ON/OFF control strategies, significant energy reductions of up to 41% can be achieved for the heating and cooling case, in terms of avoiding overheating and overcooling [5-7]. With respect to load management due to the fluctuating renewable energy converters, TABS serve as thermal stores and charging can be switched on or off [5-7]. In addition, the load shifting leads to a reduction in monetary costs if one assumes dynamic prices. The thermal comfort remains unchanged or even improves, throughout the improvements in terms of energy savings and load management.

T. Palecek [5-43] as well as Nagy and Kazmi et al. [5-44] formulate a deep reinforcement learning algorithm based on ANN to control a heating system of a building more efficiently compared to the commonly used rule-based thermostat solutions. They consequently use a mix of deep learning—which trains an ANN to automatically acquire task-relevant features—and reinforcement learning—a computational method for determining the best course of action for a problem. A neural network, consisting of a set of interconnected neurons, can solve complex problems by automatically recognizing patterns in the provided data sets. T. Palecek used a large number of weather profiles from outside temperatures in Basel between 1985 and 2017 to train an artificial neural network (ANN) to optimize the heating control in form of the supply temperature and the mass flow. Those data points included: current outside temperatures, future and current room set point temperatures, and supply and return temperatures [5-43]. One part of the concept is to predict how the room temperature will change in the next state and to make decisions about switching the heating on or off depending on the supply temperatures. The study showed that this concept helps to avoid overheating [5-43].

In his dissertation, J. Jungwirth [5-8] developed an adaptable building model based on ANN in order to reduce costs. The aim is to shift the operating time for electrical heating and cooling systems according to the electricity tariffs that vary depending on the time and cost. A TABS is implemented in the investigated model, an office building. The increased flexibility of heating and cooling operation reduces monetary costs and meets the requirement of ensuring thermal comfort throughout the simulation period [5-8]. Assuming fluctuating electricity tariffs, resulting from increased renewable energy generation by the year 2030, the ANN control strategy leads to energy cost savings of around 63% when applied to an exemplary building [5-8]. The flexible and cost-optimized operation of the TABS with the help of an adaptable model offers great potential for a demand-side management [5-8].

Even so, the AMLR algorithm from Schmelas [5-7], the deep reinforcement learning algorithm based on ANN from T. Palecek [5-43] and Nagy and Kazmi et al. [5-44], and the adaptable building model based on ANN from J. Jungwirt [5-8] all require modern building technology systems to perform the optimization in the real built environment. Furthermore, in the training phases of the models, professional equipment is required. This shrinks down the use case to a small share of the market and increases the costs for such a control strategy that a standard office or residential building does not represent a suitable application. Furthermore, users may find the algorithms and data structures difficult to understand due to their complexity, and there is a risk that this will worsen the building's performance gap, hence increasing energy consumption and/or lowering thermal comfort. This paper attempts to present a more straightforward, intelligent approach that is unaffected by these issues.

5.2 Concept for Weather Predictive Control

This section first presents the fundamentals of the concept and targets the key factors of the prediction process. The following subsections then outline the integration of the concept into the control of the heating and cooling, ventilation, and sun protection systems. The literature review presents the need for a simple, intelligent control strategy for TABS. This also forms the baseline for the authors in the case of the development of the weather predictive controls strategy. The strategy has to be simple and straightforward, with no complicated data management, so that its practical implementation is feasible. This means that in practice, a control device such as a Raspberry Pi is connected to the building technology system. This plug-and-play device can download local weather conditions at its forecast using only an internet connection. The weather predictive control strategy takes into account the actual and the future weather conditions so as to adapt the thermal comfort needs of the actual building and, if possible, execute the implemented energy harvesting strategy. Furthermore, the device must work with a feedback signal to constantly adapt the thermal zones and evaluate the thermal comfort in the room. However, the top priority is that the user can control the building technology at any time and override the algorithm suggestions.

Given that local weather conditions around the world can be accessed with an internet connection, the weather predictive strategy is possible regardless of the user's location. Figure 5-5 below graphically displays the overall concept of the weather predictive control. The left side of the figure represents the ambient dry bulb air temperature and the solar irradiation from the weather data. These function as the prediction parameters for the concept. The four managed building technology systems are outlined in the middle column: sun protection, ventilation, and heating and cooling system. These systems are the control parameters that use the information generated by the prediction parameters to optimize the control. The thermal comfort and the energy demand represent the evaluation parameters in the right side of the figure. This paper analyses the individual variants according to these evaluation parameters.

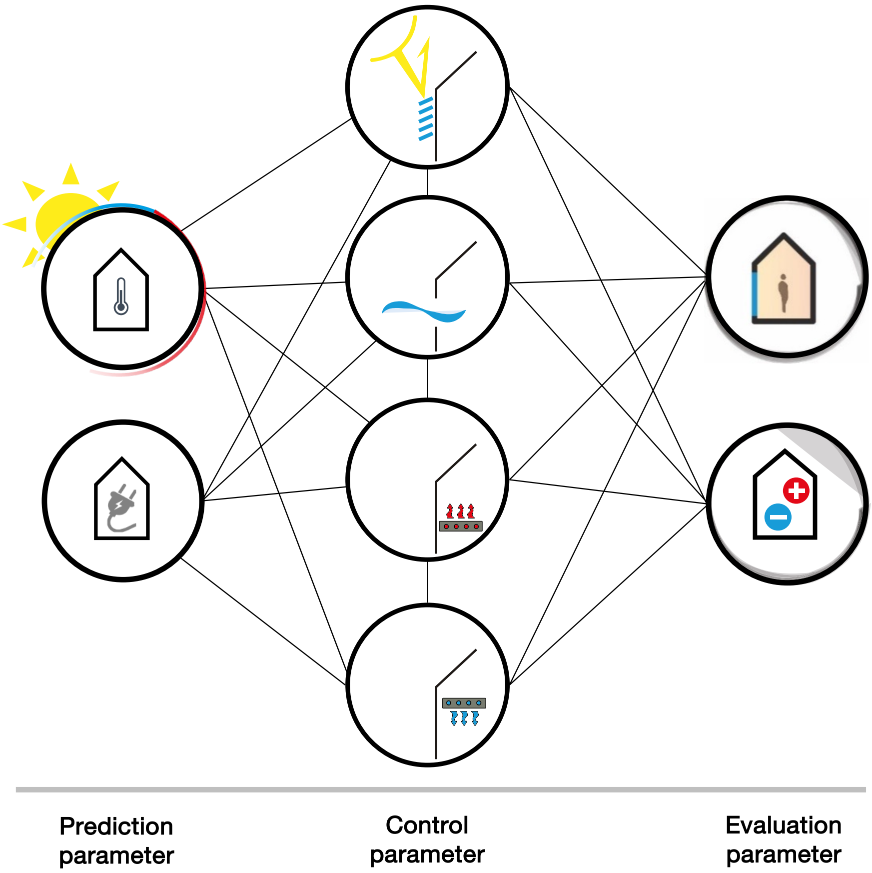


Figure 5-5: Graphical illustration of the concept and its individual prediction, control, and evaluation parameters (own representation)

Now that we know the overall concept of the weather predictive control, one of the key roles in this concept is the issue of the time step of the prediction: How far into the future should we look? Should we adopt a single or multiple approach and consider only one or several values of the prediction parameters in the future? The prediction approach in this paper relies on the concept of a weighted moving average over the next 24 h, because after 24 h the probability of the same conditions occurring is very high. The weighted moving average is a system that is also used to evaluate thermal comfort according to DIN 4108, since adaptive thermal comfort is defined by the weighted moving average of the past ambient temperature over the indoor temperature and is therefore quite common in practice. The following Equation (1) describes the prediction approach, where X_{future} is the target future value. The values X_t time steps t are added up from 1 to 24 h, and weighted according to the weighting factor α with an increasing mathematical power in each time step. This means that time steps closer to the actual time are weighted higher, but all weather conditions over the next few hours will still have an impact on the prediction. Overall, this results in a flattened trend of the predicted value to control the building technology under consideration.

$$\mathrm{X}_{future} = 1 - a \cdot \sum_{t=1}^{24} X_t \cdot \alpha^t \tag{5-1}$$

5.2.1 WPC—Heating and Cooling System

The active layer functions as a heating and cooling system that eventually reaches the desired set point temperature during the active phase. The active layer has different sup-ply temperature settings. Two of them can be adjusted in the user interface. The one for cooling is set to 18 °C, following the recommendation of the Ausbau Atlas [5-45]. The initial set point temperature for heating is 30 °C. The specific power is assumed to be 40 W/m^2 when heating and 50 W/m^2 when cooling [5-45]. The threshold of the average ambient dry bulb air temperature over the last 24 h (Tambm24) determines the season of the year. Temperatures above 15 °C exceed the lower limit and allow for a potential cooling of the system. If the average ambient dry bulb temperature is below 12 °C, the heating mode is activated. Further heating is only possible when the supply temperature is higher than the return temperature (Tout) of the system, and the opposite is true for the cooling mode. In addition to this, the heating and cooling mode are only enabled when users are in the room and thus the working schedule is active. Finally, the heating/cooling process stops when the up-per/lower dead band of the hysteresis is reached, according to the comfort band by DIN EN 16798-1 [5-22]. The following Figure 5-6 illustrates the control scheme for the heating system. Although it is not shown in this paper, the cooling system's control mechanism operates in reverse with the indicated, altered thresholds:

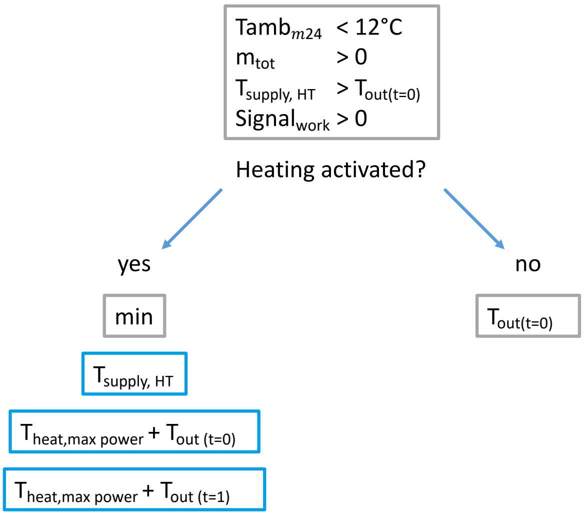


Figure 5-6: Heating scheme set-up (own representation)

Both cases of heating and cooling present an advanced control strategy considering the predicted weather conditions. The operative temperature functions as the control measure. For the WPC, the ambient dry bulb air temperature ($Tamb_{future}$) and the total solar radiation ($Q_{sol,future}$) at a future time step are implemented into the equation of the active layer. These two future parameters are calculated for every time step of the thermal simulation following the principle of Equation (1).

The solar radiation of the future time steps first reduces the supply temperature of the active layer, represented by a calculated temperature difference $\delta T_{Qsol,future}$. The calculation process expressed by a temperature difference of the heat and cold transfer of the medium can be seen in Equation (2):

$$\delta T_{\mathrm{Qsol,future}} = \frac{Q_{\mathrm{sol,future}}}{\frac{\dot{m} \cdot c_w}{3.6}} \tag{5-2}$$

This temperature difference is implemented in the equation of the heating and cooling curve of the supply temperature. This means that in the initial equation, the current ambient dry bulb air temperature (Tamb) is replaced with the $\mathrm{Tamb}_{\mathrm{future}}$ and subtracted by $\delta T_{\mathrm{Qsol,future}}$ for the final supply temperatures. The axis interceptions, slopes, and lower limits are determined according to the test curve of the dissertation of Martin Schmelas and the guidelines in the Ausbau Atlas by Hausladen and Tichelmann [5-7&5-45]. The heating and cooling curve change as expressed in Equations (3) and (4). Besides the direct decrease in the supply temperatures, the maximum heating and cooling power (P_HT; P_CL) are also modified depending on the solar gains of the future time steps, outlined in Equations (5) and (6):

$$T_{\mathrm{supply,HT}} = \max(25.4 - 0.27 \cdot \mathrm{Tamb}_{\mathrm{future}}, 22) - \delta T_{\mathrm{Qsol,future}} \tag{5-3}$$

$$T_{\mathrm{supply,CL}} = \min(25.4 - 0.27 \cdot \mathrm{Tamb}_{\mathrm{future}}, 18) - \delta T_{\mathrm{Qsol,future}} \tag{5-4}$$

$$P_{\mathrm{HT}} = \max\left(P_{\mathrm{HT,max}} - Q_{\mathrm{sol,future}}, 0\right) \tag{5-5}$$

$$P_{\mathrm{CL}} = \max\left(P_{\mathrm{CL,max}} + Q_{\mathrm{sol,future}}, 90\right) \tag{5-6}$$

The reduction in power as well as the modified heating and cooling curves are aimed at reducing overall heating and cooling demand while at the same time improving the overall improvement in thermal comfort. The lower part of the adaptive comfort band is used as a reference for heating, and the upper part for cooling, to keep the heating and cooling energy to a minimum [5-22]. This concept is converted and implemented in the active layer type of the thermal simulation.

5.2.2 WPC—Sun Shading System

The shading system in this paper and in the norms (e.g., DIN 4108-2 [5-17] in Germany) are regulated according to the sum of direct and diffuse radiation onto the window surface area. By opening up and closing the shading system, solar radiation can enter the room to generate heat that in the summer periods potentially leads to overheating or the necessity of a cooling system. The shading device studied in this paper is a set of venetian blinds with an fc-value of 0.8. According to the norm DIN 4108-2, the individual irradiation limit onto the window surface depends on the orientation of the room, and in general, a shading system is activated only above an outdoor air dry bulb at a temperature above 14 °C [5-17]. For a northeast-to-northwest-oriented room, the shading system of an office building is activated above a threshold of 150 W/m^2. For other orientations, the irradiation limit is set to 200 W/m^2. The floating future radiation during the following 24 h on the window's surface area is integrated into the radiation control in this study when it exceeds a threshold of 150 W/m^2. The shading control signal considering the weather predictive control is outlined in the following Equation (7):

$$\mathrm{signal}_{\mathrm{shading}} = \mathrm{gt}(\mathrm{Tamb}, 14) \cdot (\mathrm{gt}(\mathrm{rad}_{\mathrm{sur}}, 200) + \mathrm{gt}\left(\mathrm{rad}_{\mathrm{sur,future}}, 150\right)) \tag{5-7}$$

5.2.3 WPC—Ventilation System

J. Hopfe, in her dissertation, points out the sensitivity of computer-based models, suggesting that the performance of a model is tightly tied to the ventilation systems and the infiltration [5-46]. In this study, a natural ventilation system is used in addition to the normal infiltration related to building construction, to promote thermal comfort in the office spaces. An electrical automation to open the windows as well as the manual possibility for the user to open the window is assumed. During the day within the work schedule, the ideal user performs the operation of the window according to the thermal comfort ranges of DIN EN 16798-1 [5-22], while during the summer period, nighttime, and periods when the office users are absent, the automation operates the window to perform potential night time cooling. In general, the standard infiltration and natural ventilation in simulations are represented with the metric of air changes (AC) per hour (air change rate). In this paper it is divided in the following modes: basic infiltration (AC = 0.2), tilted window (AC = 1.5), intermittent opening (AC = 3); and completely open window (AC = 6). Here, again, the air change rate is a simplified concept to represent natural ventilation in a simulation model, which simplifies a complex process of multiple pressure differences into a single value. This leads to a reduction in the quality of the simulation, but a detailed computational fluid dynamic (CFD) simulation would distract from the main focus of the paper.

The following Equations (8)–(11) (for the work schedule) and (12)–(14) (for night ventilation) outline the control strategy for infiltration, the natural ventilation system, and the implementation of the weather prediction. The ventilation concept only follows temperatures and not volatile organic compound (VOC) thresholds in the room, so as to focus only on the energy consumption. In general, the indoor air temperature has to be higher than the ambient outdoor temperature to trigger a cooling. During the work schedule the three ventilation modes are activated according to the indoor air temperature thresholds 23, 25, and 27 °C. As the standards (e.g., DIN 15798) do not recommend specific thresh-olds, the implementation is based on the authors' own experience. During the nighttime, the thresholds are set to 23 and 26 °C for the tilted window and completely open window modes, respectively. In addition to the basic control, additional potential ventilation is activated when future ambient dry bulb temperature is above the thresholds 23, 25, and 27 °C during work hours, or above 23 or 27 °C during the nighttime mode, resulting in the individual air change rates.

During work hours:

$$\mathrm{AC_{work}} = 0.2 \cdot \mathrm{signal_{work}} \cdot \mathrm{lt}(\mathrm{AC_{23}}, 1.5) \cdot \mathrm{lt}(\mathrm{AC_{25}}, 3) \cdot \mathrm{lt}(\mathrm{AC_{27}}, 6) \tag{5-8}$$

$$\mathrm{AC_{23}} = 1.5 \cdot \mathrm{gt}(\mathrm{Tair}, \mathrm{Tamb}) \cdot \mathrm{lt}(\mathrm{AC_{25}}, 3) \cdot \mathrm{lt}(\mathrm{AC_{27}}, 6) \cdot \mathrm{gt}(\mathrm{gt}(\mathrm{Tair}, 23) + \mathrm{gt}(\mathrm{Tamb_{future}}, 23), 0) \tag{5-9}$$

$$\mathrm{AC_{25}} = 3 \cdot \mathrm{gt}(\mathrm{Tair}, \mathrm{Tamb}) \cdot \mathrm{lt}(\mathrm{AC_{27}}, 6) \cdot \mathrm{gt}(\mathrm{gt}(\mathrm{Tair}, 25) + \mathrm{gt}(\mathrm{Tamb_{future}}, 25), 0) \tag{5-10}$$

$$\mathrm{AC_{27}} = 6 \cdot \mathrm{gt}(\mathrm{Tair}, \mathrm{Tamb}) \cdot \mathrm{gt}(\mathrm{gt}(\mathrm{Tair}, 27) + \mathrm{gt}(\mathrm{Tamb_{future}}, 27), 0) \tag{5-11}$$

At night time:

$$\mathrm{AC_{night}} = 0.2 \cdot \mathrm{lt}(\mathrm{AC_{night,23}}, 1.5) \cdot \mathrm{lt}\big(\mathrm{AC_{night,27}}, 6\big) \cdot (1 - \mathrm{signal_{work}}) \tag{5-12}$$

$$\mathrm{AC_{night,23}} = 1.5 \cdot \mathrm{gt}(\mathrm{Tair}, \mathrm{Tamb}) \cdot \mathrm{lt}(\mathrm{AC_{27}}, 6) \cdot \mathrm{gt}(\mathrm{gt}(\mathrm{Tair}, 23) + \mathrm{gt}(\mathrm{Tamb_{future}}, 23), 0) \tag{5-13}$$

$$\mathrm{AC_{night,27}} = 6 \cdot \mathrm{gt}(\mathrm{Tair}, \mathrm{Tamb}) \cdot \mathrm{gt}(\mathrm{gt}(\mathrm{Tair}, 27) + \mathrm{gt}(\mathrm{Tamb_{future}}, 27), 0) \tag{5-14}$$

5.3 Thermal Simulation

To analyze and evaluate the effect of the WPC, a thermodynamic model was set up. The correctness of a digital thermal simulation relies on detailed data implementation and profound expertise with the simulation tool. Thereby a common way to guarantee the correctness of a model is a validation, comparing measured and simulated values. The validated base case model and its local weather conditions, simulation variants, and individual energy and thermal comfort performance outcomes are all presented in the next two sections as the basis for the final discussion and conclusion.

5.3.1 Base Case Model

The digital thermal model is created in the software plug-in TRNLizard, a parametric tool for the visual programming environment Grasshopper of the CAD-software Rhinoceros 7. TRNLizard interacts as a communication tool which links building property information to the thermal simulation tool TRNSYS, which performs the actual dynamic thermal simulation. The base case model consists of an in situ measurement test facility of an office room located on a rooftop in the urban environment of Munich. The exposed location, at a height of approximately 28 m above ground, is mainly influenced by the urban Munich weather conditions (48°08′20″, 11°34′30″). The central, main office room has a length of 4.30, a width of 4.30, and a height of 3.30 m. The main orientation, including a large glass façade (window-to-wall ratio of 90%), faces 23° southwest. Venetian blinds function as the shading system, while the windows can be operated manually and automatically. In the thermal simulation, a slab activation acts as the heating and cooling system, representing the TABS. For heating, the supply temperature is 25 °C and 16 °C for cooling. The heating power is about 40 W/m^2 and the cooling power is approximately 50 W/m^2.

The validation of the thermal model has already been performed and described in detail in a previous study in 2022 by Hepf et al. [5-47]. Using the ASHRAE guideline 14:2002 and its criteria of the normalized mean bias error, the coefficient of variation of the root mean square error, and the coefficient of determination, it was shown that after adapting the infiltration and the thermal bridges, the thermal model was validated according to the four type weeks [5-47]. The thermal model data comprises local weather data measured at the test facility and the highly insulated thermal envelope (roof: u-value 0.222 W/(m^{2}K), external wall: u-value 0.175 W/(m^{2}K), floor: u-value 0.266 W/(m^{2}K), internal wall: u-value 0.437 W/(m^{2}K), window: u-value 0.68 W/(m^{2}K). The thermal bridges are set to 0.1 W/(m^{2}K) and the basic infiltration air change rate is 0.2 1/h.

Figure 5-7 shows the global horizontal radiation, the cumulative values on a monthly basis for the ambient temperatures, and the monthly maximum and minimum ambient temperature. In the winter months, the global horizontal radiation and the ambient temperatures are lower than in the summer months. Therefore, the peak of 234 kWh/(m^{2}a) occurs in July, and the highest average ambient temperature of 20.8 °C was measured in August, whereas the highest maximum temperature of 39.8 °C occurs in July. December is the coldest winter month with the lowest average and a minimum ambient temperature of -4.2 °C. In July and December, the highest and lowest radiation can be observed. The highest radiation and thus the highest cooling energy demand is estimated in the months of July and August, while the highest heating demand is expected to occur in the winter months of December and January. In the transition periods, cooling and heating demands can alternate; this gives the WPC the potential to outperform a simple building control strategy.

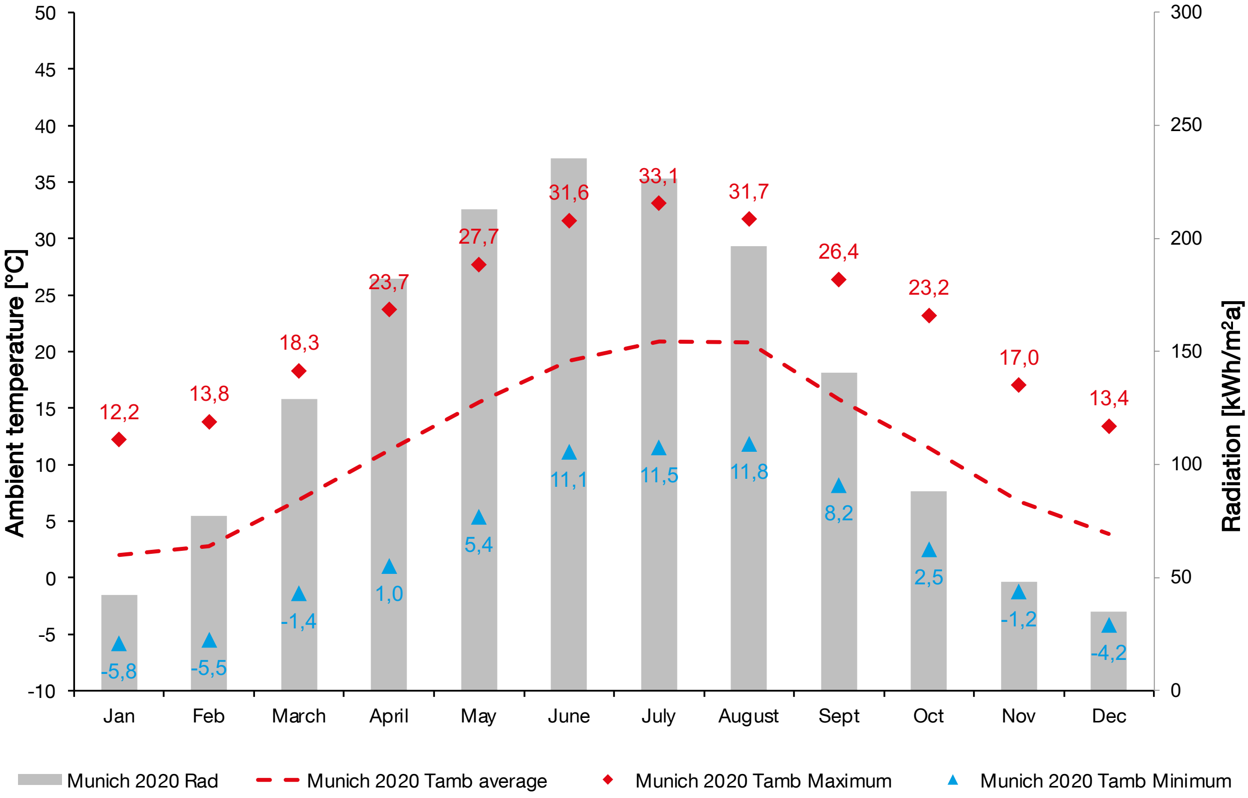


Figure 5-7: Cumulative global horizontal radiation and maximum, minimum, and average ambient temperatures per month measured in Munich 2020 (own representation)

5.3.2 Results

To evaluate the effect of the WPC, three simulation variants of light, middle, and heavy construction were each tested with and without the use of the WPC. In the simulation variant without the WPC, standard control algorithms were used. The heating and cooling system uses a common weather-dependent control for the TABS: The ventilation system and un-protected control perform similarly to the WPC control, using the actual Tamb instead of the future values. Overall, the simulation variants without WPC already use an advanced control strategy to set the basis for a fair comparison. The characteristics of the heating and cooling energy demand and the over and under temperature hours (OTH; UTH) serve as the evaluation criteria for the thermal comfort performance. The subsequent Figure 5-8 displays the simulation results. The individual graphs are arranged in rows. The top two figures represent the light-, the second two the middle-, and the bottom two the heavyweight construction simulation variants. On the left-hand side, the individual point clouds display the simulation hours in relation to the comfort band, using the operative temperature over the mean ambient temperature during the operational time. The grey point cloud outlines the standard simulation variant whereas the colored values represent the simulation variant with the WPC. The figures on the right outline the annual accumulated simulation results. The left four columns of the graphs correlate with the left y-axis outlining the heating and cooling demand with and without the WPC. The four right columns show the over and under temperature hours, connected to the right y-axis. The simulation variants with the WPC are represented by solid-colored columns, while the standard control variants are represented by dashed columns.

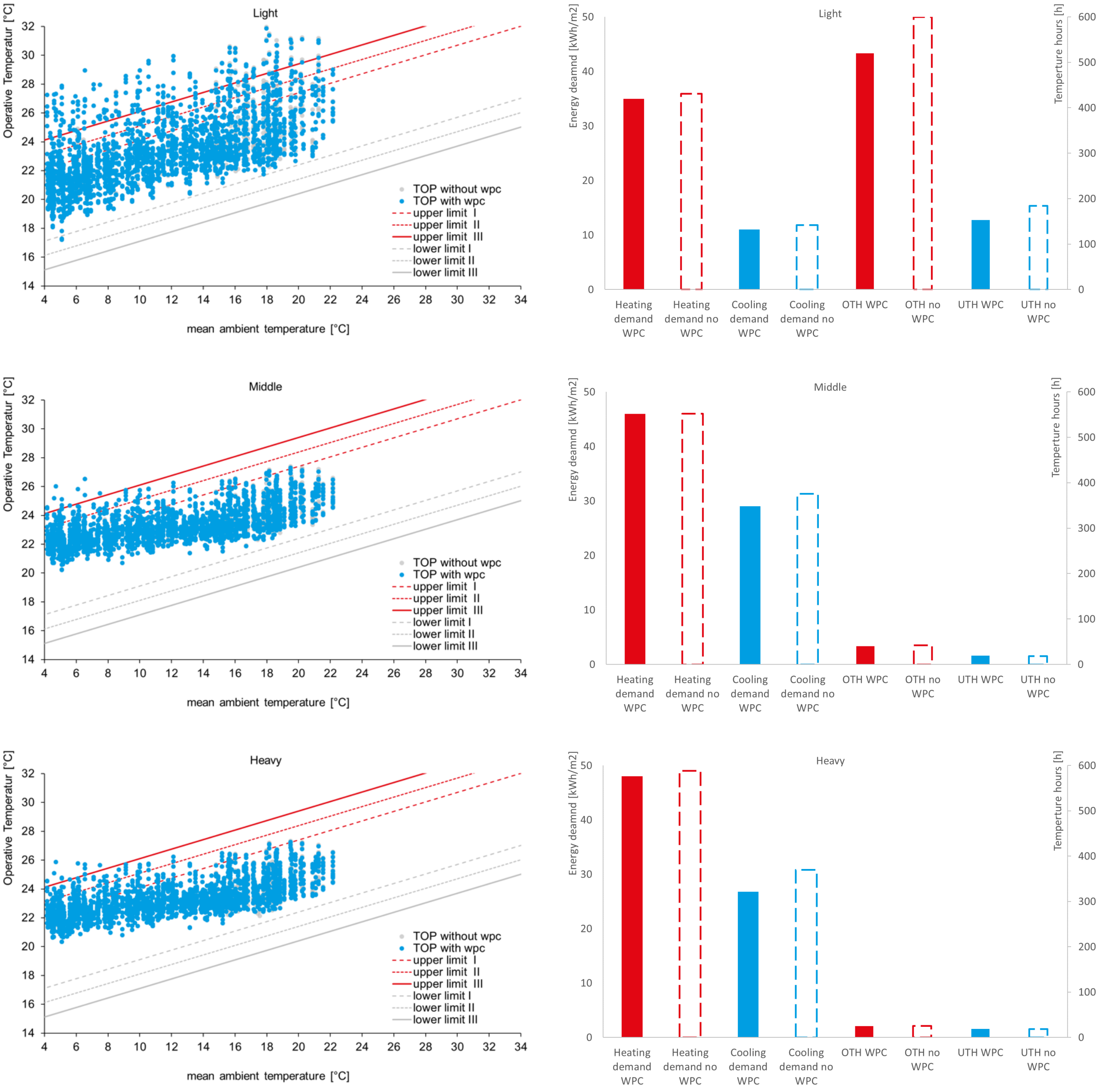


Figure 5-8: Simulation Results: Left column: Comfort hours with (blue) and without WPC (grey) for a lightweight (top), middle (middle) and heavy (bottom) construction; right column: Heating (red) and cooling (blue) demand and over (red) and under temperature hours (blue) with (solid color) and without (dashed) WPC (own representations)

The effect of the thermal mass on the energy and comfort performance can be seen in the simulation variants. The simulation variants with the lightweight constructions summarize the highest and excessively high over and undertemperaturehours, with more than 500 over and more than 150 undertemperaturehours. This is also visible in the correlated point clouds. This results in a lower energy demand for heating and cooling, which is associated with poorer comfort conditions. No comfort can generally be provided due to the lack of thermal mass. Even in the summer period, the cooling power is not enough to reduce the overtemperaturehours. The middle and heavyweight constructions fulfill the comfort requirements according to DIN EN 16798-1. Based on this and the increase in thermal mass, the energy demand for heating and cooling rises. This results in almost no over and undertemperaturehours; this is also visible in the point clouds. Overall it can be said that the higher the mass, the greater the comfort, but also the higher the energy requirement. These results are in line with other studies that analyze the effect of the thermal mass on energy performance and comfort [5-12&5-13].

The influence of the weather predictive control is also visible in parts of the results. Already in the light simulation variant, where comfort is not sufficiently provided, the WPC performs slightly better using less energy and resulting in fewer uncomfortable hours (although still too many). The middleweight construction simulation variants show nearly the same performance with and without the WPC. At 29.0 kWh/(m^2a) the cooling demand is a little less than without the WPC (31.2 kWh/(m^2a)). In the heavy construction simulation variants, the cooling energy demand of the WPC is 14% lower (26.8 instead of 30.8 kWh/(m^2a). The energy demand for heating is nearly equal. Except for the cooling demand in the heavy construction, all simulation variants perform nearly alike in terms of energy demand, with or without WPC. Overall, the simulation variants with WPC have slightly lower over and undertemperaturehours. It is to be noted that the simulation variants without the WPC already show a semi-advanced control strategy that mirrors the effect of the WPC as, e.g., a comparison with a standard ON/OFF control, as outlined in the literature review.

5.3.3 Evaluation

To evaluate the overall hypothesis, we answer our initially proposed research questions:

Is it possible to optimize the thermal comfort of a room with a WPC?

Considering the lightweight simulation variant, it is not possible to improve the thermal comfort in the simulated room, as the overall thermal comfort cannot be provided in this simulation variant. Even though the simulation variant with WPC performs better, we see no improvement in the thermal comfort, while the overall performance of the room is uncomfortable. Nevertheless, for the middle and heavy simulation variants, an improvement can be seen. In the middle simulation variant, the heating and cooling demand performs only slightly better, whereas with the heavy simulation variant, the WPC room utilizes noticeably less cooling and slightly less heating energy. Overall, an improvement in thermal comfort can be achieved but is very much dependent on the room's environment and construction. It seems to indicate that cooling energy especially can be saved with an increased thermal mass.

Is it possible to generate energy savings with a WPC?

Only a small amount of energy could be saved by using the WPC instead of the weather-dependent TABS control, throughout all simulation variants. Percentagewise, the energy savings decrease along with increasing thermal mass, but still do not show significant improvements. Neither a decrease in the energetic performance nor a significant increase in energy demand can be seen with the use of a WPC, as it only slightly affects the overall energy performance of the simulated room.

The energy demand and thermal comfort of a Munich-based office building can be optimized compared to a state-of-the-art control strategy by the simple approach of a weather predictive control of inert buildings.

This overall hypothesis statement is therefore believed to partly true, as the energy performance and the thermal comfort are only slightly improved by the weather predictive control. However, in more specific detail, the thermal comfort is technically improved with the WPC while the energy performance does not decrease. The control case with the Munich-based office building narrows down the potentials of the weather predictive control to one location. The overall potential and further prospects for the WPC are summed up in the following section.

5.4 Discussion

To outline the main findings, this section is divided into subsections dealing with the localization, utilization, and transformation of the weather predictive control potentials. Finally, the limitations of this study are presented to prepare for the final conclusion.

5.4.1 Location of the Potentials

Smartphones, tablets, and computers are everywhere in modern society, and with them, the infinite possibility to access data. This is also true for weather data and weather forecasts, which people use on a daily basis to prepare themselves for the day. By a somewhat paradoxical contrast, this is not currently the case for buildings, even though their performance is mainly influenced by the local weather conditions. Therefore, the potential for a weather predictive control is unquestioned. For a variety of system configurations, this can bring a huge benefit in the energy and comfort performance of a building, especially when equipped with thermal mass, as shown in this paper. For office buildings with inert building technology, the energy savings and comfort improvement potential are present and already accessible with a simple approach such as the WPC, as outlined in this paper.

5.4.2 Utilization of the Potentials

Using a weather predictive control generates thermal comfort improvements, especially by reducing cooling energy demand in the summer months, and generates slight annual energy savings for heating. The simple control approach outlines state-of-the-art building technology regulation. This increases with increasing thermal mass of the building, even though there are already some comfort improvements with lightweight constructions. The results of this paper show that locations with a higher demand for cooling energy will increase the potentials of the optimized control strategy. Furthermore, locations with a higher fluctuation when switching between the heating and cooling mode, mainly within the transition periods between summer and winter, will enlarge the potential, as a standard control for TABS does not perform well during these periods.

5.4.3 Transformation of the Potentials

With ongoing climate change, the increasing fluctuation in power generation caused by the higher share of renewable energies, as well as with the changes in the global energy price fluctuations and uncertainties in the building control, become more frequent. This leads to higher CO_2 emissions and energy prices in the operation of the building and increases the demand for local storage systems and smart building control strategies. Smart control strategies are only applicable to the majority of the building stock when the focus of the implementation is on a simple approach and detached from high-tech solutions. In a moderate climate, such as Munich, the effects can already be proven, but further investigation is needed into the holistic effects of the WPC. Various locations, with more extreme weather conditions, a fluctuating energy supply, and different building constructions, can give valuable insight into further potentials for the WPC.

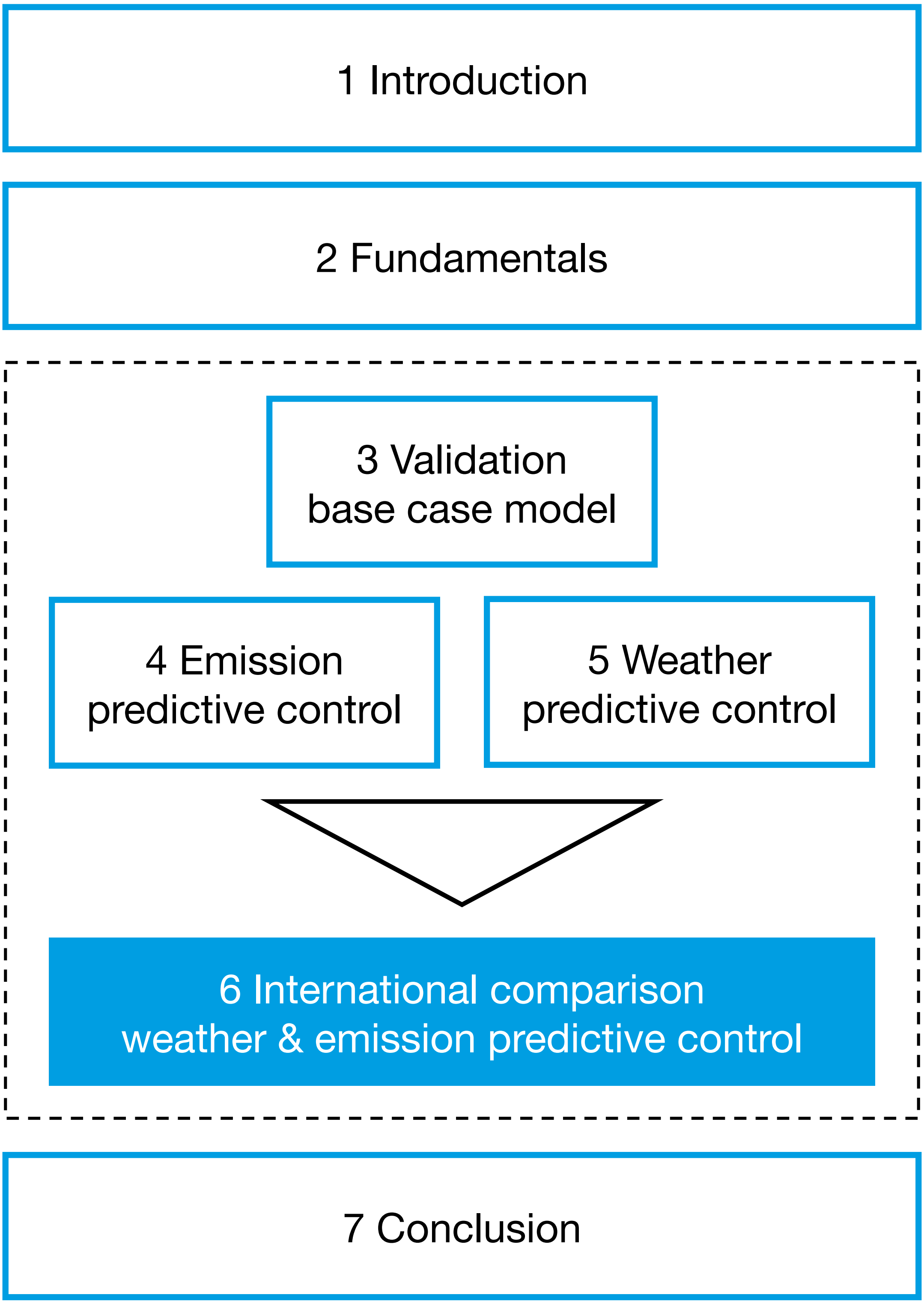
5.4.4 Limitations

The characteristic data in this paper is based on an in situ test facility with a very exposed location. This single test case limits the statements of this paper. Common office rooms with only one outside façade, which form the majority of office rooms today, are not represented by this paper. Furthermore, the test facility with its vacuum insulation panels represents a very well-insulated thermal envelope, and the window properties are of high standard too; this does not represent the current office building stock in countries such as Germany. According to this presumption, the simulation's ventilation system severely simplifies the complex process of ventilating a room and reduces it to merely the air change rate. This may skew the findings and cause the conclusions to be misleading. To evaluate the simulation results this paper uses the parameters thermal comfort and operational energy of a building but excludes the overall energy performance of a building like, e.g., the grey energy of the building. Additional parameters, e.g., CO_2, could increase the statements' scope. The idea of under- and overtemperaturehours might also affect the quality of the data in the continuous process of rethinking current thermal comfort models and may result in incorrect conclusions that can be improved in future research. In addition to that, the results of the comparison are rather small, as the WPC was compared with an already advanced control strategy. As the literature review already points out, advanced control strategies such as the WPC outperform ON/OFF control strategies for TABS noticeably.

5.5 Conclusions

Overall, the simple concept of a weather predictive control using future ambient temperature and future radiation shows an improvement in the energy performance and slight improvements in the thermal comfort for the office building in the moderate climate of Munich. Especially in the summer months, the cooling energy demand can be reduced, in particular in buildings with increased thermal mass. It is further evident that a simple approach such as the WPC, without a huge amount of data or the computational power of an artificial intelligence, can already achieve energy savings. This consequently does not lead to rebound effects, such as an increase in energy consumption or operation costs caused by power-intense calculation algorithms, or the creation of digital twins of the building. This leads to savings that are commonly not considered in the optimization processes. Simple approaches such as trend generation using the logarithmically mitted future average, energy performance, and thermal comfort can be improved. Performing a counter-validation and applying the weather predictive control strategy in the in situ test facility would increase the quality of the data. In addition to that, a detailed representation of the energy supply for heating and cooling would increase the quality of the results. However, in general, we consider the following three steps to be vital to increase the future impact of the WPC and to transform the potentials into a broader field:

- Performing an international study to investigate the potentials in different climates.
- Applying the concept to other use cases with higher representation in the building market.
- Introducing a further evaluation parameter, namely CO_2, to transfer the potentials to holistic energy balance.


1 Introduction
2 Fundamentals
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4 Emission predictive control
5 Weather predictive control
6 International comparison weather & emission predictive control
7 Conclusion

6 International Comparison of Weather and Emission Predictive Building Control

Summary

Building operational energy alone accounts for 28% of global carbon emissions. A sustainable building operation promises enormous savings, especially under the increasing concern of climate change and the rising trends of the digitalization and electrification of buildings. Intelligent control strategies play a crucial role in building systems and electrical energy grids to reach the EU goal of carbon neutrality in 2050 and to manage the rising availability of renewable energy. This study aims to prove that one can create energy and emission savings with simple weather and emission predictive control (WEPC). Furthermore, this should prove that the simplicity of this approach is key for the applicability of this concept in the built world. A thermodynamic simulation (TRNSYS) evaluates the performance of different variants. The parametrical study varies building construction, location, weather, and emission data and gives an outlook for 2050. The study showcases five different climate locations and reveals heating and cooling energy savings of up to 50 kWh/(m^{2}a) and emission savings between 5 and 25% for various building types without harming thermal comfort. This endorses the initial statement to simplify building energy concepts. Furthermore, it proposes preventing energy designers from overoptimizing buildings with technology as the solution to a climate-responsible energy concept.

Author Contributions

Conceptualization, C.H., B.G., C.M., and T.A.; methodology, C.H. and B.G.; software, C.H. and B.G.; validation, C.H., C.M., and T.A.; formal analysis, C.H. and B.G.; investigation, C.H., B.G., and T.A.; resources, C.H., B.G., C.M., and T.A.; data curation, C.H. and C.M.; writing—original draft preparation, C.H.; writing—review and editing, C.H., B.G., C.M., and T.A.; visualization, C.H. and B.G.; supervision, C.M. and T.A.; project administration, C.H.

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6.1 Introduction

With climate neutrality being the EU's goal in 2050, dramatic changes in the building industry are more than necessary, as the sector accounts for 40% of the global carbon emissions [6-1]. The building operation alone is responsible for 28% [6-2]. In addition to the renovation strategies addressing the building envelopes, the modern approach to electrifying the building operation using heat pumps promises energy savings and, thus, CO_2-reductions. However, not only the building but also the mobility industry is increasingly focusing on electric concepts. Combined with the increasing fluctuation in electrical energy production based on the rising share of renewable sources in the grid, intelligent control strategies are essential [6-3]. Today, additional energy will be provided by a power plant that still has spare capacity. These marginal power plants usually run on fossil fuels and emit a high amount of CO_2 [6-4].

Various concepts and data-driven control strategies, based on model predictive control, deep learning, weather forecast, or artificial intelligence, have been developed in the last decade, outlining energy and CO_2-saving potentials [6-3, 6-5–8]. Thereby, a few hurdles make it difficult to transform the concept into practice: data-intense algorithms, the creation of digital twins, or the necessity of highly educated employees to manage building technology. Standard building users or building operation managers are no data science experts and cannot apply these concepts to the built world. In international norms and codes, it is standard to consider a continuous static emission factor over the year. Several studies show that this leads to substantial rebound effects and does not represent reality. These studies ask for an hourly-based, dynamic emission value to address the fluctuation in the emissions in the electrical energy grid in a correct manner and to open up the potential for intelligent control strategies. [6-3, 6-9–11] As this phenomenon depends on the electrical energy grid and the local weather conditions of a building, this is not only a problem for Germany but demands international application, as presented in this contextual parametric study.

This Introduction further outlines the objective of the topic by formulating an overall hypothesis and linked research questions. Further, the methodology explains the simulation structure and revises two previous individual simulation approaches that form its basis. The following section Data and Methods describes the simulation base case model and the considered simulation variants for the parameter study. Finally, this section illustrates the weather and the characteristics of the emission data of the electrical grid for all five climate locations. Section 6.3, Results and Evaluation, presents the main findings of the thermal simulations and prepares for the section 6.4 Discussion and 6.5 Conclusion, where the initially stated hypothesis and research questions are evaluated.

6.1.1 Objective

As previously outlined, the electric demand in the building and the electricity grid continues to play a significant role in mitigating the effects of ongoing climate change. Nevertheless, with these sustainable transformations in energy supply for buildings and mobility (e.g., using heat pumps or electric cars), the overall demand for electrical energy rises significantly and becomes less predictable. To account for this scenario, the share of renewable energy must be significantly increased. But for renewable energies, especially for photovoltaics (PVs), the electrical output depends on the local weather conditions, leading to prominent fluctuations in supply. This situation plays a significant role in the transformation process of the overall goal of the European Union and transformed into German law with the Generation contract, of climate neutrality in 2050 [6-6–12]. This momentum is further transformed into German law, called the Generation contract [6-12, 6-13]. This leads to the main idea of this paper, which demands a simple approach, performing a weather and emission predictive control of building technology. This paper presents a parametric study of five different locations, considering the individual climate and electricity emission conditions. To evaluate the impact of the concept, this paper addresses the following hypothesis and the connected research questions for each climate location:

The simple concept of weather and emission predictive control improves the overall energy performance and emission balance of a building without harming thermal comfort.

- What impact does insulation and thermal mass have on the performance of the WEPC?
- How does a photovoltaic system impact the emission balance using the WEPC with thermal and electrical storage?
- Does the WEPC improve a room's energy performance and CO_2 balance without compromising thermal comfort?
- How does the WEPC perform in 2050, considering future weather and emission data that account for an increased share of renewable energies?

6.1.2 Methodology

This study combines the concepts of a series of papers and summarizes the overall approach. The first paper validated the thermodynamic model using an in situ measurement room [6-14]. Both the second and third papers outlined a concept focusing on the impact of a CO_2-optimized and weather predictive control [6-3, 6-15]. This paper combines the two building control approaches into one simulation model using a validated thermodynamic simulation model. Based on these assumptions, a parametric study focuses on the impact of thermal mass, insulation, and a thermal and electrical storage system with PV. This parametric study is completed with an outlook on the behavior of control strategies in the future, assuming weather and emission data for 2050. These parameters are varied for five different climate locations to evaluate the effect on an international level. Finally, based on this parametric study, the initial research question and the linked hypotheses are answered. The following two sections review the overall approaches of the previous studies and outline the main findings of the two individual concepts.

Review – Impact of a dynamic emission factor optimized control

With the electrification of energy production for buildings and mobility, the electricity grid's emission factor (EF) plays a significant role in evaluating sustainability. Currently, the calculation of the CO_2 emission footprint focuses on static EFs. However, with the increasing fluctuation in the electrical grid on both the demand and supply side, the EF behavior becomes more and more dynamic. On the one side, this enhances the criticism of the miscalculation of emission footprints. On the other side, it opens up enormous potential for CO_2 savings, going hand in hand with smart control strategies. The dynamic emissions are calculated according to the following equation:

$$E_{dyn} = \sum_{t=1}^{8760} \left(p_{net}(t) \cdot \frac{ef(t)}{1000} \right) \tag{6-1}$$

This study suggests that the dynamic balance for different building system variants deviates considerably from the static approach and opens possibilities to decrease emissions [6-3]. The research gap, founded on the literature review, outlines that the emission balance of a building operation changes when using dynamic EFs that map fluctuations at an hourly resolution. The results show that the dynamic balance approach deviates from the static one. Further, this paper’s predictive loading strategies outperform standard control strategies. This increases with building systems with inert storage units and/or PV integration, where charging time plays a significant role. As this paper focuses on a German location, the authors motivate further research on an international level with different electricity grids and weather conditions. They add that a broader view of the concept, such as the predictive control of variables focusing on energy efficiency, could result in new possibilities and transform buildings in thermal and emission short-term storage.

Review – Impact of a dynamic emission factor optimized control

With the ongoing digitalization and electrification trends in Germany, using electrical heat pumps, the energy supply for buildings follows that pass. This leads to the demand for smart control strategies, especially with inert building systems. This study deals with a simple weather predictive control (WPC) approach, using thermally activated building systems (TABS) to create energy savings while providing thermal comfort [6-15]. The research gap of this paper is based on the phenomena of the performance gap [6-16], as well as on the energy saving potentials of the concepts of thermal mass [6-17, 6-18] and insulating additively manufactured façade elements [6-19], the availability of weather data [6-8, 6-15], and the dynamic nature of thermal comfort perception [6-20–23]. It is apparent that various smart building control approaches are data-intensive and complex, which limits their implementation. The WPC instead uses the future ambient temperature and solar radiation that every office building usually measures. The heating, cooling, ventilation, and sun protection systems are addressed to increase thermal comfort and improve the energy performance of a Munich-based office building. Via a logarithmically mitted trend of future weather data, the building technology is adapted to the actual time step of the control algorithm. Using WPC for TABSs, this paper shows that thermal comfort improves without increasing the energy demand. In office buildings with high thermal mass, this trend is further improved. The overall goal of using a simple approach like the WPC is to improve performance while sticking to the fundamentals of an easy application in the built environment. Finally, this paper concludes that a future parametric study can identify further possibilities for the impact of the WPC. Furthermore, it is outlined that the approach should be extended to broader parameters such as CO_2 to evaluate the building operation. This supports the Euro-pean carbon roadmap goal of climate neutrality in 2050 [6-12]. The following equations for the heating and cooling curve, sun shading, and natural ventilation control perform as the weather predictive control, using the future radiation and ambient temperature for optimization:

Heating and cooling curve

$$T_{supply,HT} = \max(25.4 - 0.27 \cdot Tamb_{future}, 22) - \delta T_{Qsol,future} \tag{6-2}$$

$$T_{supply,CL} = \min(25.4 - 0.27 \cdot Tamb_{future}, 18) - \delta T_{Qsol,future} \tag{6-3}$$

Sun shading

$$signal_{shading} = gt(Tamb, 14) \cdot (gt(rad_{sur}, 200) + gt\left(rad_{sur,future}, 150\right)) \tag{6-4}$$

Ventilation (daytime)

$$AC_{work} = 0.2 \cdot signal_{work} \cdot lt(AC_{23}, 1.5) \cdot lt(AC_{25}, 3) \cdot lt(AC_{27}, 6) \tag{6-5}$$

$$AC_{23} = 1.5 \cdot gt(Tair, Tamb) \cdot lt(AC_{25}, 3) \cdot lt(AC_{27}, 6) \cdot gt(gt(Tair, 23) + gt(Tamb_{future}, 23),0) \tag{6-6}$$

$$AC_{25} = 3 \cdot gt(Tair, Tamb) \cdot lt(AC_{27}, 6) \cdot gt(gt(Tair, 25) + gt(Tamb_{future}, 25), 0) \tag{6-7}$$

$$AC_{27} = 6 \cdot gt(Tair, Tamb) \cdot gt(gt(Tair, 27) + gt(Tamb_{future}, 27), 0) \tag{6-8}$$

6.2 Data and Methods

This section outlines the fundamental data used to perform the thermodynamic simulation. The section on thermodynamic simulation describes the overall workflow, software structure, and the tools used to perform the two-step simulation. The following subsections detail the base case model Solarstation and the simulation variants. The last section explains the weather and emission data of the five different climate and electricity grid locations to prepare for the results of the following section.

6.2.1 Thermodynamic simulation

This paper uses three simulation software tools. The fundamental thermodynamic building simulation is performed in TRNLizard, representing the parametric version of TRNSYS 18 in the software environment of Rhino 3D [6-24, 6-25]. TRNLizard is illustrated in the visual programming interface Grasshopper. Here, the building and weather data are implemented. HoneyBee, [6-26], the second simulation software, performs the radiation simulation for the PV system. The third (static) simulation is performed in Grasshopper only. Here, the previously generated building energy data, radiation data, and the hourly emission data of the electrical grid evaluate the emission balance, focusing on the building operation.

Figure 6-1 displays the workflow of the thermal simulation. The first simulation step in TRNLizrad uses weather and building-related data to generate annual energy and comfort data for the building. The weather predictive control uses the logarithmically mitted trend of local weather data. In the second step, a radiation analysis with HoneyBee is performed. Combined with the previously generated building energy data and the annual emission factor, these data evaluate the impact on emission performance using the Grasshopper software tool. Here, the previously outlined CO_2-predictive control can be applied, focusing on the 24-hour minima of CO_2 emissions. In general, this paper uses the thermal comfort, the energy demand, and the emission balance as evaluation parameters.

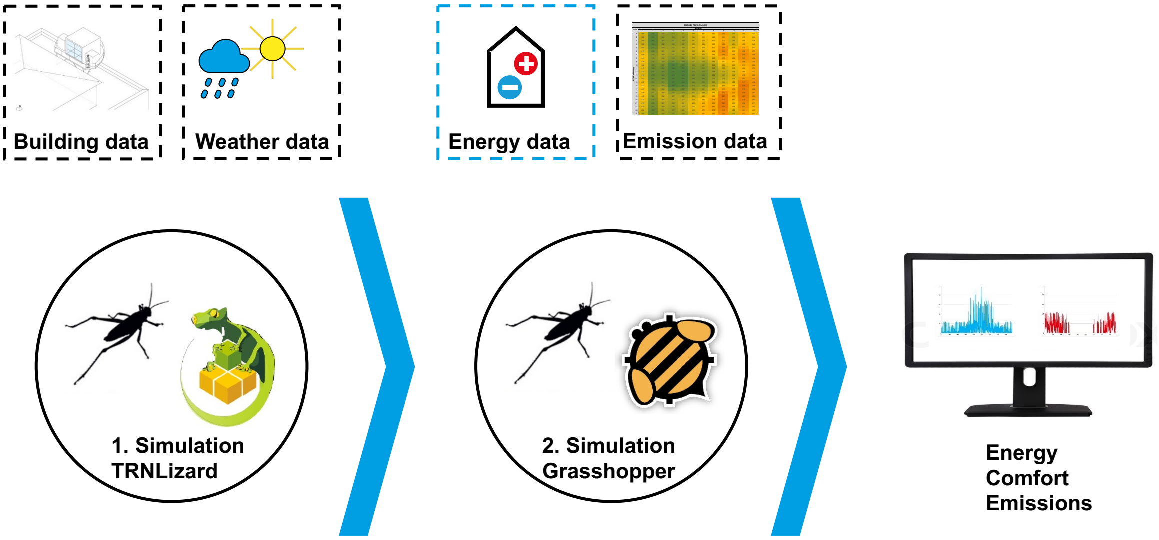


Figure 6-1: Graphical overview of the simulation workflow (own representation)

Base case model

The basic building model represents an in-situ test facility, the Solarstation, a 23° southwest-oriented office room located on a rooftop in the urban environment of Munich. The room has a length of 4.30 m, a width of 4.30 m, a height of 3.30 m, and a large glass façade with a window-to-wall ratio of 90%. Venetian blinds, manually and automatically operable windows, and TABS represent the building technology. This covers a shading, ventilation, heating, and cooling system. The thermal characteristics of the building constructions are as follows: roof U-value 0.222 W/(m^{2}K), external wall U-value 0.175 W/(m^{2}K), floor U-value 0.266 W/(m^{2}K), internal wall U-value 0.437 W/(m^{2}K), window U-value 0.68 W/(m^{2}K), thermal bridges 0.1 W/(m^{2}K) and infiltration air change rate 0.2 1/h. In a previous study, the digital, thermodynamic model was validated with local weather and building measurement data, following the criteria of the ASHRAE guideline 14:2002 [6-14, 6-27] The validation can be confirmed using the normalized mean bias error, the coefficient of variation of the root mean square error, and the coefficient of determination for four type weeks.

The building system model displays the thermal and electrical storage in combination with a photovoltaic system. In general, the electrical power of the PV system is used to charge the storage. In that case, in practice, the thermal storage uses a heat pump to charge up. The discharging capacity is equivalent to the simulated energy demand of the building simulation without transportation losses (e.g., cables or ducts). The details of the system configuration and the prioritization of energy usage are outlined in detail in a previous paper [6-3].

The control strategy of the building technology has two modes: with and without predictive control (WEPC On/Off). In the predictive mode, the control strategy consists of two parts. The weather predictive control uses a 24 hour logarithmically mitted trend of the future ambient temperature and solar radiation. This means that time steps closer to the present are weighted higher, but all 24 time steps have an impact. The control parameters of sun shading, ventilation, heating, and cooling systems are adapted compared to a standard control strategy. The detailed equations of the concepts about weather predictive control are outlined in a previous paper [6-15]. The second part of the predictive mode addresses the energy supply when filling the storage. Therefore, the minima of the next 24 hour time steps of the emissions are identified in every time step to create a five-hour period to load up the storage system. The following parameters are adapted to the building model: storage capacity, rated charging capacity, un-loading capacity, control strategy for charging, limit temperature for charging, storage losses, and storage efficiency. The standard loading strategy instead comprises a constant period to set the storage from 10 a.m. to 4 p.m. to use the PV energy production during the daytime.

Simulation variants

This paper uses a parametric study to answer the initially stated research questions and the hypothesis. The simulation is performed various times with slight changes in the assumptions to identify the impact. These changes are divided into simulation variant categories.

The first simulation variant category focuses on the impact of the climate location. Thereby, five different locations in different climate zones according to Köppen Geiger are chosen, representing a moderate, tropical, subtropical, dry, and cold climate. This simulation variant category not only varies the climate location but also compares the concept's impact on different levels of the electricity grid system, as the locations, by nature, are connected to their countries' national electricity grid.

One of the primary outcomes of both previous studies was that the intelligent control strategies' energy and CO_2-saving potentials could be much higher with poorly insulated buildings. This forms the second simulation variant category. Hence, the U-values of the measurement room, which fulfill the thermal requirements of the German building code [6-28], are increased for the external wall from 0.22 to 1.0 (W/m^{2}K) and the window from 0.7 to 1.7 (W/m^{2}K). These buildings could have more saving potential and represent the not-refurbished, primary building stock worldwide, not only in Western countries like Germany.

As mentioned in both previous studies, the third simulation category, thermal mass, considerably impacts Munich's energy and CO_2 performance. Again, this paper analyzes the effect of light, middle, and heavy constructions. According to Din 4108-2, thermal mass quality is evaluated with the specific heat capacity Cw/A. These are the categories as follows: heavy : (Cw/A >130 (K m^2)), middle (Cw/A between 130 (K m^2) and 50 (K m^2)) and light (Cw/A >50 (K m^2)) [6-29]. This is especially interesting in combination with well- and not-well-insulated buildings, as it analyses the effect of traditional and non-traditional building styles in the various climate locations.

As emission and energy storage are two of the main objectives of this concept, the fourth category focuses on building technology. One simulation represents a thermal and electrical storage building system and an ideal heat pump. The second variant adds a photovoltaic system, enlarging the concept. The building technology is sized according to the previous studies. The thermal storage has a capacity of 2.52 kWh and a loading power of 0.37 kW, while the electrical storage comprises a capacity of 0.9 kWh and holds 0.25 kW loading power. The office is connected to a 1 m^2 PV area, and the COP for the air-to-air heat pump for heating is 5.24, while the COP for cooling accounts for 4.0, representing a ground-floor system. This analysis can help to understand the impact of a building as an energy or potential CO_2 storage.

The last variant category focuses on the outlook and future behavior of the built world. Thereby, weather data for the year 2050 following the IPCC scenario RCP 8.5 are assumed to estimate the impact of the predictive control strategy [6-30]. In addition, the emission factor is lowered in all locations by 50%. While this assumption is rather simple and will only give a small insight into future behavior, predicting future emission factors depends on many factors, e.g., politics, society, funding for renewable energies, and local conditions to extend the renewable powers. These factors are highly unpredictable. Developing a more precise prediction method for the emission factor is beyond the scope of this paper. Figure 6-2 illustrates an overview of the simulation variant categories that result in 240 simulation variants.

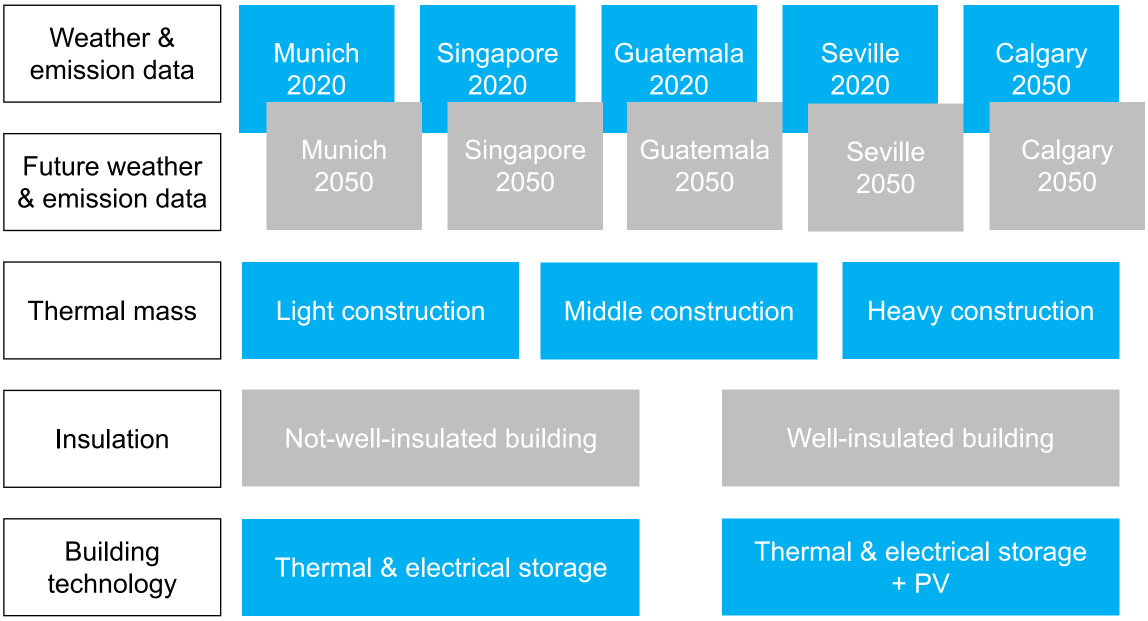


Figure 6-2: Graphical summary of the simulation variant categories (own representation)

6.2.2 Weather data and emission data

The following subsections outline the weather and emission data of the five climate locations. To generate an overall, worldwide impression of the impact of the energy and emission-saving potential of the control strategy, the first criterion in the sections of the location is their climate category according to Köppen Geiger: Munich, Germany (moderate – Cfb), Singapore City, Singapore (tropical – Af), Guatemala City, Guatemala (subtropical – Cwa), Sevilla, Spain (hot/dry summer – Csa) and Calgary, Canada (cold – Dfc). At the same time each location is connected to its national electricity grid, with a different dynamic composition and behavior regarding emissions, mainly based on the share of integrated renewable energies.

Two types of graphs are used to analyze the individual climate locations. The first focuses on the weather data, displaying the temperature and radiation. The minimum and maximum temperature of the month and the dynamic annual dry bulb temperature are outlined in °C, linked to the left y-axis. The right axis displays the monthly radiation in kWh/m^2. Solid lines show the weather data for 2020, whereas dashed lines represent the future weather data for 2050. The weather data found in each location's typical meteorological year (TMY) data set is interpolated for 2050 using the IPCC RCP 8.5 scenario [6-30, 6-31]. The thresholds for the axis are identical for all climates to maintain comparability, even though it sometimes reduces the readability of the graphs.

The second figure outlines the annual dynamic emission data of the location. The carpet plot follows the daily 24 hours on the y-axis, while on the x-axis, the months of the year are listed. This forms an overview of the hourly emission factor averaged each month, with high emission values in red and low values in green. The data use the production capacity, level of consumption, electricity import and export, and the electricity price of the power grid to calculate an hourly emission value [6-32]. The thresholds of the color scale are kept constant for all five locations to maintain comparability, even though it reduces the data quality for each site.

Moderate Climate – Munich

Munich is in southern Germany and has a humid continental climate with cold winters and mild summers (Köppen Geiger: Cfb). In 2020, the city had an average ambient temperature (TAMB) of 10.4°C, with maximum temperatures reaching 36.5°C and minimum temperatures dropping to -7.6°C (Figure 6-3) [6-33]. The primary solar radiation hits in the summer, but in the spring and fall seasons, solar radiation can cause overheating. Heating systems are standard, while cooling units, for the most part, are only used in formal offices.

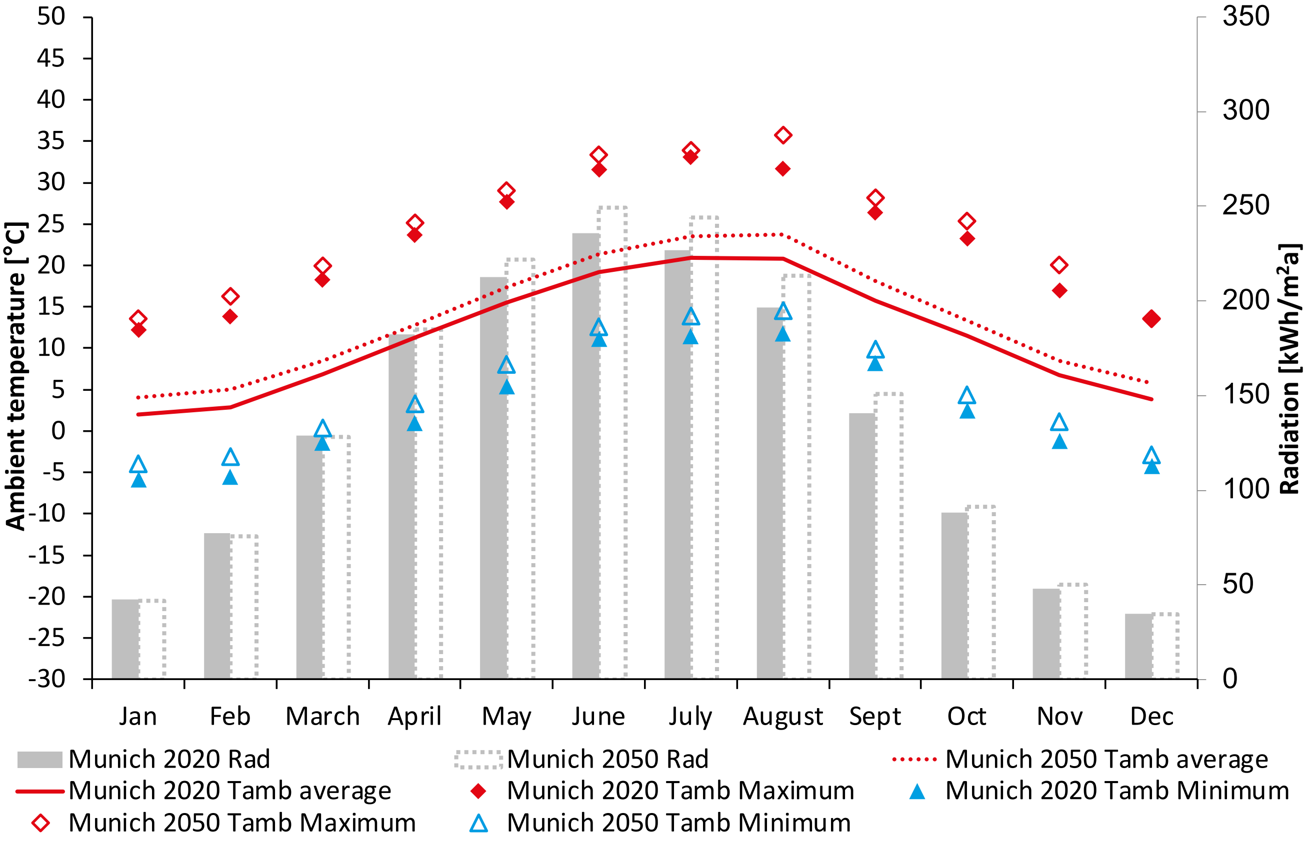
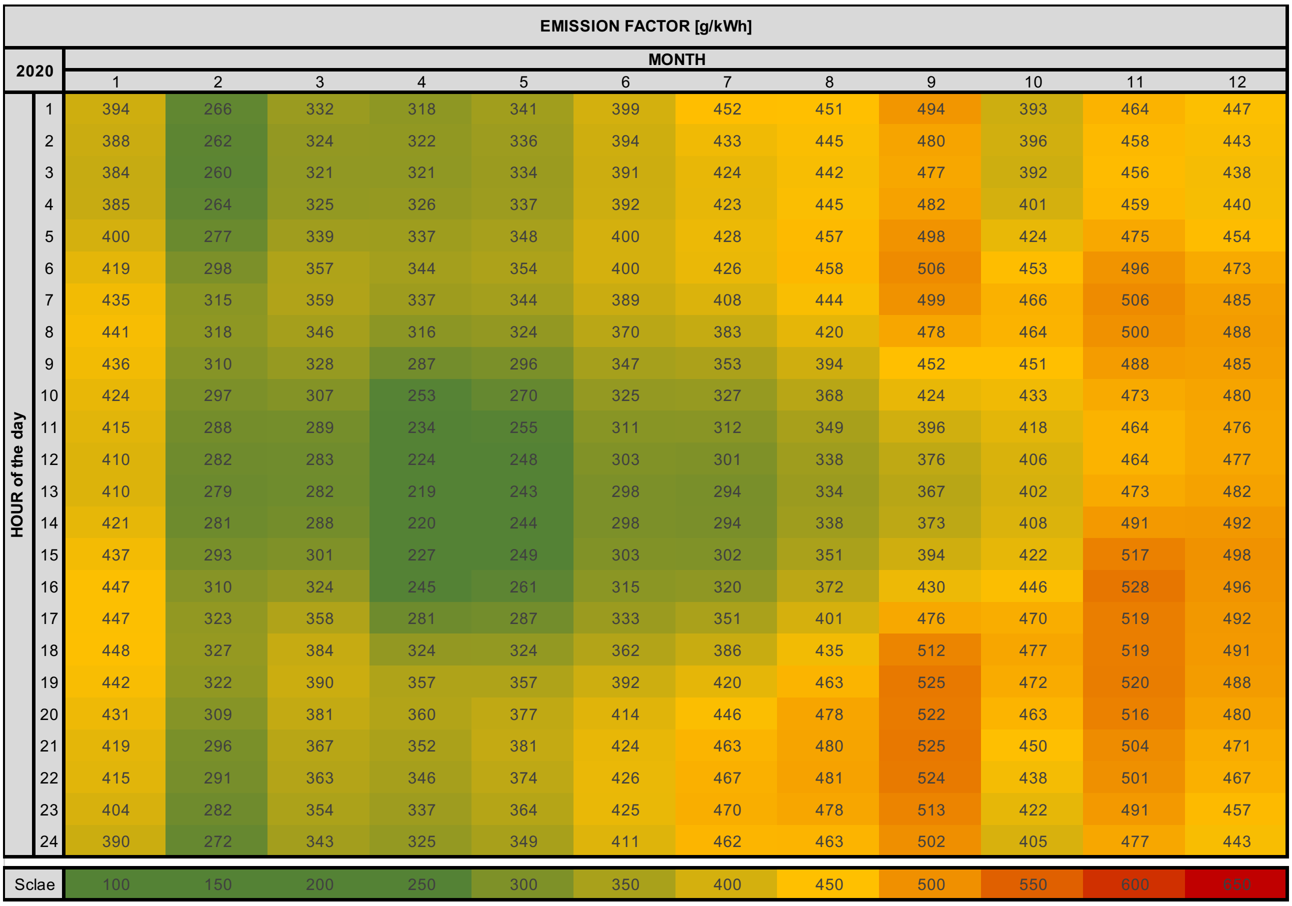


Figure 6-3: Cumulative global horizontal radiation and maximum, minimum, and average ambient temperatures per month in Munich 2020 and 2050 (own representation – data [6-31])

Figure 6-4 illustrates the overall annual CO_2 emissions [6-32]. During the day, emissions are generally lower based on photovoltaics, especially in summer. In the cold periods, including spring, emissions are lower all across the day, as wind energy dominates the emission value. The overall average value of 392 g/kWh is still relatively high and leaves room for improvement.



EMISSION FACTOR [g/kWh]													
2020		MONTH											
		1	2	3	4	5	6	7	8	9	10	11	12
HOUR of the day	1	394	266	332	318	341	399	452	451	494	393	464	447
	2	388	262	324	322	336	394	433	445	480	396	458	443
	3	384	260	321	321	334	391	424	442	477	392	456	438
	4	385	264	325	326	337	392	423	445	482	401	459	440
	5	400	277	339	337	348	400	428	457	498	424	475	454
	6	419	298	357	344	354	400	426	458	506	453	496	473
	7	435	315	359	337	344	389	408	444	499	466	506	485
	8	441	318	346	316	324	370	383	420	478	464	500	488
	9	436	310	328	287	296	347	353	394	452	451	488	485
	10	424	297	307	253	270	325	327	368	424	433	473	480
	11	415	288	289	234	255	311	312	349	396	418	464	476
	12	410	282	283	224	248	303	301	338	376	406	464	477
	13	410	279	282	219	243	298	294	334	367	402	473	482
	14	421	281	288	220	244	298	294	338	373	408	491	492
	15	437	293	301	227	249	303	302	351	394	422	517	498
	16	447	310	324	245	261	315	320	372	430	446	528	496
	17	447	323	358	281	287	333	351	401	476	470	519	492
	18	448	327	384	324	324	362	386	435	512	477	519	491
	19	442	322	390	357	357	392	420	463	525	472	520	488
	20	431	309	381	360	377	414	446	478	522	463	516	480
	21	419	296	367	352	381	424	463	480	525	450	504	471
	22	415	291	363	346	374	426	467	481	524	438	501	467
	23	404	282	354	337	364	425	470	478	513	422	491	457
	24	390	272	343	325	349	411	462	463	502	405	477	443
Sclae		100	150	200	250	300	350	400	450	500	550	600	650

Figure 6-4: Emission data of the electricity grid in Germany 2020, according to the hours per day and month over the year (own representation – data [6-32])

Looking ahead to 2050, climate models predict Munich will experience an overall warming trend, with average temperatures increasing by 2-3°C [6-34]. This increase in temperature is likely to be accompanied by more frequent and intense heat waves, as well as an increase in the frequency and severity of extreme weather events such as heavy rainfall and flooding. Based on the urban heat island effect, these numbers could even be exceeded in a city like Munich [6-35]. However, several measures could be taken to mitigate the impacts, including implementing green roofs, creating urban parks and green spaces, and installing water areas. As Germany is part of the EU and committed to climate neutrality, a significant increase in renewable energies and lower emissions all across the year can be expected.

Tropical climate – Singapore

In 2020, Singapore experienced warm and humid weather conditions throughout the year, categorized Af by Köppen Geiger. Figure 6-5 shows that Singapore's ambient temperature remains consistent, with average highs from 29 to 33°C and lows from 23 to 27°C, with heavy rainfalls in the rainy season. The city-state is near the equator, resulting in a tropical climate with minimal seasonal variations, as illustrated in Figure 6-5. However, the humidity levels often make the perceived temperature feel higher than the actual readings. Singapore also receives significant solar radiation throughout the year due to its proximity to the equator. The city experiences around 1900 to 2200 hours of sunshine annually [6-36].

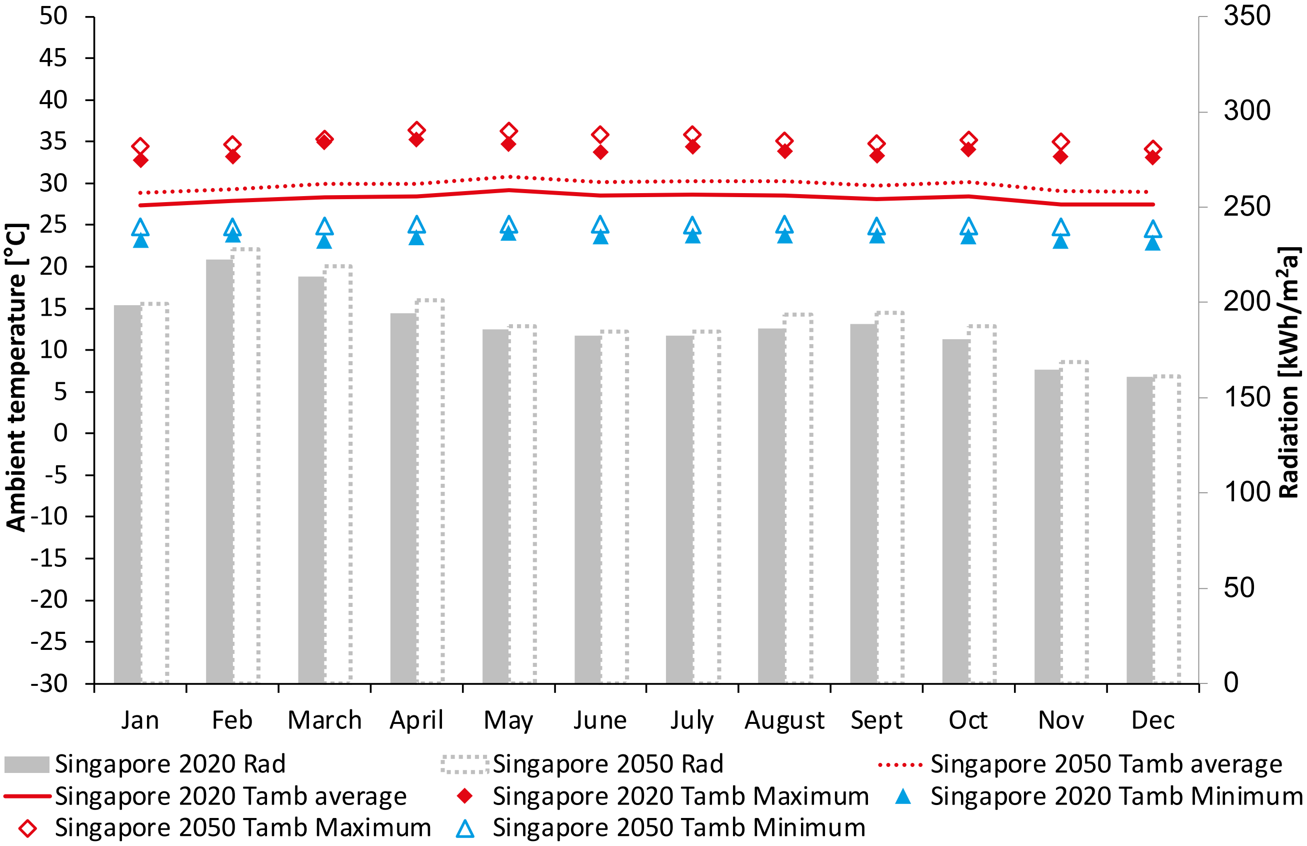
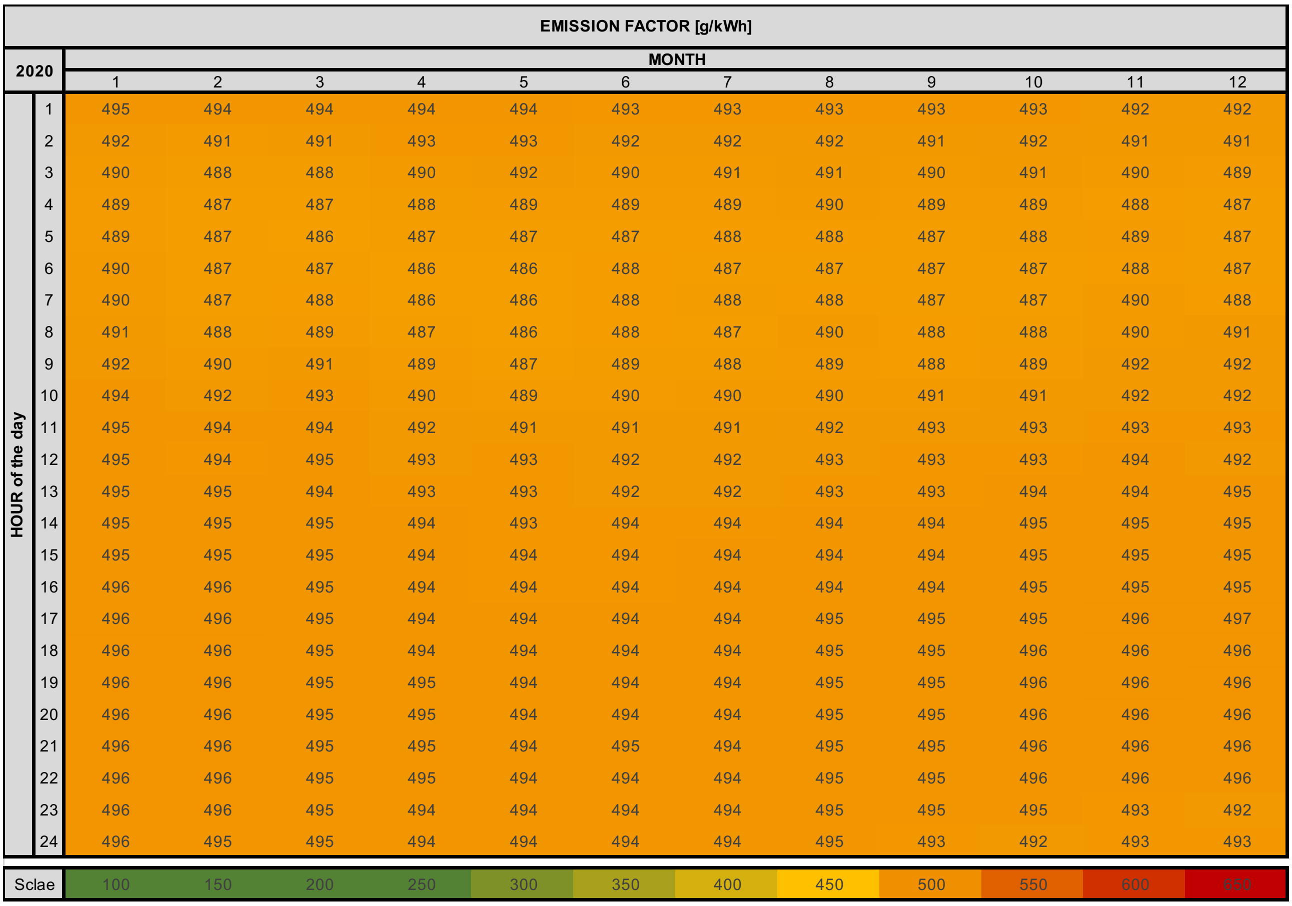


Figure 6-5: Cumulative global horizontal radiation and maximum, minimum, and average ambient temperatures per month in Singapore 2020 and 2050 (own representation – data [6-31])

As a small, densely populated city-state with limited land resources, Singapore heavily relies on imported energy sources, mainly natural gas, to generate electricity. Natural gas is a cleaner fossil fuel than coal and oil, resulting in lower but nearly constant yearly emissions, as shown in Figure 6-6. But of course, the state needs to use its very high potential for renewable energies in the future, as high solar radiation is present all year long.



EMISSION FACTOR [g/kWh]													
2020		MONTH											
		1	2	3	4	5	6	7	8	9	10	11	12
HOUR of the day	1	495	494	494	494	494	493	493	493	493	493	492	492
	2	492	491	491	493	493	492	492	492	491	492	491	491
	3	490	488	488	490	492	490	491	491	490	491	490	489
	4	489	487	487	488	489	489	489	490	489	489	488	487
	5	489	487	486	487	487	487	488	488	487	488	489	487
	6	490	487	487	486	486	488	487	487	487	487	488	487
	7	490	487	488	486	486	488	488	488	487	487	490	488
	8	491	488	489	487	486	488	487	490	488	488	490	491
	9	492	490	491	489	487	489	488	489	488	489	492	492
	10	494	492	493	490	489	490	490	490	491	491	492	492
	11	495	494	494	492	491	491	491	492	493	493	493	493
	12	495	494	495	493	493	492	492	493	493	493	494	492
	13	495	495	494	493	493	492	492	493	493	494	494	495
	14	495	495	495	494	493	494	494	494	494	495	495	495
	15	495	495	495	494	494	494	494	494	494	495	495	495
	16	496	496	495	494	494	494	494	494	494	495	495	495
	17	496	496	495	494	494	494	494	495	495	495	496	497
	18	496	496	495	494	494	494	494	495	495	496	496	496
	19	496	496	495	495	494	494	494	495	495	496	496	496
	20	496	496	495	495	494	494	494	495	495	496	496	496
	21	496	496	495	495	494	495	494	495	495	496	496	496
	22	496	496	495	495	494	494	494	495	495	496	496	496
	23	496	496	495	494	494	494	494	495	495	495	493	492
	24	496	495	495	494	494	494	494	495	493	492	493	493

Sclae	100	150	200	250	300	350	400	450	500	550	600	650

Figure 6-6: Emission data of the electricity grid in Singapore 2020, according to the hours per day and month over the year (own representation – data [6-32])

Climate change in Singapore is having a significant effect on both the environment and architecture of the city. Elevated temperatures and increased rainfall patterns are already being observed in Singapore, which could lead to increased air pollution, rising seas, and compromised biodiversity in the region [6-37]. Furthermore, changes in the climate, from extended rainfall periods to more extreme and frequent storms, present the city with many challenges in adapting building styles to withstand climatic conditions [6-38]. In order to remain sustainable, Singapore has to gradually adapt its urban infrastructure to become more climate resilient [6-39]. Therefore, renewable energies could play a significant role. Solar radiation is very high, and there are several potentials for hydropower. The government has set ambitious goals and outlined strategies to integrate renewable or renewable energies into its energy mix, such as the 2030 Green Plan or the Solar Nova Program, with the aim to have 2 GWp by 2030.

Subtropical Climate – Guatemala

The capital of Guatemala (Köppen Geiger: Cwa) is situated in a valley at an elevation of approximately 1,500 meters above sea level. The ambient temperature in Guatemala City remains relatively stable throughout the year, with average highs ranging from 25 to 28°C and average lows ranging from 13 to 16°C, displayed in Figure 6-7. Due to its altitude, the city enjoys a temperate climate characterized by mild temperatures, especially in the evenings and early mornings. The rainy season, from May to October, brings occasional heavy downpours, while the dry season, from November to April, experiences sunny days with limited rainfall. In terms of solar radiation, Guatemala City benefits from abundant sunlight. Being close to the equator, the city experiences a consistent day length throughout the year, resulting in substantial solar exposure and, therefore, allowing ample opportunities for solar energy utilization and solar power generation.

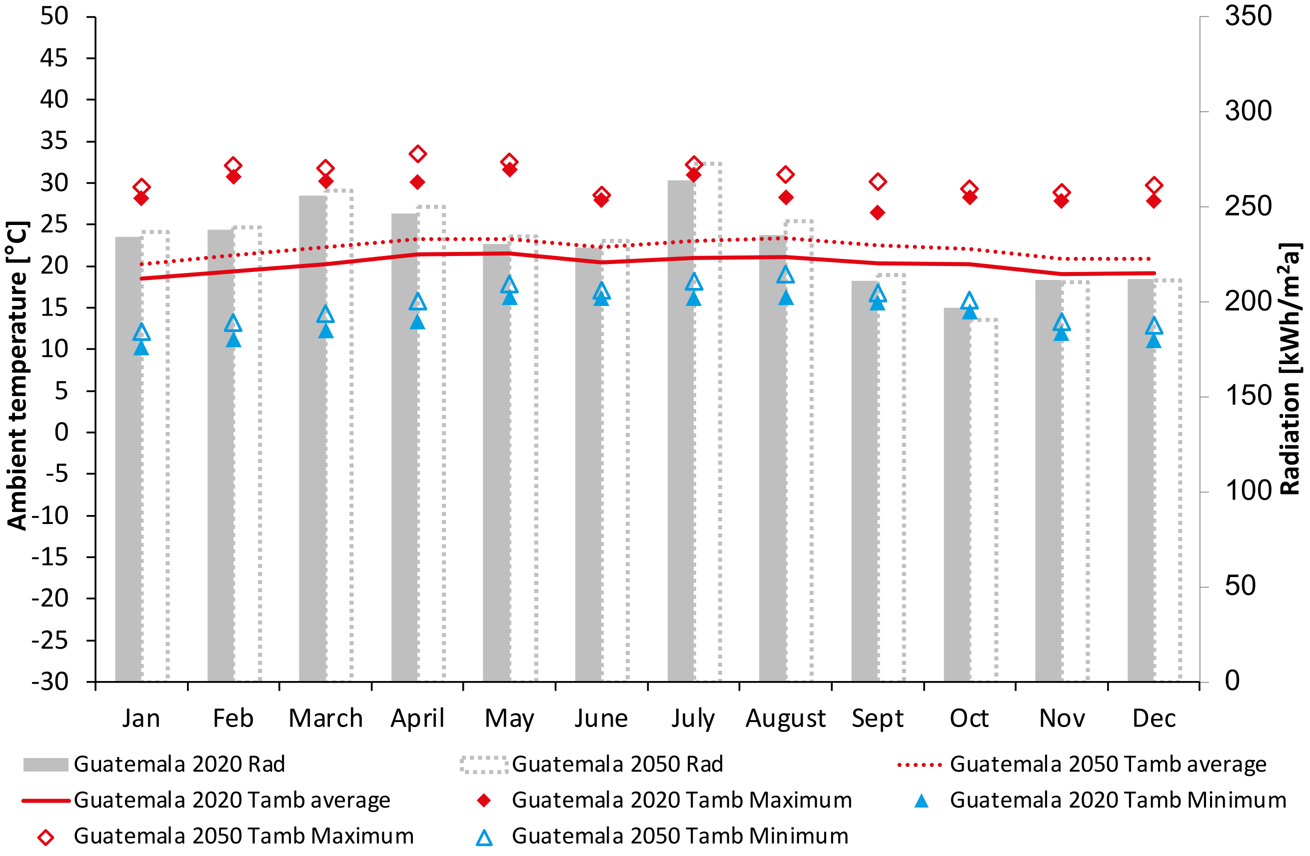
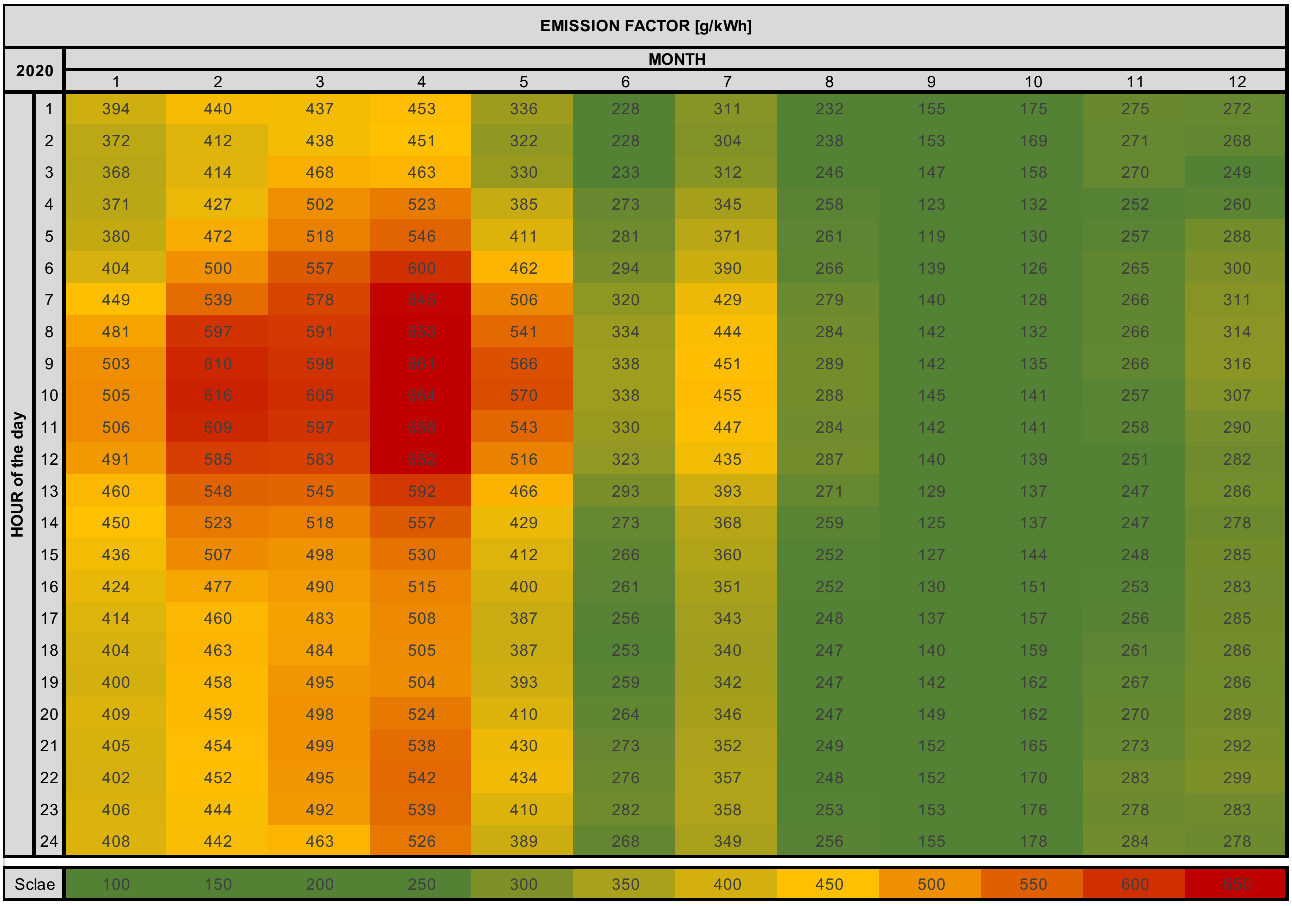


Figure 6-7: Cumulative global horizontal radiation and maximum, minimum, and average ambient temperatures per month in Guatemala City 2020 and 2050 (own representation – data [6-31])

The electricity grid in Guatemala is a complex system that plays a significant role in meeting the country's energy needs. Guatemala's electricity generation primarily relies on renewable and non-renewable energy sources. As Figure 6-8 outlines, the emission factor in Guatemala's electricity grid is relatively low compared to many other countries. Hydropower is Guatemala's dominant renewable energy source, accounting for a substantial portion of electricity production. However, Guatemala has significant potential for expanding its use of renewable energies beyond hydropower. The country has untapped resources for solar energy and wind power. It is essential to note that Guatemala also relies on fossil fuels such as oil and coal for electricity generation.



EMISSION FACTOR [g/kWh]

2020	MONTH											
HOUR of the day	1	2	3	4	5	6	7	8	9	10	11	12
1	394	440	437	453	336	228	311	232	155	175	275	272
2	372	412	438	451	322	228	304	238	153	169	271	268
3	368	414	468	463	330	233	312	246	147	158	270	249
4	371	427	502	523	385	273	345	258	123	132	252	260
5	380	472	518	546	411	281	371	261	119	130	257	288
6	404	500	557	600	462	294	390	266	139	126	265	300
7	449	539	578	645	506	320	429	279	140	128	266	311
8	481	597	591	653	541	334	444	284	142	132	266	314
9	503	610	598	661	566	338	451	289	142	135	266	316
10	505	616	605	664	570	338	455	288	145	141	257	307
11	506	609	597	655	543	330	447	284	142	141	258	290
12	491	585	583	652	516	323	435	287	140	139	251	282
13	460	548	545	592	466	293	393	271	129	137	247	286
14	450	523	518	557	429	273	368	259	125	137	247	278
15	436	507	498	530	412	266	360	252	127	144	248	285
16	424	477	490	515	400	261	351	252	130	151	253	283
17	414	460	483	508	387	256	343	248	137	157	256	285
18	404	463	484	505	387	253	340	247	140	159	261	286
19	400	458	495	504	393	259	342	247	142	162	267	286
20	409	459	498	524	410	264	346	247	149	162	270	289
21	405	454	499	538	430	273	352	249	152	165	273	292
22	402	452	495	542	434	276	357	248	152	170	283	299
23	406	444	492	539	410	282	358	253	153	176	278	283
24	408	442	463	526	389	268	349	256	155	178	284	278

Sclae	100	150	200	250	300	350	400	450	500	550	600	650

Figure 6-8: Emission data of the electricity grid in Guatemala 2020, according to the hours per day and month over the year (own representation – data [6-32])

Predicting the exact weather conditions in Guatemala City in 2050 is challenging, but climate projections suggest increasing ambient temperatures. According to the Guatemalan National Institute of Seismology, Volcanology, Meteorology, and Hydrology [6-40], temperatures are expected to rise due to global climate change. This could lead to more frequent and intense heat waves, affecting public health, agriculture, and water resources, mainly due to the urban heat island effect and urbanization. Based on the already sufficient climate potential for renewable energies, the future emission factor primarily depends on financial and political decisions. To promote renewable energy, Guatemala has implemented policies and incentives to encourage private investments in renewable energy projects [6-41]. Neighboring countries like Costa Rica have already proved that a complete renewable energy grid is possible in that climate.

Hot Mediterranean Climate – Seville

Seville, a city in southern Spain, experiences a Mediterranean climate with dry, hot summers and mild winters (Köppen-Geiger: Csa). The ambient temperature in Seville during 2020 remained consistently high, especially in the summer months. Average highs ranged from 30 to 40°C, with occasional heatwaves leading to even higher temperatures. As shown in Figure 6-9, winters are relatively mild, with average lows ranging from 4 to 8°C-. Like most of Spain, Seville benefits from solar radiation throughout the year. Rainfall is scarce during the summer, with occasional strong showers in the winter months. The relatively dry conditions and high solar radiation levels contributed to Seville’s reputation as one of Europe's hottest cities [6-42].

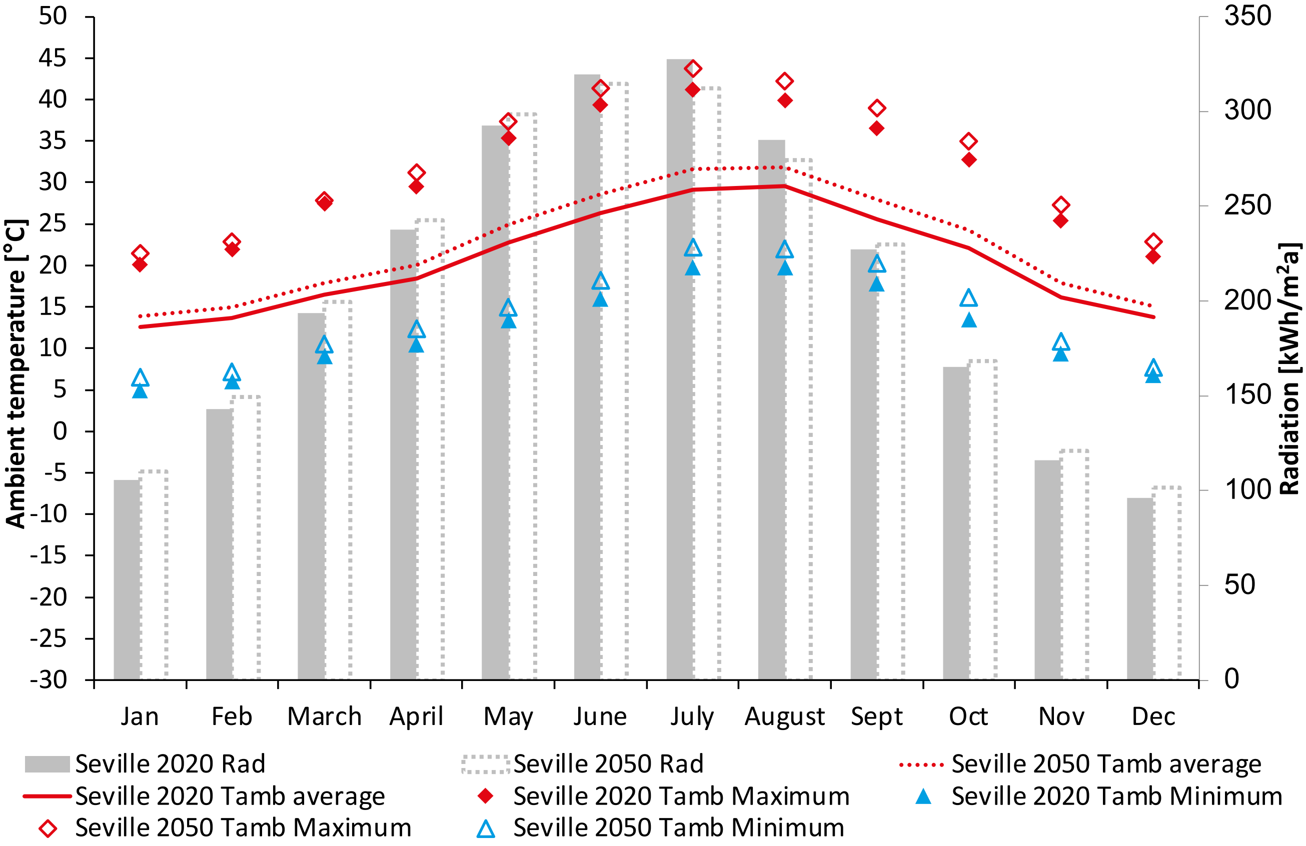
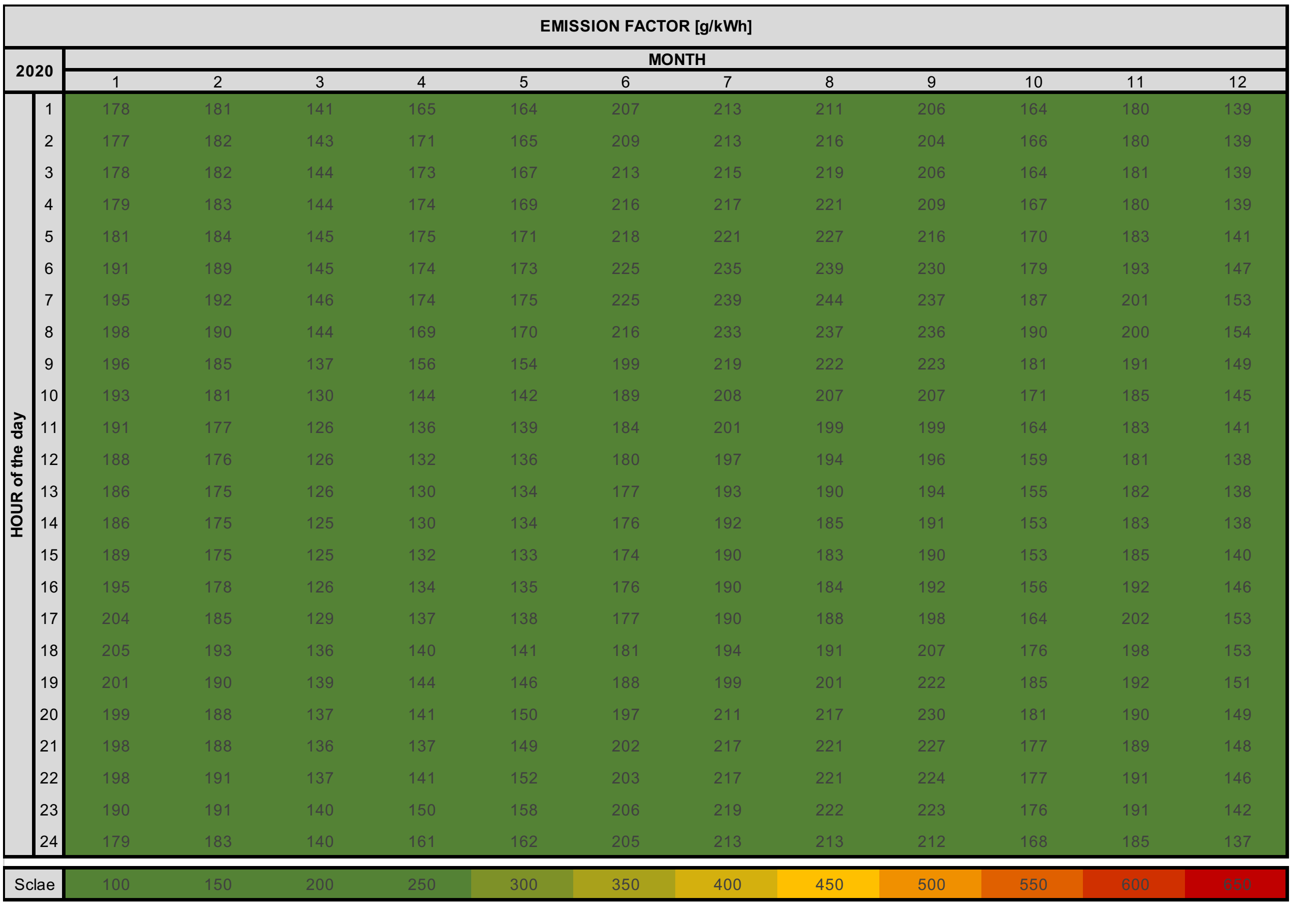


Figure 6-9: Cumulative global horizontal radiation and maximum, minimum, and average ambient temperatures per month in Seville 2020 and 2050 (own representation – data [6-31])

The emission factor in the electricity grid of Spain is influenced by the energy sources used for power generation. Historically, the region has relied on fossil fuels, such as natural gas and coal, contributing to greenhouse gas emissions. However, there has been a growing emphasis on reducing emissions and transitioning to cleaner energy sources in recent years all over Spain. With its high mountains in the middle and the overall high solarization, hydropower, wind, and solar power generation are easily accessible in the area. The country has been actively transitioning to renewable energy sources, with a considerable share of over 50% of its electricity coming from wind, solar, and hydroelectric power [6-43]. As a result, Spain's electricity grid already has a low annual emission value of 178 g/kWh compared to countries heavily reliant on coal-fired power plants, as shown in Figure 6-10.



EMISSION FACTOR [g/kWh]

2020		MONTH											
		1	2	3	4	5	6	7	8	9	10	11	12
HOUR of the day	1	178	181	141	165	164	207	213	211	206	164	180	139
	2	177	182	143	171	165	209	213	216	204	166	180	139
	3	178	182	144	173	167	213	215	219	206	164	181	139
	4	179	183	144	174	169	216	217	221	209	167	180	139
	5	181	184	145	175	171	218	221	227	216	170	183	141
	6	191	189	145	174	173	225	235	239	230	179	193	147
	7	195	192	146	174	175	225	239	244	237	187	201	153
	8	198	190	144	169	170	216	233	237	236	190	200	154
	9	196	185	137	156	154	199	219	222	223	181	191	149
	10	193	181	130	144	142	189	208	207	207	171	185	145
	11	191	177	126	136	139	184	201	199	199	164	183	141
	12	188	176	126	132	136	180	197	194	196	159	181	138
	13	186	175	126	130	134	177	193	190	194	155	182	138
	14	186	175	125	130	134	176	192	185	191	153	183	138
	15	189	175	125	132	133	174	190	183	190	153	185	140
	16	195	178	126	134	135	176	190	184	192	156	192	146
	17	204	185	129	137	138	177	190	188	198	164	202	153
	18	205	193	136	140	141	181	194	191	207	176	198	153
	19	201	190	139	144	146	188	199	201	222	185	192	151
	20	199	188	137	141	150	197	211	217	230	181	190	149
	21	198	188	136	137	149	202	217	221	227	177	189	148
	22	198	191	137	141	152	203	217	221	224	177	191	146
	23	190	191	140	150	158	206	219	222	223	176	191	142
	24	179	183	140	161	162	205	213	213	212	168	185	137

Sclae		100	150	200	250	300	350	400	450	500	550	600	650

Figure 6-10: Emission data of the electricity grid in Spain 2020, according to the hours per day and month over the year (own representation – data [6-32])

Climate projections suggest a continuation of rising ambient temperatures in Seville. According to the Spanish Meteorological Agency, Seville is expected to experience an increase in average temperatures due to climate change and even less frequent but heavier rainfalls [6-42, 6-44]. This could lead to more intense heat waves, with the summer climate transforming into desert-like scenarios. Spain is actively promoting the integration of renewable energies into its electricity grid to combat climate change and enhance sustainability. Renewable energy sources such as hydropower, solar photovoltaic systems, wind farms, and biomass facilities are gaining traction. Solar power is abundant in Seville, making it an attractive option for clean energy production. Based on the Western standard and the holistic potentials in various renewable energy sources, Spain has all the measures to follow the European roadmap of climate neutrality in 2050 [6-12].

Cold Climate – Calgary

As a city in a continental, cold climate (Köppen Geiger: Dfc), Calgary's weather is characterized by distinct seasons. Figure 6-11 presents that the ambient temperature in Calgary during 2020 varied significantly across the seasons. Winters were cold, with average highs ranging from -5 to -2°C, while average lows dropped from -13 to -9°C. Spring and fall brought milder temperatures, with average highs around 10 to 15°C, and summers were warm, with average highs ranging from 20 to 25°C. The weather in Calgary is also influenced by periodic weather systems, such as Chinook winds, which can lead to rapid temperature fluctuations in winter months. Solar radiation in Calgary sees considerable variation throughout the year. Summers experience long daylight hours, providing solar exposure, while winters have shorter daylight periods [6-45].

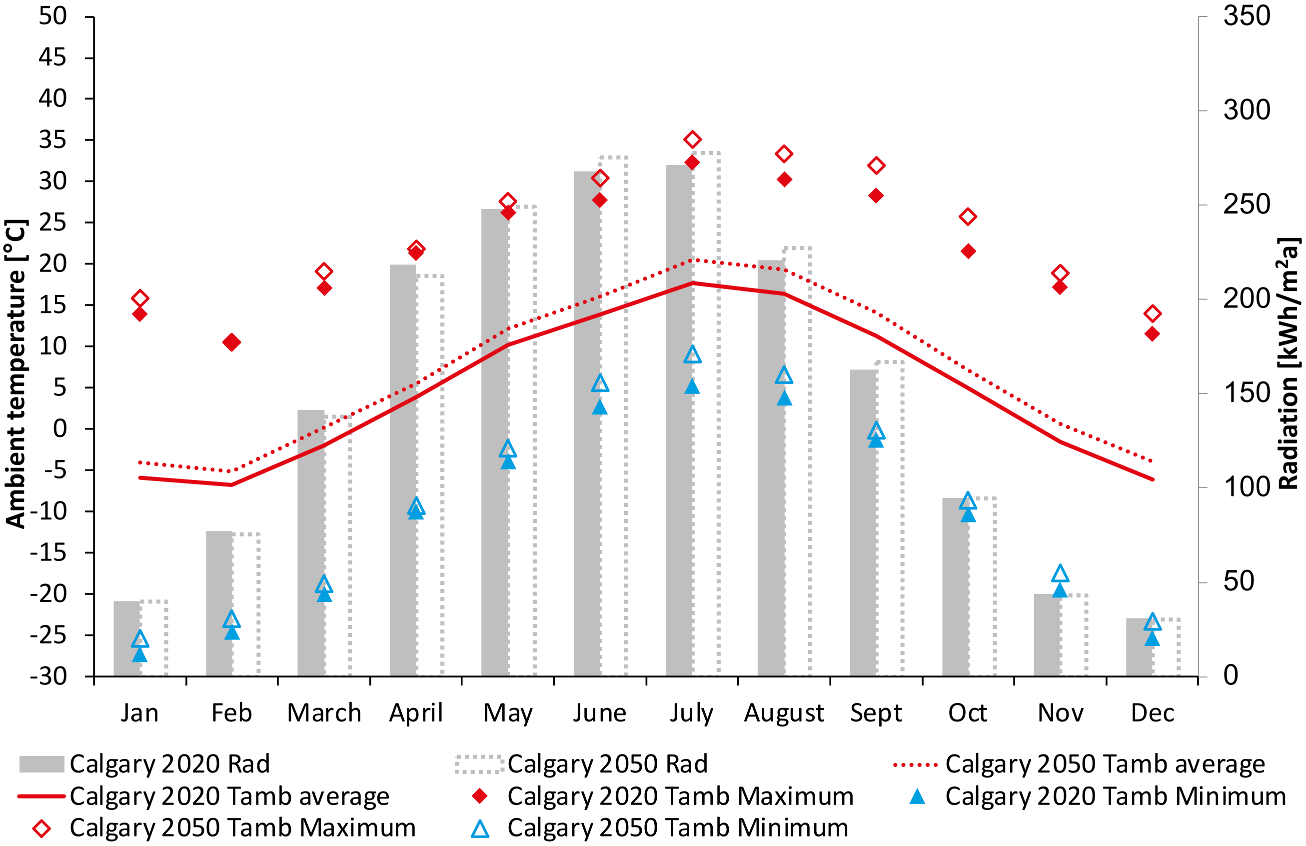
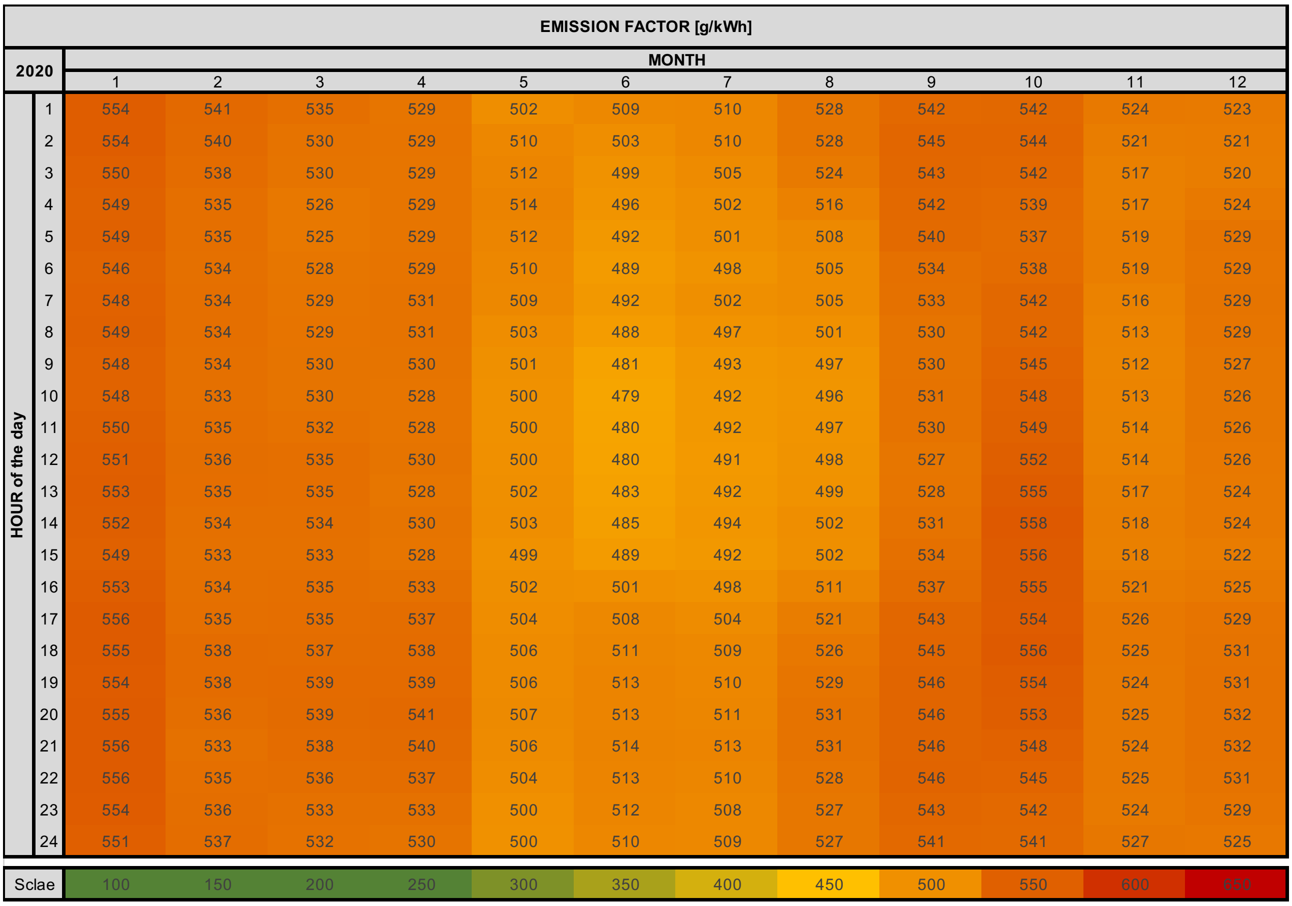


Figure 6-11: Cumulative global horizontal radiation and maximum, minimum, and average ambient temperatures per month in Calgary 2020 and 2050 (own representation – data [6-31])

Alberta's electricity grid has historically relied on fossil fuels, especially coal and natural gas. This dependence on fossil fuels leads to high greenhouse gas emissions. However, in recent years, the province of Alberta and the state of Canada have been making significant strides in incorporating renewable energies into their electricity grid, e.g. with the International Airport of Calgary founding on a geothermal heat pump [6-46]. Renewable energy sources, such as wind, solar, and hydroelectric power, have been integrated into the grid but still comprise a small share. The city's solar potential is moderate compared to more sun-exposed regions, but solar energy remains a viable option for electricity generation and other applications. This results in an annual high emission value with an average of 525 g/kWh, as shown in Figure 6-12.



EMISSION FACTOR [g/kWh]												
2020	MONTH											
HOUR of the day	1	2	3	4	5	6	7	8	9	10	11	12
1	554	541	535	529	502	509	510	528	542	542	524	523
2	554	540	530	529	510	503	510	528	545	544	521	521
3	550	538	530	529	512	499	505	524	543	542	517	520
4	549	535	526	529	514	496	502	516	542	539	517	524
5	549	535	525	529	512	492	501	508	540	537	519	529
6	546	534	528	529	510	489	498	505	534	538	519	529
7	548	534	529	531	509	492	502	505	533	542	516	529
8	549	534	529	531	503	488	497	501	530	542	513	529
9	548	534	530	530	501	481	493	497	530	545	512	527
10	548	533	530	528	500	479	492	496	531	548	513	526
11	550	535	532	528	500	480	492	497	530	549	514	526
12	551	536	535	530	500	480	491	498	527	552	514	526
13	553	535	535	528	502	483	492	499	528	555	517	524
14	552	534	534	530	503	485	494	502	531	558	518	524
15	549	533	533	528	499	489	492	502	534	556	518	522
16	553	534	535	533	502	501	498	511	537	555	521	525
17	556	535	535	537	504	508	504	521	543	554	526	529
18	555	538	537	538	506	511	509	526	545	556	525	531
19	554	538	539	539	506	513	510	529	546	554	524	531
20	555	536	539	541	507	513	511	531	546	553	525	532
21	556	533	538	540	506	514	513	531	546	548	524	532
22	556	535	536	537	504	513	510	528	546	545	525	531
23	554	536	533	533	500	512	508	527	543	542	524	529
24	551	537	532	530	500	510	509	527	541	541	527	525
Sclae	100	150	200	250	300	350	400	450	500	550	600	650

Figure 6-12: Emission data of the electricity grid in Alberta, Canada 2020, according to the hours per day and month over the year (own representation – data [6-32])

Climate projections suggest an increase in ambient temperatures. According to the Government of Canada's Climate Atlas, Calgary is expected to experience warmer temperatures due to ongoing climate change [6-45]. By 2050, average temperatures may rise by several degrees Celsius, leading to more frequent summer heat. These warmer conditions could impact various sectors, including agriculture, water resources, and public health, and increase the potential of solar radiation. Incentives and policies have been put in place to support the growth of renewable energies. The transition to renewable powers in Canada's electricity grid aligns with global efforts to combat climate change and promote more sustainable energy. As renewable energy technology advances, Alberta is poised to expand its clean energy capacity further and reduce its reliance on fossil fuels in the coming years [6-47]. One big advantage of Canada is the ratio between population and land area. Furthermore, Alberta has abundant renewable energy potential, including wind and hydroelectric power. Considering these potentials, in combination with the wealth of the state, under the right political circumstances, the energy transition for Canada can be performed straightforwardly.

6.3 Results and Evaluation

Following the fundamental data structure, this section outlines the thermodynamic simulation results for each climate location. Three graphs per location illustrate the three evaluation categories for the previously outlined simulation variants for 2020: energy demand, thermal comfort, and emission balance. The energy demand on the left shows the annual heating and cooling demand in kWh/(m^2a) (Q_heat, Q_cool). The thermal comfort in the middle graph analyzes the over-and undertemperturehours according to ASHRAE 55 2004 (OTh; UTh) [6-48]. The graph on the right shows the emission performance in kgCO_2/m^2. Please pay attention to the scaling factor for the emissions. In each variant section, the dashed line presents the future scenario using the weather and emission data for 2050, while the full color illustrates the simulation variants for 2020. The simulation variant abbreviations are as follows: On/Off – weather and emission predictive control or standard control; C-L, C-M, C-H – construction light, middle, or heavy; I-L, I-H – insulation light or heavy and SC, SC_PV– system configuration with thermal storage or with thermal and electrical storage and PV. With these simulation results, the previously mentioned research questions are evaluated for each climate location. The first paragraph of each section addresses the general findings of the simulation results, followed by the influence of the thermal mass, insulation, and storage capacity in the second paragraph. The last paragraph features the overall functionality of the WEPC and gives an outlook of 2050, using the future scenario. Lastly, it is to be noted that simulation variants are only considered to perform well when fulfilling the thermal comfort requirements.

6.3.1 Moderate Climate – Munich

The heating demand in all simulation variants in Munich varies between 40 and 100 kWh/(m^2a), and the cooling demand is significantly lower from 10 to 30 kWh/(m^2a). The highest heating demand is recognized with WEPC Off, which has a high thermal mass and low insulation, and it is performed lowest with WEPC On, which has a middle thermal mass and high insulation. The highest cooling demand is necessary for WEPC On, with high thermal mass and insulation, and is lowest for WEPC Off, with middle thermal mass and low insulation. In general, one can see that the light construction variants do not fulfill the thermal comfort requirements. The emissions in Munich are quite constant. The simulation variants with PV create energy savings in a range of -50 kgCO_2/(m^2a) while without PV, the emissions vary around +40 kgCO_2/(m^2a).

Tackling the impact of the WEPC, one can see in Figure 6-13 that with WEPC, the heating demand decreases drastically (up to 50%), while the cooling demand in absolute numbers only slightly increases. This is also true for the over- and undertemperaturhours for the middle and heavy construction variants that are below the threshold. Independent of the control strategy, it is clearly visible that the higher the insulation, the lower the heating demand. On top of that, it is also true that the lower the thermal mass, the lower the heating and cooling demand. The emissions only slightly vary for the individual simulation categories. The lighter the construction for ESC with PV, the more energy savings increase. Furthermore, it shows that for SC1 with PV, the emission savings are higher with thermal insulation. The simulation variants without a PV system show constant values for emission performance, except for the light simulation variants.

Overall, the WEPC works very well in Munich's moderate climate. The heating demand, particularly for massive constructions, is improved significantly without harming thermal comfort. The cooling demand only increases slightly in absolute numbers and confirms the fact that cooling demand was not generally necessary in Munich in 2020. The future scenarios show a small decrease in heating and a significant decrease in cooling demand, particularly for heavy constructions. But again, the simulation variants with WEPC reduce the increase compared to those without WEPC. The emissions decrease overall with the future scenario in 2050 by up to 50%. The SC only with storage systems reduces with and without WEPC by 50%. In contrast, the emission savings for the simulation variants with PV only decrease by 45%, as the photovoltaic system still improves the emission performance and solar radiation changes slightly in 2050.

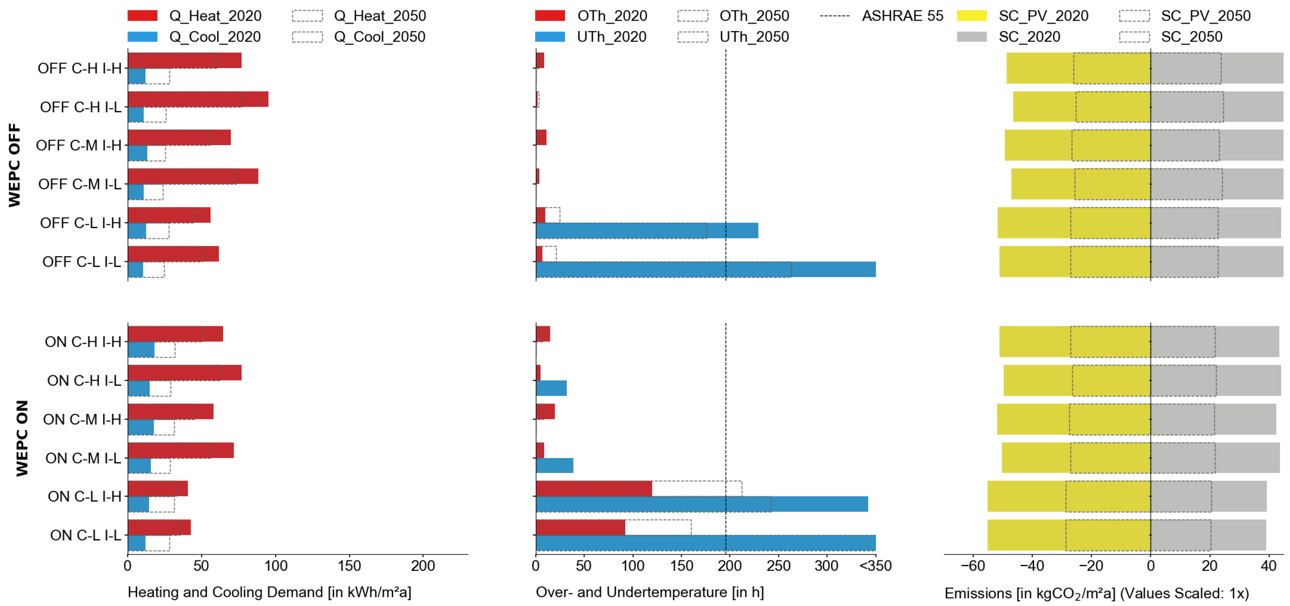


Figure 6-13: Munich's annually cumulated simulation results for 2020 and 2050: heating and cooling demand (left), over-and undertemperaturehours (middle) and emissions (right) (own representation)

6.3.2 Tropical Climate – Singapore

In the tropical climate of Singapore, no heating energy is needed, while cooling dominates the energy balance with 80 to 200 kWh/(m^{2}a) for the individual simulation variants. This very high cooling demand indicates that thermal comfort can be provided for the middle and heavy construction variants. In contrast, the light simulation variants cannot stay below the threshold in all cases. In some rare moments, UThs exist that can be linked to an overcooling of the building by the powerful cooling system. Considering the scaling factor, the emissions for SC are in a range of up to +80 kgCO$_2$/(m^{2}a). For the simulation variants with PV, the saving reaches values up to -110 kgCO$_2$/(m^{2}a).

The increase in thermal mass leads to a decrease in the cooling energy demand and does not have a big effect on the OThs. Higher thermal insulation slightly increases the cooling energy. Thermal mass only slightly decreases the emission savings with PV around 2-4 kgCO$_2$/(m^{2}a), while thermal mass and insulation does not have a noticeable impact. Overall, the emission balances for the simulation categories stay on a similar level that can be linked to the constantly high level of emissions in Singapore's electricity grid all day and year.

Figure 6-14 illustrates all WEPC variants that have cooling demands up to 40 kWh/(m^{2}a) lower than with a standard control. In addition to that, the results show that the WEPC variants have no OThs anymore. The small increase in the UThs is a small sign of over-cooling in the morning hours when WEPC anticipates office users. For the standard control, the future cooling demand in 2050 rises with ~10 kWh/(m^{2}a), whereby with the WEPC, the cooling demand nearly stays at the same level. Overall, simulation variants with WEPC have around 10 kgCO$_2$/(m^{2}a) fewer emissions with SC and the same amount of emission savings with PV. The future variants show that the emission savings for SC_PV are reduced by 50%, while the system configurations without PV show a decrease until 2050 of around 55% on average.

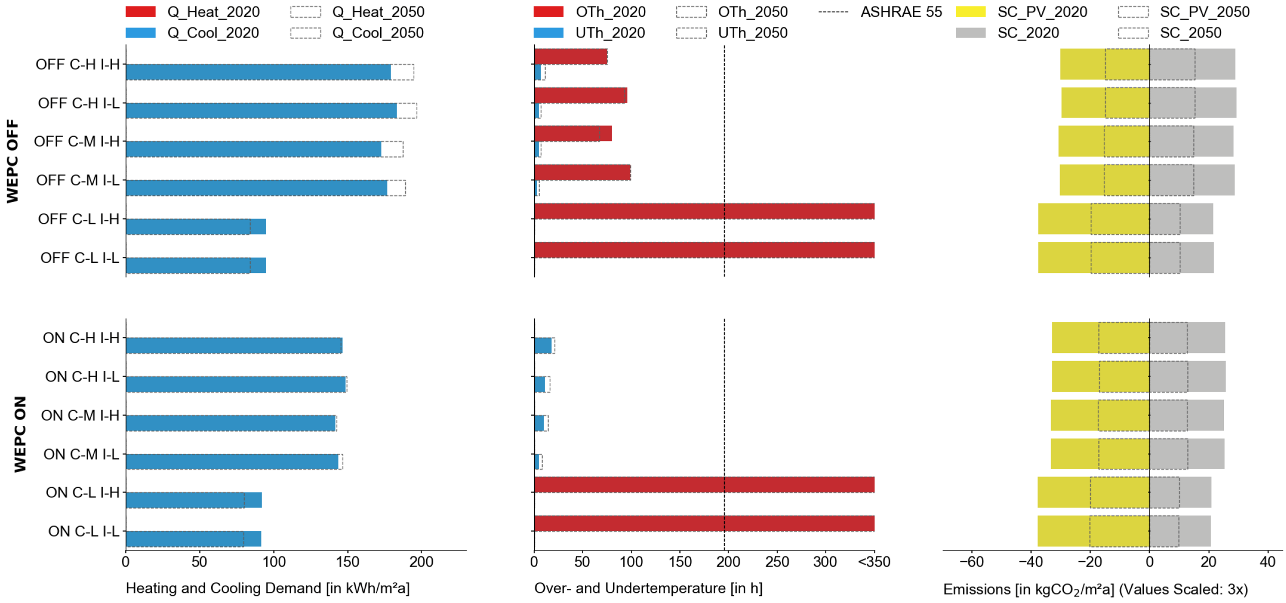


Figure 6-14: Singapore's annually cumulated simulation results for 2020 and 2050: heating and cooling demand (left), over- and undertemperaturehours (middle) and emissions (right) (own representation)

6.3.3 Subtropical Climate – Guatemala City

The very pleasant and constant temperature of the subtropical Guatemala City leads to no heating demand and no OThs and UThs. Further, it is a location where light construction variants can fulfill the thermal comfort conditions. The cooling energy demand varies between 50 and 100 kWh/(m^2a). The lowest cooling demand, 52 kWh/(m^2a), occurs for a simulation variant with WEPC On, middle heavy construction, and with low thermal insulation. The emission savings with PV stay consistently at a very high level of -340 kgCO_2/(m^2a), which can be linked to the constantly high solar yields in the diurnal climate of Guatemala. In contrast, the emission performances without using solar electrical energy vary on medium-high between +100 and +120 kgCO_2/(m^2a) for the year 2020, considering the scaling factor of 6. The previously described low emission values for Guatemala's electricity grid are responsible for this good performance.

In a subtropical climate, the effect of thermal mass is not consistently visible in the considered simulation variants. For the standard control, there is no trend noticeable for the thermal mass, but more thermal insulation for the middle and light variants leads to a small increase in cooling energy. In the cases of WEPC being active, more thermal mass leads to a lower cooling energy demand. Furthermore, the cooling energy demand decreases by 10-15% with less thermal insulation for the predictive control. With WEPC active, the emission savings for SC_PV increase from -340 to up to -360 kgCO_2/(m^2a), as well as the emission performances for SC decrease from +120 to the lowest of +100 kgCO_2/(m^2a) for the light construction variant.

Figure 6-15 shows that simulation variants with WEPC generally perform better with up to 50% less cooling energy than their standard control equivalents. This especially works well for simulation variants with high thermal mass. In 2050, the cooling energy demand will increase for all variants, especially for the WEPC active with up to 30 kWh/(m^2a), but there are still no noticeable OThs. For SC, the emissions with WEPC decrease by 20%, and the emission savings with PV increased by up to 25 kgCO_2/(m^2a). This proves the impact of predictive control in 2020. In 2050, both SC and SC_PV will be reduced to 50%, connected to the lower emission values of the electricity grid.

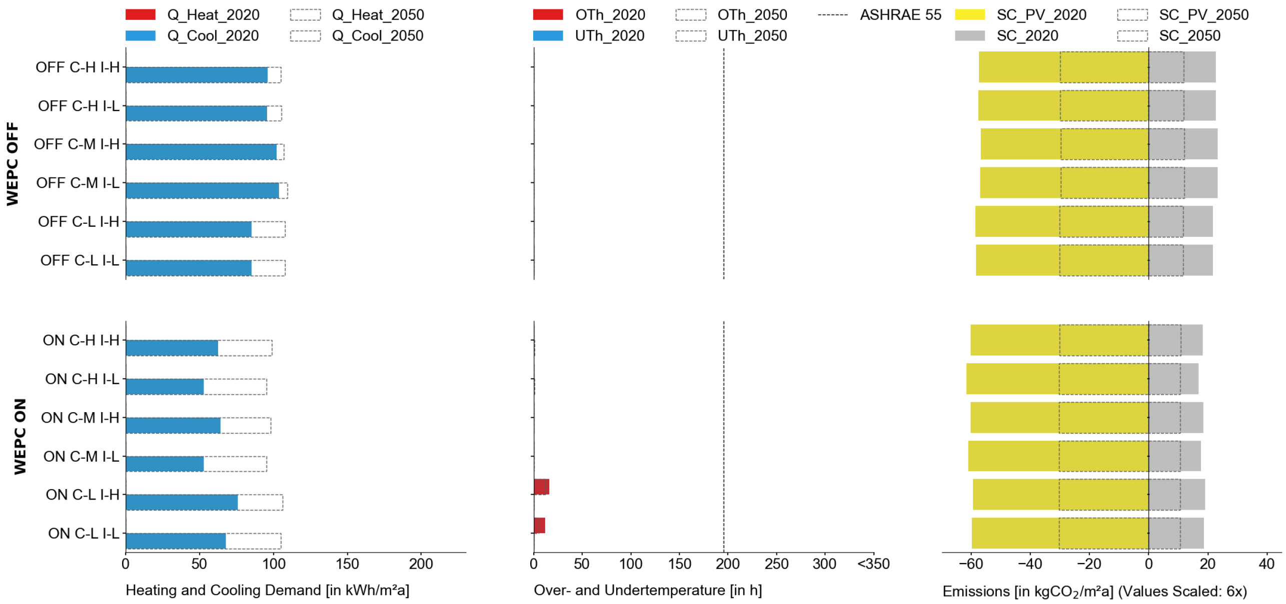


Figure 6-15: Guatemala's annually cumulated simulation results for 2020 and 2050: heating and cooling demand (left), over- and undertemperaturehours (middle) and emissions (right) (own representation)

6.3.4. Hot Mediterranean Climate – Seville

In Andalusia's hot climate, no heating demand is necessary, while cooling demand dominates with 40 to 110 kWh(m^{2}a). Thus, all simulation variants have no noticeable UThs, while OThs exist in all cases. The light constructions cannot stay below the thermal comfort threshold. The highest cooling demand is needed with a standard control, high thermal mass, and low insulation, while the best-performing variant that fulfills the comfort is WEPC, middle heavy, and low insulation. The middle and heavy constructions show only slight OThs based on the night cooling potentials of Seville. The permanently low EFs in the Spanish electricity grid lead to very few differences in emission performances, with SC +20 kgCO$_2$/(m^{2}a), while the photovoltaics variants create energy savings around -55 kgCO$_2$/(m^{2}a).

A decrease in thermal mass leads Seville to lower cooling demands, while a decrease in thermal insulation only slightly increases the cooling demand. The OThs are higher with less insulation but stay in range except for the light constructions. The emissions do not show a variation in the simulation variant categories. But again, the overall trend of energy savings only exists with a PV and electrical storage and thermal storage system.

Overall, the WEPC variants perform better than their standard equivalent with 20-40 kWh/(m^{2}a) less cooling demand and up to 50 h less OTHs. In 2050, nearly all simulation variants show an increase of up to 10 kWh(m^{2}a) in cooling energy demand and an increase in OThs, as displayed in Figure 6-16. For the WEPC variants, the increase is slightly smaller. For heavy construction, the cooling energy demand rises more in absolute values. Future scenarios for SC and SC_PV decrease their permeances by ~50%. This is connected to the overall lower emission values in the Spanish electrical grid.

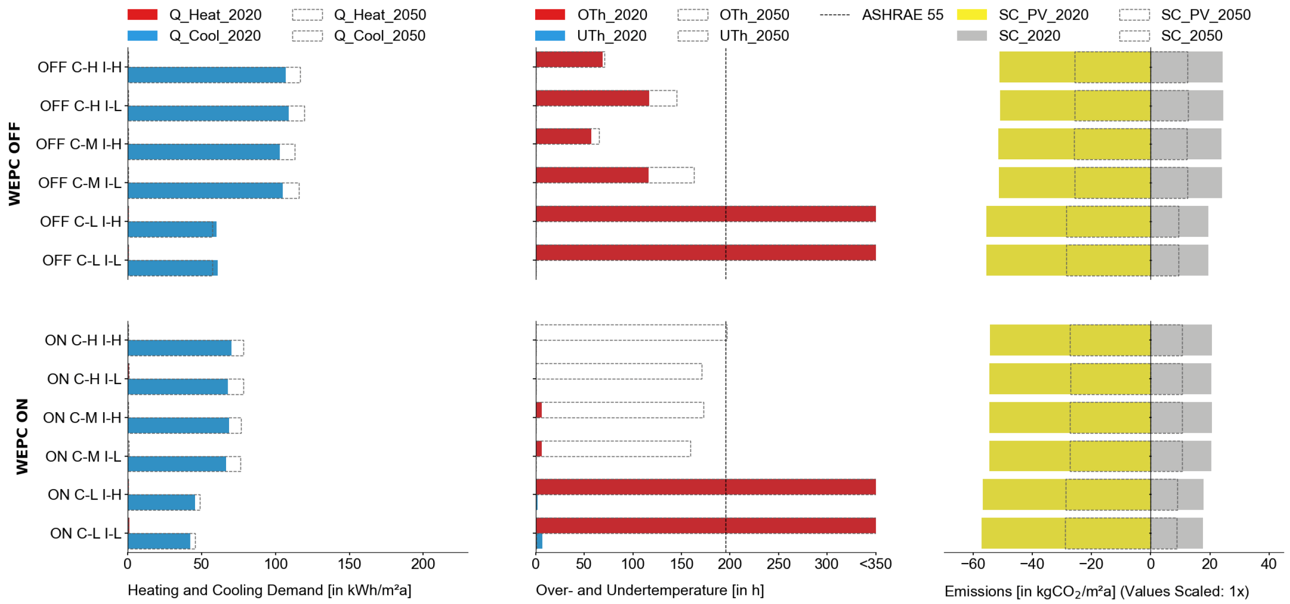


Figure 6-16: Seville's annually cumulated simulation results for 2020 and 2050: heating and cooling demand (left), over-and undertemperaturehours (middle) and emissions (right) (own representation)

6.3.5 Cold Climate – Calgary

Calgary's heating and cooling demands vary between 190 and 70 kWh/(m^{2}a), with the highest variant with WEPC Off and a high thermal mass and low insulation and the lowest with WEPC with a middle thermal mass and increased insulation. The cooling demand for all variants is between 5 and 15-kWh/(m^{2}a) and therefore is neglectable. Thermal comfort can mainly be fulfilled except for the light construction variants and the simulation variant with WPC active, high thermal mass, and low thermal insulation, where the UThs are too high. The emissions in 2020 without PV showed similar results, differing around +80 kgCO$_2$/(m^{2}a). The system configuration with PV presents emission savings of up to -90 kgCO$_2$/(m^{2}a).

The less insulated simulation variants in Calgary show an increase in heating demand, while variants with a lower thermal mass show a decrease in heating demand. The cooling demand at 5-15 kWh/(m^{2}a) is neglectable and stable for all simulation variants. Again, the trend of outperforming the WEPC is visible, as all WEPC variants use around 30-40 kWh/(m^{2}a) less heating energy demand than their standard counterpart, especially for variants with heavy constructions. This reduction in energy results in an increase in UThs for the WEPC variants, but they mostly stay in the ASHRAE comfort range. The emissions with WEPC show around 10% less emissions, which results in around 12 kgCO$_2$/(m^{2}a) less for SC and more emission savings for SC_PV.

The WEPC shows significant heating energy savings for the cold climate of Calgary and only in one case impairs thermal comfort. All future variants for 2050 show less heating demand based on the increasing temperatures in Alberta. This also decreases the UThs. Even with a slight increase in cooling energy and the OThs in the future, the authors consider a cooling system unnecessary. With more thermal mass, the heating demand will decrease more in the future. The emission savings decrease with the lower future EFs and increase the emission saving effect by 50%. All results are illustrated in the Figure 6-17.

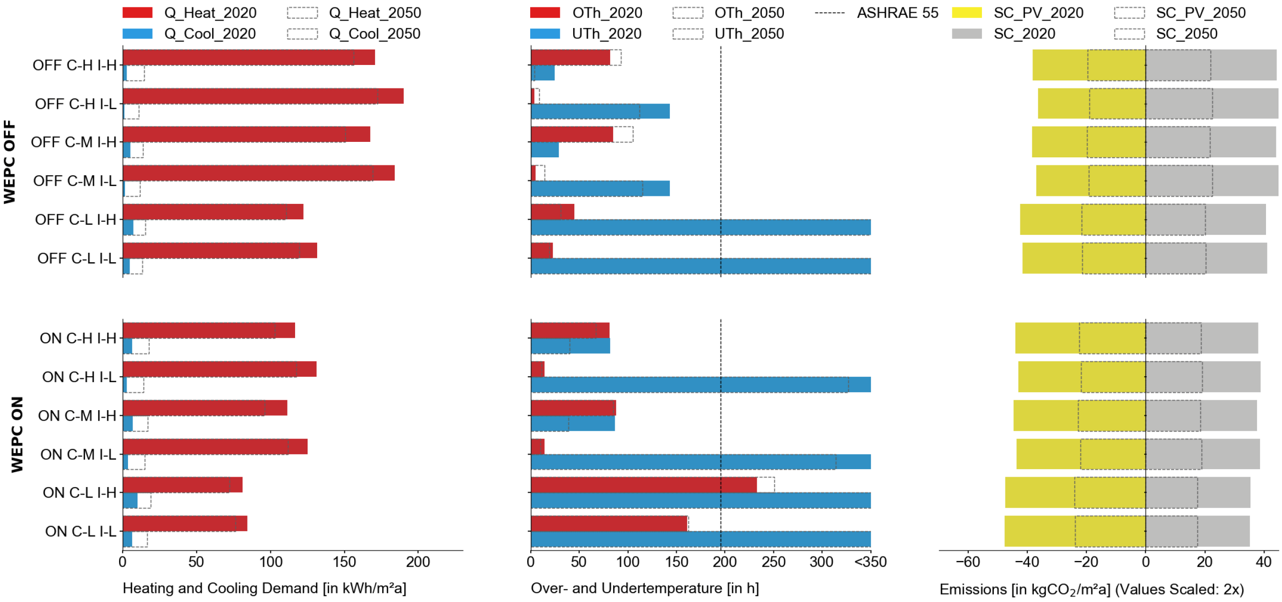


Figure 6-17: Calgary's annually cumulated simulation results for 2020 and 2050: heating and cooling demand (left), over-and undertemperaturehours (middle) and emissions (right) (own representation)

6.4 Discussion

This discussion starts with the main findings of this work. First, an overview of the simulation results that prepares for the summarizing hypothesis is given, followed by answers to the individual research questions. Several universal validity trends can be observed based on the initially stated research questions and during this international parametric study. Finally, this section outlines the limitations of this work.

6.4.1 Main findings

The ensuing two box plots show an overview of the simulation results, outlining the difference in energy and emissions between the equivalent simulation variants with WEPC On and Off for the five climate locations. Overall, one can see that the WEPC impacts heating, cooling, and emission performance. The single box elements of the graphs illustrate the range of the different performances for each climate location. The small, black dots represent the individual simulation variants.

Considering the energy performance in Figure 6-18, one can see that in all locations, but especially in Guatemala, where the variation in performance is very large, energy savings of around 50-100% can be archived with the WEPC. The emission performances in Figure 6-19 show similar results but with smaller ranges between 5 and 25%. Therefore, it is clearly visible that emission performances are more optimized without a PV system. This is linked to the personal use of solar energy with the PV system, which lowers the effect of the WEPC.

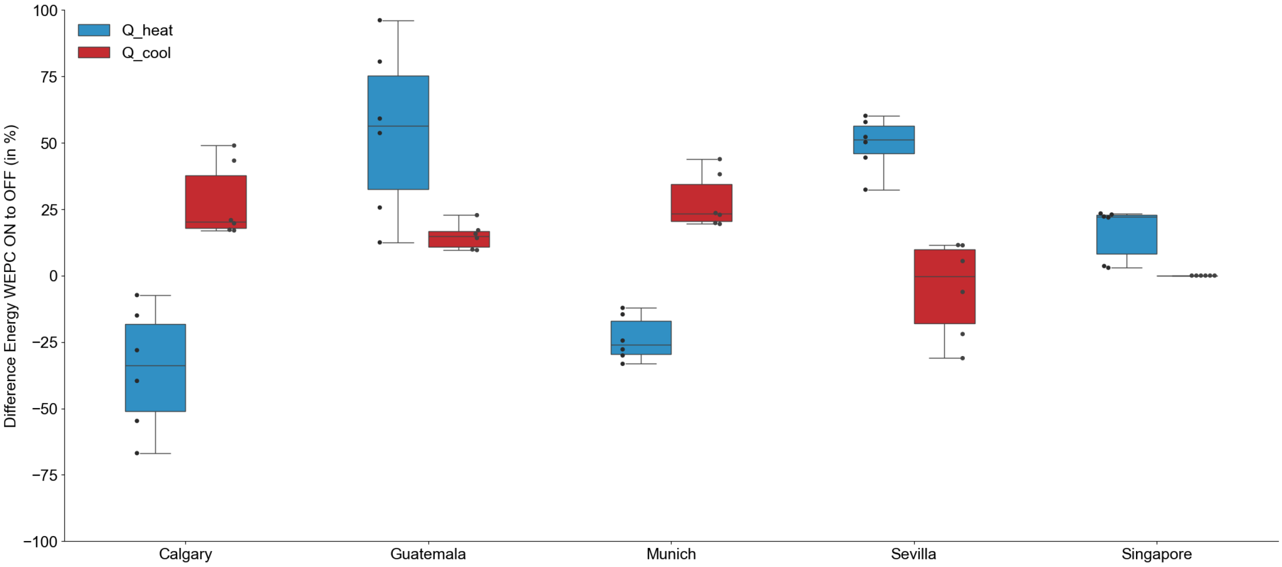


Figure 6-18: Comparison of heating and cooling energy demand differences between WEPC On and Off in percentage for all climate locations (own representation)

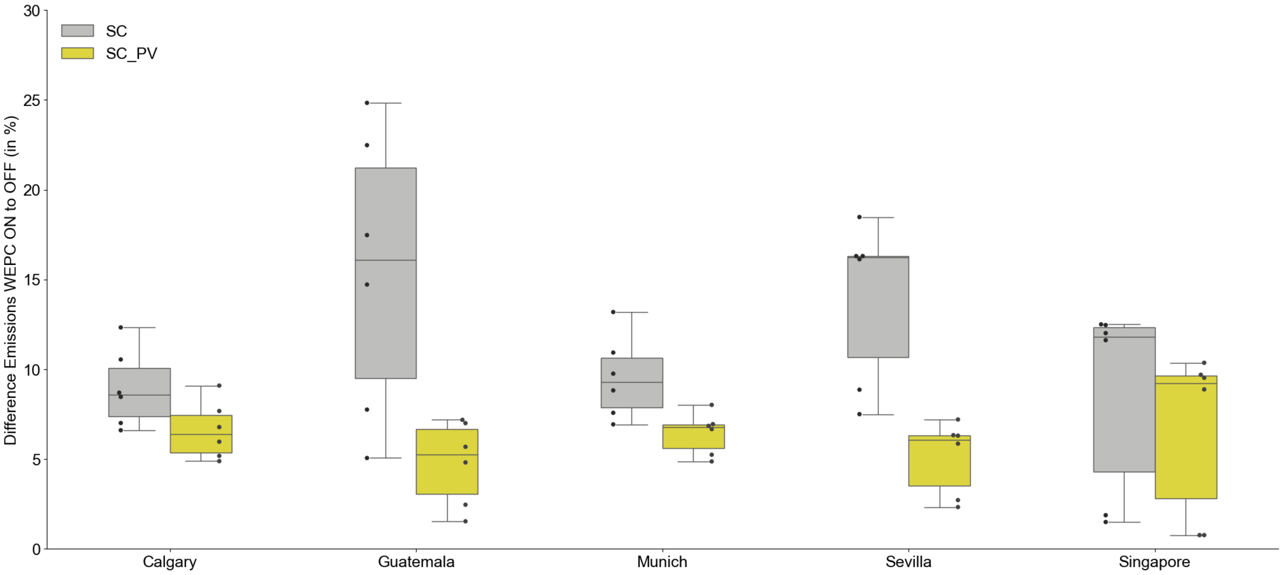


Figure 6-19: Comparison of emission performance differences between WEPC On and Off for SC and SC_PV in percentage for all climate locations (own representation)

Summarizing the results for the individual climate locations shows that the overall hypothesis that a weather and emission predictive control of buildings improves the energy performance and the emission balance without limiting thermal comfort can be answered with yes, in many parts. Not all simulation results can archive improvements in all evaluation categories simultaneously, but an improvement is mostly detectable. These savings are sometimes represented in the energy or the emission savings. However, it is also clearly visible that energy savings do not always result in the same amount of emission savings and vice versa. This overall outcome proves that a simple control strategy, without a complex, data-intense approach, already creates energetic and emission improvements and protects from rebound effects and overengineering buildings.

What impact does insulation and thermal mass have on the performance of the WEPC?

With the increases in thermal mass, the heating and cooling energy demand rises. But it prevents OThs and UThs, especially in the mornings when the building technology often cannot fulfill the thermal comfort requirements, according to ASHRAE 55 2004. The light construction variants mostly cannot fulfill thermal comfort requirements except for the subtropical climate in Guatemala. Thus, one can see that TABS does not perform well with light building constructions except for the very pleasant subtropical climate. Increasing thermal insulation leads to a noticeable decrease in heating energy and often mildly decreases the cooling energy demand. This potentially results in fewer UThs but can also lead to more OThs.

How does a photovoltaic system impact the emission balance using the WEPC with thermal and electrical storage?

For the system configuration with thermal and electrical storage, the emission factor is mainly determined by the emission values of the electrical grid. Negative emission values, thus emission savings, are only possible with owner occupancy of a photo-voltaic system. However, the WEPC positively impacts the emission performances of both system configurations. The performances of SC and SC_PV can be improved by ~10% using the intelligent control WEPC.

Does the WEPC improve a room's energy performance and CO_2 balance without compromising thermal comfort?

In heating-dominant climate locations, WEPC creates significant energy savings. This also leads to improvements in emission performance compared to a standard control. The cooling demand can noticeably be lowered for Spain and Guatemala, but only small savings can be achieved in Singapore. This is found in the constantly high temperatures in the tropical climate without the possibility for night cooling or seasonal temperature decreases. Generally, a variation in the different simulation categories can only be achieved with fluctuating emission grids, as in Germany and Guatemala. Energy savings cannot always be transferred into emission savings, as storage systems also need to be controlled in an intelligent manner. Only small differences can be achieved in stable conditions, as is the case for Canada, Singapore, and Spain. With a flexible comfort concept like ASHRAE 55 2004, energy and, thus, emission savings are possible. The authors claim that more flexibility in thermal comfort in office buildings enlarges the saving potential.

How does the WEPC perform in 2050, considering future weather and emission data that account for an increased share of renewable energies?

In 2050, nearly all simulation variants show an increase of up to 20 kWh/(m^2a) in cooling energy demand and an increase in OThs. The future heating demand will be lowered by up to 20% compared to 2020. This also decreases the UThs. The emission savings with photovoltaic systems decrease with the lower future EFs. This also reflects on the emission performances without photovoltaics and leads to a decrease of up to 50% in emissions. Overall, simulation variants with WEPC will show better emission and energy performance in the future than their standard equivalent. This strengthens the initial approach to simplify the control algorithms and proves that optimization with a simple approach like the WEPC is possible. It also creates advantages in future weather and emission scenarios.

6.4.2 Limitations

During the calculation and analysis, the authors had to set boundary conditions and make assumptions to complete this study. The ensuing paragraphs present the limitations of this approach, separated into building, comfort, emission, and weather aspects that should motivate further research. Still, overall, it must be noted that this study only analyses potentials and theoretical savings where further research has to put this concept into practice.To fulfill the parametric study, several building assumptions had to be drawn to define the base case and the individual simulation variants. The very exposed office room set the base with its single façade, orientation, and very high window-to-wall ratio. Furthermore, the room's geometry, infiltration, building technology system TABS, fixed PV area on the roof, and natural ventilation are set. A holistic parametric study needs to be conducted to identify the impact of each parameter. In addition, the quality of the simulation of building technology and the ventilation system is standard. Still, it could be extended with a detailed model of the building energy systems or a computational fluid dynamic simulation for the ventilation. Furthermore, this study uses over-and undertemperaturhour, according to ASHRAE 55 2004, to evaluate thermal comfort conditions accurately. Further comfort concepts, such as a time-dependent thermal comfort, have other advantages that this study could not show. Other building uses, like residential or educational buildings with varying hours of occupancy and dress codes, could also be the focus of further research. In addition to that, it compromises the adaptive comfort band of ASHRAE, a wide range that supports the concept of WEPC, whereby other thermal comfort concepts would harm the results. The dynamic emissions for this paper represent hourly values for the whole country, whereby, with an increase in renewable energies, the values can vary significantly in different regions of a country. Furthermore, the dynamic emission values are not integrated directly into the thermal simulation, as they are used in a second, separated simulation step. Predicting the emission values is found on a fixed decrease of emissions by 50%. This is a hard assumption and gives only a very low-level prediction of emissions in the future. Overall, the boundary conditions of this study only comprise the emissions in the operational phase of the buildings, while constructive manners like thermal mass influence and demand for a holistic life cycle analysis of all building phases. Finally, the weather data of the five climate locations use the TMY data sets to represent the general circumstances of a zone. Still, within the individual zones, various climates exist that could be represented with measured data. The findings of this study give an overall tendency for each climate zone but do not prevent further, detailed analysis. Lastly, the weather data prediction is based on the official IPCC scenario RPC 8.5. This represents a moderate baseline emission prediction scenario, whereby more extreme conditions can be expected with the ongoing trend of climate change.

6.5 Conclusion

This section outlines a conclusion of the concept of weather and emission predictive control. The underlying hypothesis is evaluated and analyzed in the following subsections: localization, utilization, and transformation of the potential. The authors of this paper reprise the hypothesis and present an outlook of this approach for future work.

6.5.1 Localization of the Potential

People use weather and emission data daily, preparing for their work life or planning a weekend trip into nature. As this paper outlines, weather and emission data hold great potential to optimize building operations. Previous studies also mention the possibility and the lack of application of such concepts that, in the authors' opinions, are based on the complexity and inertness of data-intense control algorithms [6-9–11]. Building operation managers and even more building users are not experts in building data science and do not accept complex and expensive control algorithms. This opens the potential for this simplified building control approach for an application in the built world only found on simple calculations and an internet connection. Small devices like smartphones, Raspberry Pi, and thermostats can apply this. This simplicity is the basis for the potential of this approach, and this paper proves on a theoretical level the international energy and emission savings in various climates, especially when equipped with thermal mass and electrical storage systems in fluctuating electricity grids.

6.5.2 Utilization of the Potential

Using the WEPC for TABS creates various energy and emission savings building variants in all five considered climate locations. Massive buildings, especially in heating-dominant places like Munich or Calgary, can save heating operational energy while fulfilling thermal comfort requirements. These savings increase with more thermal mass and less insulation. However, in Guatemala City, Sevilla, or Singapore, where a lot of cooling energy is required, the WEPC can slightly lower the energy and emission balance. Furthermore, this study confirms that locations with a higher variability when switching between heating and cooling modes (mainly within the transition from summer to winter) will increase the saving potential compared to the standard control for TABS. In locations with a fluctuating emission factor with higher amounts of renewable energies, like Germany or Guatemala, the WEPC with PV and an electrical storage system can decrease the operational emission balance. In locations with steady (high or low) emission factors, the WEPC only slightly outperforms a standard control strategy. Overall, the simple approach can decrease emissions and energy demand.

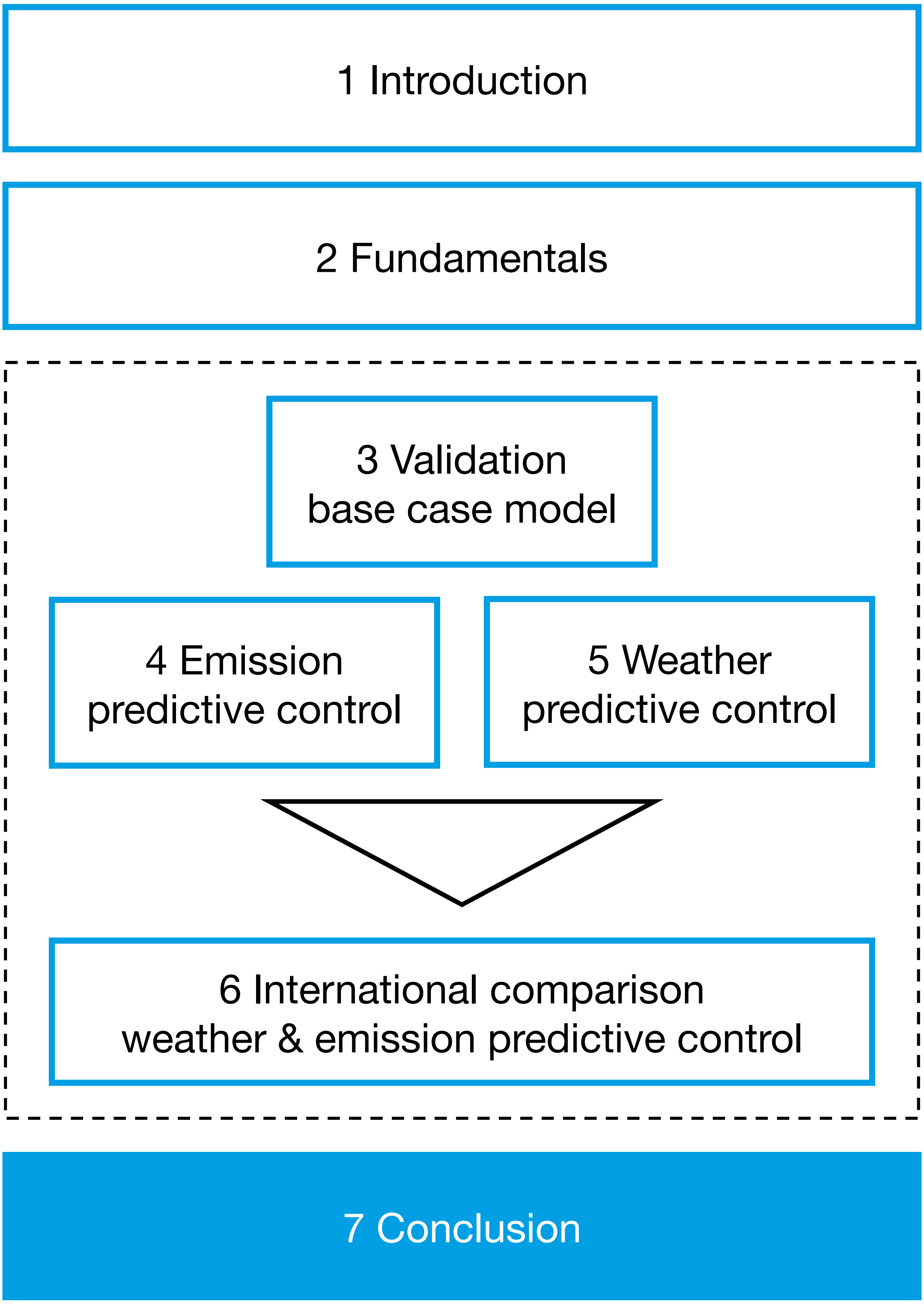
6.5.3 Transformation of the Potential

Ongoing climate change, in combination with the rising share of renewable energies, leads to a significant increase in the fluctuation of the energy price and emissions in the electrical energy grid. As the building energy supply is increasingly electrified, this rising fluctuation holds excellent potential for emission savings. This paper proves the necessity of innovative control strategies for building operations and the demand for more local storage systems. With the WEPC, buildings can be transformed into short-term energy and emission storage to support the concept of decentralization. The simulation variant with high thermal mass, an electrical storage system, and PV shows promising emission savings when using WEPC. But also, Seville, representing an electrical grid with all year long steady low emission, shows that with a low carbon emission still, an optimization using an intelligent control strategy is possible. To transform the potential of this study into the building stock, innovative control strategies have to focus on simplicity and be detached from high-tech solutions. Furthermore, the future scenarios with a substantial increase in renewable energy, especially in photovoltaics, outline that under ongoing climate change, the demand for storage systems will increase, and intelligent control strategies can enhance the saving potential. This strengthens the overall approach to simplifying the optimization algorithms.

6.5.4 Outlook

Based on the broad findings and statements of this study, the authors identify steps to further develop the simple concept of WEPC and strengthen its application in the built world:

- Extend and re-evaluate weather data prediction to further parameters to strengthen energy optimization.
- Extend the concept to the building design and the dimensioning of building technology to prepare for a whole life-cycling analysis considering emissions in all building phases.
- Develop and apply a more detailed future scenario algorithm for emission data to generate a better understanding of emissions saving in the future.
- Apply the concept to a built energy system for revalidation.


1 Introduction
2 Fundamentals
3 Validation base case model
4 Emission predictive control
5 Weather predictive control
6 International comparison weather & emission predictive control
7 Conclusion

7 Conclusion

Summary

The aim of this dissertation is to explore the possibilities and limitations of an intelligent, weather-and-CO_2-predictive control strategy for building technology in order to optimize the energy and emission performance of a building. Following the first fundamental chapters, chapters 3 to 6 outlined the process to evaluate the impact on an international level using various building types, locations, and emission simulation scenarios. This final chapter closes the circle by providing an overall conclusion. The ensuing sections bring all the work together and provide an answer to the initial main research question, evaluate the research impact and applicability, point out the limitations of this dissertation, draw a final conclusion, and give an outlook for future research projects.

7.1 Main Findings

This section summarises the main findings of this work. One of the main findings of the research performing a dissertation is the answer to all research questions. That's why one must focus on a specific problem and address this topic in a hypothesis using a suitable methodology. This work focuses on an intelligent control strategy and outlines the fact that the transition to a climate-friendly building sector is not a matter of if; it is a matter of how. In theory, there is enough renewable energy available on Earth, and it is just a question of how this transformation to a renewable energy grid can be applied. In that transformation, the initially addressed potentials of the weather data, the thermal inertia, and the thermal comfort in buildings open up tremendous possibilities for optimization. Therefore, this simple approach of intelligent control strategies for TABS holds great potential. Even though this only addresses a small part of the transformation process, it is mandatory to integrate these potentials into future energy grids. The following section repeats the central hypotheses and research questions of the individual evaluating chapters and finalizes with this dissertation's main underlying research hypothesis.

Chapter 3 – Validation

Is it possible to validate a thermal model through the local weather and thermal data of the test facility according to the ASHRAE Guideline 14:2002, and which are the key parameters?

The research question in this section addresses the validation process using the parametric thermal simulation tool TRNLizard, and can be answered with: Yes; the thermal model can be calibrated and validated according to ASHRAE-Guideline 14:2002. For the measurement type weeks, the three validation parameters normalized mean bias error (NMBE), the coefficient of variation of root mean square error (CV(RMSE)), and the Coefficient of Determination (R^2) can be held within their limits. Therefore, the validation is fulfilled. The infiltration rate and the thermal bridges can be recognized as the two crucial parameters for the validation process. Lowering these parameters leads to an optimized thermal behavior of the thermal simulation for the summer and winter weeks and enables the thresholds to keep the limitation ranges. Based on the light construction of the measurement room Solarstation, the thermal behavior tends to fluctuate quickly. In the author's opinion, with more thermal mass, the validation quality incr eases, especially in the shoulder seasons. Since the validation was proven successful, the validated thermal simulation model is ready to be used in the following research studies and forms the basis for testing various intelligent control strategies.

Chapter 4 – CO_2 -predictive control

Using dynamic, hourly emission factors to calculate the CO_2 emissions for the building operation generates emission savings, which are not represented in the common calculation concept based on static, imprecise data.

Overall, the answer to this hypothesis is yes. The results of this study show that using dynamic, hourly CO_2 values to calculate the emission balance reveals significant differences.

One of the most significant findings indicates that the shift from static to dynamic emission factors could lead to a remarkable difference of up to 30% in GHG emissions. This effect is particularly pronounced when using predictive control strategies combined with electrical storage systems. The predictive control strategy combined with electrical storage systems resulted in a significant reduction in carbon dioxide emissions, specifically around 12% lower in comparison to a static calculation. As emission factors play a substantial role in evaluating building performance, the validity of static emission factors must be questioned. In particular, the simulation results for this specific office building using a heat pump and/or electrical battery storage systems in combination with predictive control strategies open up the possibility for emission load shifting, resulting in a lower emission performance of up to 40 g CO_2/kWh (total carbon emissions ~400 g CO_2/kWh) compared to the standard control. Significant emission savings can be achieved in office buildings, especially during midday. The emission-predictive control strategies outperform the simple approaches in low-emission phases in the German winter by up to 30%. Furthermore, these trends become more pronounced in future simulation scenarios that consider weather and emission data for 2040. In this case, the savings between the standard and predictive control are marginal, as overall emissions decrease to only 62 g CO_2/kWh in 2040. However, the net load is reduced by 18% compared to the standard control, whereas this reduction in 2018 was only 4%. Since this study focuses on the German grid with a specific location in Munich, further research is necessary to expand its outlook. Additional predictive variables focus on energy efficiency and thermal comfort. Expanding the study internationally would confirm and strengthen the results and help transform buildings into short-term storage to reduce operational carbon emissions.

Chapter 5 – Weather-predictive control

The energy demand and thermal comfort of a Munich-based office building can be optimized compared to a state-of-the-art control strategy by the simple approach of a weather-predictive control of inert buildings.

In summary, the research clearly demonstrates that adopting a weather predictive control strategy can yield significant energy savings while improving thermal comfort in the inert building technologies of a Munich-based office building using TABS. The WPC leads to a reduction in total energy consumption by up to 12.3% compared to the standard control methods. These potentials, mainly occurring during the transition from summer to winter and vice versa, can be addressed with the WPC, outperforming standard control approaches for TABS. The WPC generates 5 kWh/(m2 a) cooling energy savings for an already low cooling energy demand at a total of 50 kWh/(m2 a). Furthermore, using the weather predictive control generates thermal comfort improvements, primarily where the thermal comfort, represented by the PMV improved notably by approximately 1.4 points. For a building with higher thermal mass, the total energy savings from the WPC strategy increase to 15%.In conclusion, the implementation of a Weather Predictive Control strategy offers a viable solution for enhancing energy efficiency and thermal comfort in buildings utilizing inert technologies. The WPC system is characterized by its simplicity and scalability, utilizing readily available data, such as ambient temperature and solar radiation forecasts, to optimize building operations. This practicality makes the WPC strategy an attractive option for a wide range of building types, without the need for complex and costly data-intensive building management systems. Finally, this study outlines that a broader perspective, handling more control parameters, further building locations, and more adequate use cases, e.g., representation of the majority of the building stock market, would be relevant to analyze the potential of the WPC.

Chapter 6 – International Comparison of Weather and Emission Predictive Building Control

The simple concept of weather and emission predictive control improves the overall energy performance and emission balance of a building without harming thermal comfort.

The outcomes across diverse climate locations confirm the overarching research hypothesis that implementing a weather and emission predictive control in buildings enhances energy efficiency and optimizes emission levels without compromising thermal comfort.

In the moderate climate of Munich, the heating demand decreases by up to 50%, while the cooling demand in absolute numbers only slightly increases for the middle- and lightweight simulation variants. The maximum carbon emissions savings in Munich are around 5 kgCO2/(m2a) with WEPC. In the cooling energy-dominant Singapore, all WEPC variants outperform the standard control by up to 40 kWh/(m2a) while at the same time decreasing the overtemperature hours for the middle and heavy simulation variants, reducing them to 0 OThs. At the same time, the WEPC variants have around 10 kgCO2/(m2a) fewer emissions. In the pleasant subtropical climate of Guatemala City, which has no OThs or UThs, the WEPC variants generally perform better, achieving up to 50% less cooling energy use compared to their standard control equivalents. Furthermore, the WEPC decreases the carbon emissions by 20% in this location. In Seville, the WEPC variants perform better than their standard equivalent with 20–40 kWh/(m2a) less cooling demand and up to 50 fewer OTHs. Given the already low emissions in the Spanish electricity system, the WEPC variants have only marginally lower carbon emissions. In the cold climate of Calgary, all WEPC variants use around 30–40 kWh/(m2a) less heating energy demand than their standard counterpart, especially for variants with heavy constructions. The emissions with WEPC show around 10% less emissions, resulting in approximately 12 kgCO2/(m2a).

A discernible enhancement is generally observed across all five climate locations, manifesting as improvements in energy efficiency, emission reductions, or comfort. Notably, the correlation between energy savings and emission reductions is not consistently proportional, underscoring that a simple control strategy, without data-intensive methodologies, fosters energy and emission improvements while mitigating rebound effects and preventing overengineering in building systems. The analysis of insulation and thermal mass impact on WEPC performance reveals increased energy demand with higher thermal mass, leading to challenges in fulfilling thermal comfort requirements, particularly in light constructions. Photovoltaic systems positively impact the emission balance when used with WEPC, achieving an average improvement of 10% in these system configurations. WEPC significantly reduces energy demand in heating-dominant climates.

Cooling demand reduction varies by location, with substantial improvements in Spain and Guatemala but smaller savings in Singapore. Furthermore, this study asserts that WEPC will perform well in 2050, demonstrating better emission and energy performance than standard controls, even in scenarios with increased shares of renewable energies. This supports the notion that the simple WEPC algorithm can effectively optimize building energy performance in diverse climates, particularly due to its adaptability and simplicity.

Overall Statement of this Dissertation – Connecting the dots

This dissertation's main findings validate the initial hypothesis that a simple weather and emission predictive control can generate energy and emission savings for buildings while maintaining thermal comfort.

It is important to highlight that this simple optimization approach generates significant energy and emission savings within this general study in various climates. This supports the validity of the statement and, conversely, highlights the robustness of the WEPC. By providing savings in various climates with different building constructions, the robustness of this approach is already emphasized and should encourage more research in the field of simple optimization. The study investigates the application of predictive control strategies to enhance energy efficiency and reduce emissions in buildings across various climatic conditions. This thesis validates a thermal model based on ASHRAE Guideline 14:2002, confirming that the TRNLizard simulation tool can effectively model thermal behavior when calibrated using local weather and thermal data. The research further explores the implementation of dynamic hourly emission factors, revealing a potential reduction in greenhouse gas (GHG) emissions of up to 30% compared to static methods. Moreover, it emphasizes the efficacy of a weather predictive control strategy for optimizing energy demand and thermal comfort, particularly with increased thermal mass. Internationally, the study highlights the benefits of WEPC across diverse climates, with significant reductions in heating demand (up to 50% in Munich) and cooling energy use (up to 50% in Guatemala City). Carbon emissions savings are notable, with WEPC achieving reductions of around 20%. The research underscores that simple predictive control strategies can yield substantial energy and emission improvements without overcomplicating building management systems.

In conclusion, this dissertation demonstrates the effectiveness of simple predictive control strategies in optimizing building energy performance and reducing emissions across different climates. This aligns with approaches in other fields, such as Pareto efficiency in macroeconomics or the Ananya Algorithm in data optimization, where basic ideas can achieve the original objectives and guard against overcalculation. This thesis advocates for further exploration of these strategies on a global scale, emphasizing their potential to facilitate the transition of buildings into energy-efficient, low-emission environments while maintaining thermal comfort to achieve the goal of Climate Neutrality by 2050.

7.2 Research Impacts and Applicability

Based on the initially outlined State of the Art, State of Literature, and State of Legislation, this section presents three primary target audiences: professionals of the building industry in the field of smart control, policymakers for buildings and their technology as well as the connected academic community. Thereby, this section presents knowledge and fundamental recommendations based on the results of this work.

Practitioners

This thesis mainly addresses practitioners in the field of building technology and smart control. It outlines the existence of various smart concepts and approaches in that field. These approaches aim for energy and emission savings by combining IT companies' knowledge and engineers' expertise in the building technology world. This study shows that a simple approach can already achieve significant energy and emission savings of up to 30% in comparison to a standard control. To target the overall emission reduction goal, this thesis outlines that the simple approach can easily be reproduced and introduced into a wide field of application cases, such as office, administrative, or residential buildings. This relies on the simplicity of this concept, which does not require advanced computational skills or complex building technology systems. This supports the statement of not over-engineering building control and helps avoid the efficiency dilemma. The current trend of optimizing these approaches drives the engineering world further into the realm of intensive data management and, in the end, increases emissions. The contrary is the case. More complex approaches can lead to rebound effects, widen the performance gap, and lead to user dissatisfaction, as there is no opportunity to understand and interact with the building.

Scientific Community

This category outlines the two main knowledge gains for the scientific world. At first, one must say that the chosen workflow performs as it is supposed to. Starting with the validation of the thermodynamic model establishes a profound base for the following analyses. Following the introduction of control strategies, the final international study presents the outcomes and lays a solid foundation for further international research. In particular, applying the concept to the built environment should be a focus in future projects. Another focus should be on integrating these straightforward approaches into the early design phases of buildings to reduce the complexity and amount of technology in buildings.

The second part addresses the workflow of this thesis. This work proves that an hourly-based dynamic emission value much better represents reality and opens up the possibility for emission savings using intelligent control. Based on this theoretical analysis, further research projects addressing the dynamic CO_2 value in the built environment should be the focus. Moreover, an hourly-based CO_2 value should become the new standard for thermodynamic simulation. Furthermore, this concept should be extended and integrated into the design phase of buildings, enabling a holistic life cycle analysis.

Policymakers

This study has several touching points addressing the corresponding norms and codes. Again, in this category of recommendations, the basic theme is simplicity. Based on the variety of standards and regulations on national and international levels, building designers and engineers have the possibility of various loopholes. In the end, these lead to very highly equipped buildings. In the author's opinion, the goal should be to decrease the number of institutions and organizations and the number of norms and codes to simplify and improve the design of an energy concept. Furthermore, as demanded in several studies in the State of Literature, a wider comfort band would open up more user flexibility and strengthen the fundamentals of this thesis's concept. This would result in further energy harvesting and demand-side management to decrease energy and emission consumption. In addition, policymakers should provide incentives for building designers to integrate more thermal mass and less isolation (especially in Germany) to create savings as long as a full life cycle assessment is performed. More general but still essential for further climate-neutral buildings are the topics of a simple communication standard for the building technology systems like shading, heating, cooling, and ventilation, as well as a CO_2 tax to optimize the building correctly. This would force building energy designers away from massive active building systems and motivate a design of climate-adaptive and intelligent energy concepts.

7.3 Limitations of the Research

The results of this work are by no means a definitive statement. The potentials carefully need to be considered in the light of the specific local conditions and the building systems. Thus, in addition to the parameters taken into consideration for this work, several other factors affect the potential. In the process of this work, several assumptions and boundary conditions had to be taken to explore the aim of this study. This section highlights this dissertation's limitations, which also function as the cornerstones for further developments and research.

Metrics and Scale

This control strategy approach only focuses on one orientation of the building, geometry, and arrangement of the measurement room. Also, the solar energy collection only uses the optimal orientation with a fixed angle for the PV modules. The large window-to-wall ratio of the measurement room, as well as the exposed location, has a strong influence on the results and limits the general assumptions of this work. Further, this study focuses on office usage, which performs with constant occupation hours while, e.g., in a residential building, the usage varies more. Furthermore, this approach discusses optimizing the building technology that considers a typical office room in an abstract building and site without accounting for the potential impact of climate-responsive design strategies on building and room levels. Even though this passive approach is out of the scope of the dissertation, it could decrease the energy and emission performance significantly.

Validation

Even though the simulation software used for this dissertation is already validated, the simulation model is adapted with various assumptions and only for the location in Munich. In Munich, four type-weeks have been used for the simulation validation, where a year-round measurement would improve the validation quality and correctness of the thermodynamic model. In addition to that, the validation is only performed without an active use of the building technology. Finally, worldwide measurements are needed to confirm the results of the international study.

Building Technology

The building technology in this work focuses on inert TABS. These TABS have a slow reaction time and can cause discomfort for the user. The control strategy would differ for other, faster-acting heating and cooling units like radiators, floor-heating systems, wall and ceiling activation, or other air-and-water-based heat transfer units. In this study, it has already been shown that the approach works better with more thermal mass. With faster-acting heat transfer systems, the prediction-based algorithm could not achieve these energy and emission savings, leading to rebound effects. More detail in representing the building energy source and production would also increase the quality of the analysis.

Climate data

The weather data prediction algorithm only focuses on the temperature and the radiation. Further weather parameters like the cloud cover factor, the wind, or the pressure could give valuable insights and increase the quality of the algorithm. Furthermore, the weather data for all locations is found on TMY weather data, which represents an average based on historical records and does not reflect the projected climate change. Actual measured weather data for all locations might shift the results and thus should be considered in more detail. More room for improvement shows the weather data prediction using the IPCC scenarios. Even though in this work, the future weather data should only give a brief insight into the potentials, future weather data with higher quality could improve the results and avoid misinterpretations.

Emission Data

In general, the emission data represents hourly average values for the whole country, and in reality, it is much more detailed. In addition, this work does not consider a precise prediction for the emission data and only increases the share of renewable energies at all times to evaluate future emission conditions. This creates only a limited quality for the prediction and minimizes the quality of the outcomes.

Another limit of this approach is the boundary condition for the emission performance. The boundary condition for the emission balance in this work is building operation. That means a complete analysis considering all phases of the life cycle of a building needs to be fulfilled. This can lead to misjudgments. An increase in thermal mass, e.g., increases the carbon emissions in the production phase and affects the individual simulation variants' energy and emission performances.

7.4 Outlooks and Recommendations for Further Developments

The previously outlined limitations form the start for future potential research explorations and projects.

Implementation

A very important future research step following the aims of this dissertation would be to implement the weather and emission predictive control approach in practice. The initial validation is a good step to guarantee the correctness of the thermal model. The application of the concept to the built environment would prove the theoretical energy and emission-saving potential. After a certain training phase, the real potential of the approach will become visible. In this way, various scenarios should be tested in different climate locations.

Concept Advancement

Another focus for additional research projects could be to further develop the WEPC approach. Although one of the cornerstones of this concept is its simple structure, data-intensive prediction methods like deep learning, reinforcement learning, or model predictive control using neural networks also have their advantages. Potentially, adding more prediction parameters could improve the quality of the algorithm. Integrating new variables, such as user location or smart home technology, would also be possible. In the modern era of digitalization, a variety of new data will be generated, and it may be beneficial to use this data for intelligent control strategies like the WEPC.

Scale

Additionally, there is a need for further research, considering the scale of this work. One focal point could be testing the approach with different building technologies and heat transfer systems. Here, faster-acting systems like radiators or HVAC systems could be addressed, going hand in hand with a parametric analysis of the reaction time. However, similar systems like floor or wall heating, central building technology units, or geothermal systems leave room for optimization. Another research target to improve the concept is the usage of the building. Residential and educational buildings have significant potential for energy and emission savings. In particular, school buildings with fixed occupancy hours could present opportunities for improvement. Additionally, a larger scale, such as urban areas, neighborhoods, or district systems, should be addressed to perform potential demand-side management using local weather and emission data, transforming buildings into components of an energy and emission storage system.

Emission Data

Finally, there is significant research potential in data prediction. Even though weather data prediction is very accurate nowadays, the prediction of emission data needs improvement to create more accurate results. Therefore, the prediction models and the data sets used should be further developed. New concepts can pave the way for a more accurate control strategy. This can help improve the understanding of the actual emissions from building operations and provide a better overview of future conditions.

7.5 Concluding Reflections

Efficiency, consistency, and sufficiency are key strategies for driving holistic change in the building industry and modern society. This thesis focuses on building efficiency, representing just a small part of the effort to combat climate change. Thanks to the digitalization and the variety of simulation software nowadays, new opportunities to optimize the energy efficiency of buildings are coming up. Rapidly advancing simulation tools allow for quick parametric evaluation of recent trends. This leads the way for a new area of building planning and maximizes the possibility of finding the best solution for individual projects. With these new skill sets, architects and engineers learn new ways to think about design and can find unique solutions to balance the design and the environmental aspects of a building. This helps the process of becoming climate neutral and fosters the goal of decreasing carbon emissions worldwide.

But it is the Author's full attention to strongly emphasize that the optimization of building technology is only a tiny part of becoming climate neutral. Moreover, efficiency is already highly developed, particularly in Western engineering societies like Germany, making it a straightforward yet limited approach. Even more, it is the straightforward and mandatory part as efficiency, especially in Western engineering societies like Germany, is already very well developed. The effort to increase this efficiency even more is ineffective compared to other approaches. In part, one can speak about an efficiency dilemma, where more resources are put into developing more efficiency, which exceeds the actual savings. Therefore, a feasible design would decrease the energy demands at the base by adapting the building to the local climate conditions in the design phase. A responsible strategy would prioritize climate-friendly architectural design, emphasizing low-tech, user-oriented solutions before integrating complex building technology. Moreover, developing intelligent strategies to foster sufficiency and consistency in our society is even more critical. Changing our behaviors and how we think and live in buildings can address great potential for emissions savings.

Although this final reflection may deemphasize the application of this work, the author intends to state a clear, last message in the outcomes of this dissertation. In that respect, this dissertation ends with the statement that technology alone will not solve the environmental problems we are facing right now. The development of holistic approaches that integrate sufficiency, consistency, and efficiency, while actively involving people, is essential to creating a sustainable and climate-neutral built environment for the people.

References

[1-1] IPCC, Global Warming of 1.5°C. Cambridge University Press, 2022, available online (last access 10/2023): https://www.ipcc.ch/sr15/

[1-2] United Nations, “Paris Agreement”, Paris, 2015, available online (last access 10/2023): https://www.un.org/en/climatechange/paris-agreement

[1-3] European Union, “Energy roadmap 2050,” 2012, available online (last access 10/2023): https://energy.ec.europa.eu/system/files/2014-10/roadmap2050_ia_20120430_en_0.pdf

[1-4] Bundesministerium für Wirtschaft und Energie, “Energiedaten - Gesamtausgabe: Stand 2018,” 2018, available online (last access 10/2023): https://www.bmwk.de/Redaktion/DE/Artikel/Energie/energiedaten-gesamtausgabe.html

[1-5] Bundesministerium für Wirtschaft und Energie, “Klimaschutzbericht 2022,” Aug. 2022, available online (last access 10/2023): https://www.bmwk.de/Redaktion/DE/Downloads/Energie/klimaschutzbericht.html

[1-6] UNEP, The closing window: Climate crisis calls for rapid transformation of societies (The emission gap report 2022). Nairobi: United Nations Environment Programme, 2022, available online (last access 10/2023): https://wedocs.unep.org/bitstream/handle/20.500.11822/40874/EGR2022.pdf?sequence=1&isAllowed=y

[1-7] Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden: Gebäudeenergiegesetz - GEG, 2020, available online (last access 10/2023): https://www.gesetze-im-internet.de/geg/GEG.pdf

[1-8] Johannes Jungwirth, “Lastmanagement in Gebäuden: Entwicklung einer modellprädiktiven Regelung mit einem adaptiven Gebäudemodell zur Flexibilisierung der Wärme- und Kälteversorgung von Gebäuden,” Dissertation, Technische Universität München - Lehrstuhl für Energiewirtschaft und Anwendungstechnik, München, 2014, available online (last access 10/2023): https://mediatum.ub.tum.de/1221398

[1-9] World Energy Council, “World Energy Resources: Solar,” ISBN: 978 0 946121 29 8, 2013, available online (last access 10/2023): https://www.worldenergy.org/publications/entry/world-energy-resources-2013-survey

[1-10] Robert J. Hijmans, Susan Cameron, and Juan Parra, “WorldClim: Global weather stations,” Museum of Vertebrate Zoology, University of California, Berkeley, 2010, available online (last access 10/2023): https://databasin.org/datasets/15a31dec689b4c958ee491ff30fcce75/

[1-11] United States Environmental Protection Agency, Ed., “Report to Congress on Indoor Air Quality: Volume II: Assessment and Control of Indoor Air Pollution. EPA/400/1-89/001C,” 1989, available online (last access 10/2023): https://www.osti.gov/biblio/6958939

[1-12] Y. M. Ivanova, H. Pallubinsky, R. Kramer, and W. van Marken Lichtenbelt, “The influence of a moderate temperature drift on thermal physiology and perception,” Physiology & behavior, available online (last access 10/2023): doi:10.1016/j.physbeh.2020.113257

[1-13] S. W. Keith et al., “Putative contributors to the secular increase in obesity: exploring the roads less traveled,” International journal of obesity (2005), available online (last access 10/2023): doi:10.1038/sj.ijo.0803326

[1-14] W. Luo, R. Kramer, Y. de Kort, P. Rense, and W. van Marken Lichtenbelt, “The effects of a novel personal comfort system on thermal comfort, physiology and perceived indoor environmental quality, and its health implications - Stimulating human thermoregulation without compromising thermal comfort,” Indoor air, available online (last access 10/2023): doi:10.1111/ina.12951

[1-15] L. Schellen, W. D. van Marken Lichtenbelt, M. G. L. C. Loomans, J. Toftum, and M. H. de Wit, “Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition,” Indoor air, available online (last access 10/2023): doi:10.1111/j.1600-0668.2010.00657.x.

[1-16] W. van Marken Lichtenbelt, M. Hanssen, H. Pallubinsky, B. Kingma, and L. Schellen, “Healthy excursions outside the thermal comfort zone,” Building Research & Information, vol. 45, pp. 819–827, 2017, available online (last access 10/2023): doi:10.1080/09613218.2017.1307647

[1-17] Eingangsparameter für das Raumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden - Raumluftqualität, Temperatur, Licht und Akustik, Deutsches Institut für Normung, Dec. 2012, available online (last access 10/2023): https://www.beuth.de/de/norm/din-en-15251/155677389

[1-18] Ergonomie der thermischen Umgebung - Analytische Bestimmung und Interpretation der thermischen Behaglichkeit durch Berechnung des PMV- und des PPD-Indexes und Kriterien der lokalen thermischen Behaglichkeit, DIN EN ISO 7730:2006-05, Deutsches Institut für Normung, May. 2006, available online (last access 10/2023): https://www.beuth.de/de/norm/din-en-iso-7730/89417255

[1-19] Flexeder, Nina and Schumacher, Nils and Hepf, Christian and Nouman, Ahmad and Briels, David and Varga, Zsofia and Kamml, Michael and Paulik, Johannes and Übelhör, Valentin and Winter, Stefan and Auer, Thomas, “Potenziale hygrothermisch aktivierter Bauteile (PhyTAB),” Innovationsprogramm Zukunft Bau, Bundesinstitut für Bau-, Stadt- und Raumforschung, Bonn, 2022, available online (last access 10/2023): https://mediatum.ub.tum.de/1654231?show_id=1713789

[1-20] Hepf Christian, “Energy optimization of a geothermal heat-pump system through dynamic system simulation: A case study for the International Airport Calgary,” Master Thesis, TUM, Munich, 2018, available online (last access 10/2023): https://mediatum.ub.tum.de/node?id=1694272

[1-21] Lastverhalten von Gebäuden unter Berücksichtigung unterschiedlicher Bauweisen und technischer Systeme - Speicher- und Lastmanagementpotenziale in Gebäuden: Endbericht, Stuttgart: Fraunhofer IRB Verlag, 2014, available online (last access 10/2023): https://www.arc.ed.tum.de/fileadmin/w00cgv/klima/Publikationen/Berichte/Endbericht_Lastverhalten-von-Gebaeuden.pdf

[1-22] T. Auer et al., Gebäude als intelligenter Baustein im Energiesystem: Lastmanagement-Potenziale von Gebäuden im Kontext der zukünftigen Energieversorgungsstruktur in Deutschland, Stuttgart: Fraunhofer IRB Verlag, 2017, available online (last access 10/2023): https://www.arc.ed.tum.de/fileadmin/w00cgv/klima/Publikationen/Berichte/Endbericht_Lastmanagement-Potenziale-von-Gebaeuden.pdf

[1-23] BINE Informationsdienst, “Nutzerverhalten bei Sanierungen berücksichtigen,”, 2015, available online (last access 10/2023): https://bbu.de/system/files/publications/5-6-nutzerverhalten_reboundeffekt.pdf

[1-24] E. Delzendeh, S. Wu, A. Lee, and Y. Zhou, “The impact of occupants’ behaviours on building energy analysis: A research review,” Renewable and Sustainable Energy Reviews, vol. 80, pp. 1061–1071, 2017, available online (last access 10/2023): doi:10.1016/j.rser.2017.05.264

[1-25] Education Funding Agency, Ed., “Property data survey programme: Summary report,” Jan. 2015, available online (last access 10/2023): https://gov.uk//system/PDSP_Summary_Report.pdf

[1-26] Mojic, I., Luzzatto, M., Haller, M., Lehmann, M., Benz, M. & van Velsen, S., “ImmoGap: Einfluss der Kombination aus Nutzerverhalten und Gebäudetechnik auf den Performance Gap bei Mehrfamilienhäuser,” 2018, available online (last access 10/2023): https://www.minergie.ch/media/501469_haller_sb_immogap.pdf

[1-27] Lauss, L.; Auer, T.; Meier, A.; Rink, A.; Granmayeh, A.: “Robuste, nutzerfreundliche und kostengünstige TGA in Gebäuden,”, available online (last access 10/2023): https://www.arc.ed.tum.de/fileadmin/w00cgv/klima/_my_direct_uploads/endbericht.pdf

[1-28] ASHRAE Guideline14-2002: Measurement of Energy and Demand Savings (2005), available online (last access 10/2023): http://www.eeperformance.org/uploads/8/6/5/0/8650231/ashrae_guideline_14-2002.pdf

[1-29] Thermal Energy System Specialists, LLC, “What is TRNSYS?”, available online (last access 10/2023): https://www.trnsys.com/

[2-1] Vaillant GmbH. “Wir sorgen für ein besseres Klima”, available online (last access 9/2023): https://www.vaillant-group.com/

[2-2] Viessmann Climate Solutions SE. “Viessmann: Für unser Klima.”, available online (last access 9/2023): https://www.viessmann.de/

[2-3] Siemens Aktiengesellschaft. “Siemens Group.”, available online (last access 9/2023): https://www.siemens.com/de/de/produkte/gebaeudetechnik.html

[2-4] Carrier World Headquarters. “Carrier HEALTHY BUILDINGS.”, available online (last access 9/2023): https://www.carrier.com/carrier/en/worldwide/buildings/

[2-5] Bosch Thermotechnik GmbH. “Bosch Home Comfort.”, available online (last access 9/2023): https://www.bosch-homecomfort.com/de/de/wohngebaeude/start/

[2-6] tado GmbH. “tado° -.”, available online (last access 9/2023): https://www.tado.com/de-de **[2-7]** NETATMO Legrand Group. “NETATMO.”, available online (last access 9/2023): https://www.netatmo.com/en-eu

[2-8] Schneider Electric GmbH c/o Merten GmbH. “Wiser Home.”, available online (last access 9/2023): https://merten.de/produkte/wiser.html

[2-9] Controme GmbH. “CONTROME.”, available online (last access 9/2023): https://www.controme.com/

[2-10] Google Nest. “Nest Thermostat.”, available online (last access 9/2023): https://home.nest.com/

[2-11] Leanheat Oy. “Danfoss Leanheat.”, available online (last access 9/2023): https://leanheat.com/

[2-12] DABBEL - Automation Inteligence GmbH. “DABBEL.”, available online (last access 9/2023): https://www.dabbel.eu/

[2-13] L. Pérez-Lombard, J. Ortiz, and C. Pout, “A review on buildings energy consumption information,” Energy and Buildings, vol. 40, no. 3, pp. 394–398, 2008, available online (last access 9/2023): doi:10.1016/j.enbuild.2007.03.007

[2-14] Bundesministerium für Wirtschaft und Energie (BMWi), “Grünbuch Energieeffizienz: Diskussionspapier des Bundesministeriums für Wirtschaft und Energie,” Berlin, Deutschland, 2016, available online (last access 9/2023): https://www.bmwk.de/Redaktion/DE/Artikel/Energie/gruenbuch-energieeffizienz.html

[2-15] European Commission –Department: Energy - In Focus, Energy efficiency in buildings. Brussels, 2020, available online (last access 9/2023): https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en

[2-16] Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden: Gebäudeenergiegesetz - GEG, 2020, available online (last access 9/2023): https://www.gesetze-im-internet.de/geg/GEG.pdf

[2-17] H.-P. Schettler-Köhler, Das neue Gebäudeenergiegesetz: Wegweiser, Begründungen, Kommentare, 1st ed. (Beuth Recht). Berlin: Beuth, 2021, available online (last access 9/2023): https://www.beuth.de/de/publikation/das-neue-gebaeudeenergiegesetz/323521799

[2-18] Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 2: Mindestanforderungen an den Wärmeschutz, 4108-02:2002-07, DIN Deutsches Institut für Normung e. V., Berlin, Jul. 2003, available online (last access 9/2023): https://www.beuth.de/de/norm/din-4108-2/167922321

[2-19] DIN EN ISO 7730, Ergonomie der thermischen Umgebung – Analytische Bestimmung und Interpretation der thermischen Behaglichkeit durch Berechnung des PMV- und des PPD-Indexes und Kriterien der lokalen thermischen Behaglichkeit, DIN Deutsches Institut für Normung e.V., Berlin, 2006, available online (last access 9/2023): https://www.beuth.de/de/norm/din-en-iso-7730/89417255

[2-20] P. O. Fanger, Thermal comfort: Analysis and applications in environmental engineering (Zugl.: Lyngby, Danmarks tekniske Højskole, Diss, 1970). New York, 1972, available online (last access 9/2023): https://journals.sagepub.com/doi/abs/10.1177/146642407209200337

[2-21] G. Hausladen, ClimaDesign: Lösungen für Gebäude, die mit weniger Technik mehr können, 1st ed. München: Callwey, 2004, ISBN-13: 9783766716125

[2-22] DIN EN 16798-1:2022-03 Energetische Bewertung von Gebäuden - Lüftung von Gebäuden - Teil 1: Eingangsparameter für das Innenraumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden bezüglich Raumluftqualität, Temperatur, Licht und Akustik, 2019, Berlin, available online (last access 9/2023): https://www.beuth.de/de/norm/din-en-16798-1/349622591

[2-23] DIN EN 15251:2012-12, Eingangsparameter für das Raumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden_- Raumluftqualität, Temperatur, Licht und Akustik; Deutsche Fassung EN_15251:2007, Berlin, available online (last access 9/2023): https://www.beuth.de/de/norm/din-en-15251/155677389

[2-24] Thermal Energy System Specialists, LLC. “What is TRNSYS?”, available online (last access 9/2023): https://www.trnsys.com/

[2-25] Robert McNeel & Associates. “Rhinoceros 3D.”, available online (last access 9/2023): https://www.rhino3d.com

[2-26] Michelle Pierburg, “Erstellung eines kalibrierten hygrothermischen Simulationsmodells im Realmaßstab: Bewertung verschiedener Testfassadenelemente hinsichtlich ihres hygrothermischen Potentials,” Master Thesis, TUM, Munich, Germany, 2020, not published

[2-27] Christian Zang, “Visueller Komfort von dimmbaren Fassaden unter Berücksichtigung des thermischen Komforts und ihrer architektonischen Auswirkungen,” Master Thesis, TUM, Munich, Germany, 2019, not published

[2-28] P. Molter, “Technikintegration in offenen Fassadensystemen,” Dissertation, Technische Universität München - Professur für Entwerfen und Gebäudehülle, München, 2016, available online (last access 9/2023): https://mediatum.ub.tum.de/doc/1254651/1254651.pdf

[2-29] AHLBORN Mess- und Regelungstechnik GmbH, “ALMEMO ® Handbuch für alle ALMEMO ® Messgeräte und Sensoren,” Holzkirchen, Germany, 2020, available online (last access 9/2023): https://www.ahlborn.com/assets/uploads/Downloads/Handbuch/ALMEMO-Handbuch-2020.pdf

[3-1] United Nations (Bell, E., Cullen, J)/ Framework Convention on Climate Change, 2015: Adoption of the Paris Agreement, 21st Conference of the Parties, Paris, France: (last access March 2022): https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[3-2] European commission (2021). Paris Agreement. Paris, France, available online (last access March 2022): https://ec.europa.eu/clima/policies/international/negotiations/paris_en

[3-3] Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz 2020, Klimaschutzbericht, Berlin Germany available online (last access 2022): https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzbericht2020.pdf

[3-4] GEG: Gebäudeenergiegesetz. Bundesnetzgesetzblatt Jahrgang 2020 Teil I Br. 37; Bundesanzeigerverlag Bundesgesetzblatt Bonn 2020.

[3-5] Solar Energy Laboratory, University of Wisconsin-Madison 2017: TRNSYS 18 A TRaNsient SYstem Simulation program Standard Component Library, USA

[3-6] ASHRAE Standards Strategic Plan Ad Hoc Committee, 2019 ASHRAE STANDARDS STRATEGIC PLAN, Atlanta USA, available online (last access 2022): https://www.ashrae.org/about/news/2019/ashrae-releases-2019-2024-strategic-plan

[3-7] Molter, P. L., 2016: Technikintegration in offenen Fassadensystemen, Dissertation, TU München Germany available online (last access 2022): https://mediatum.ub.tum.de/doc/1254651/1254651.pdf

[3-8] u-wert.net GmbH, 2022: https://www.ubakus.de (Last access: Februar 2022) Forst, Germany

[3-9] Zang, C., 2019: Visueller Komfort von dimmbaren Fassaden unter Berücksichtigung des thermischen Komforts und ihrer architektonischen Auswirkungen, Master Thesis (not published), TU München, Germany

[3-10] AHLBORN Mess- und Regelungstechnik GmbH, 2020: ALMEMO ® Handbuch für alle ALMEMO ® Messgeräte und Sensoren, Holzkirchen, Germany, available online (last access 2022): https://www.ahlborn.com/download/Handbuch/de/Hb2020.pdf

[3-11] Brunet, F., 2021: Potenzialstudie zur thermischen Raumoptimierung durch eine wetterprädiktive Steuerung unter Betrachtung der thermischen Masse, Master Thesis (not published), TU München, Germany

[4-1] United Nations (Bell, E., Cullen, J Eds.). Framework Convention on Climate Change. In Proceedings of the Adoption of the Paris Agreement, 21st Conference of the Parties, Paris, France, 30 November–11 December 2015: available online (last access 05/2023):https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

[4-2] UNEP. 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector; United Nations Environment Programme: Nairobi, Kenya, 2020: available online (last access 05/2023): https://wedocs.unep.org/20.500.11822/41133

[4-3] ISE. Wege zu einem klimaneutralen Energiesystem—Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen; Fraunhofer-Institut für Solare Energiesysteme ISE: Freiburg, Germany, 2020: available online (last access 05/2023): https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/wege-zu-einem-klimaneutralen-energiesystem.html

[4-4] BMU: Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz 2020, Klimaschutzbericht; Bonn Germany,DMUB, 2020: available online (last access 05/2023): https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzbericht2020.pdf

[4-5] GEG: Gebäudeenergiegesetz. Bundesnetzgesetzblatt Jahrgang 2020 Teil I Br. 37; Bundesanzeigerverlag Bundesgesetzblatt Bonn 2020.

[4-6] Regett, A.; Heller, C. Relevanz zeitlich aufgelöster Emissionsfaktoren für die Bewertung tages- und jahreszeitlich schwankender Verbraucher. Energ. Tagesfr. 2015, 65, 46–50: available online (last access 05/2023): https://www.ffe.de/download/article/570/Artikel%20et%2007_2015.pdf.

[4-7] Seckinger, N.; Radgen, P. Dynamic Prospective Average and Marginal GHG Emission Factors—Scenario-Based Method for the German Power System until 2050. Energies 2021, 14, 1–22: available online (last access 05/2023): https://www.mdpi.com/1996-1073/14/9/2527

[4-8] Wörner, P.; Müller, A.; Sauerwein, D. Dynamische CO2-Emissionsfaktoren für den deutschen Strom-Mix. Bauphysik 2019, 41, 17–29: available online (last access 05/2023): https://doi.org/10.1002/bapi.201800034

[4-9] Müller, A.; Wörner, P. Impact of dynamic CO2 emission factors for the public electricity supply on the life-cycle assessment of energy efficient residential buildings. IOP Conf. Ser. Earth Environ. Sci. 2019, 323, 1–9: available online (last access 05/2023): https://iopscience.iop.org/article/10.1088/1755-1315/323/1/012036/meta

[4-10] DWD Klimadaten Deutschland—Stundenwerte (Archiv). 2021: available online (last access 05/2023): https://www.dwd.de/DE/leistungen/klimadatendeutschland/klarchivstunden.html

[4-11] Hepf, C.; Schmid, S.; Brunet, F.; Auer, T. Validation of Thermodynamic Building Model Based on Weather and Thermal Measurement Data; BauSIM: Weimar, Germany, 2022; pp. 189–195: available online (last access 05/2023): https://doi.org/10.26868/29761662.2022.36

[4-12] Agora Klimaneutrales Deutschland 2045—Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann—Langfassung; Agora Energiewende: Berlin, Germany, 2021: available online (last access 05/2023): https://www.oeko.de/publikationen/p-details/klimaneutrales-deutschland-2045-wie-deutschland-seine-klimaziele-schon-vor-2050-erreichen-kann

[4-13] Solar Energy Laboratory, University of Wisconsin. TRNSYS 18 A TRaNsient System Simulation Program; Standard Component Library: Madison, WI, USA, 2017.

[4-14] Ladybug Tools LLC Honeybee. 2022: available online (last access 05/2023): https://www.ladybug.tools/honeybee.html (accessed on 6 October 22).

[4-15] Jocher, T.; Loch, S. Raumpilot Grundlagen; Wüstenrot Stiftung: Ludwigsburg, Germany, 2012.

[4-16] DIN—Normenausschuss Baulicher Wärmeschutz im Hochbau, DIN-Normenausschuss Bauwesen (NABau). DIN 4108—Wärmeschutz und Energie-Einsparung in Gebäuden; Beuth Verlag GmbH: Berlin, Germany, 2013.

[4-17] DIN—Normenausschuss Baulicher Wärmeschutz im Hochbau, DIN-Normenausschuss Bauwesen (NABau). DIN V 18599-10, Energetische Bewertung von Gebäuden—Berechnung des Nutz-, End- und Primärenergiebedarfs für Heizung, Kühlung, Lüftung, Trinkwarmwasser und Beleuchtung—Teil 10: Nutzungsrandbedingungen, Klimadaten; Beuth Verlag GmbH: Berlin, Germany, 2018.

[4-18] DIN—Normenausschuss Baulicher Wärmeschutz im Hochbau, DIN-Normenausschuss Bauwesen (NABau). DIN EN 16798-1 Energetische Bewertung von Gebäuden—Lüftung von Gebäuden—Teil 1: Eingangsparameter für das Innenraumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden bezüglich Raumluftqualität, Temperatur, Licht und Akustik; Beuth Verlag GmbH: Berlin, Germany, 2019.

[4-19] Heydenreich, W.; Büller, B.; Reise, C. Describing the world with three parameters: A new approach to PV module power modelling. In Proceedings of the 23rd European Photovoltaic Solar Energy Conference and Exhibition, Valencia, Spain, 1–5 September 2008; pp.1–44: available online (last access 05/2023): https://www.eupvsec-proceedings.com/proceedings?paper=3139

[4-20] Weniger, J.; Quaschning, V.; Tjaden, T. Optimale Dimensionierung von PV-Speichersystemen. PV Magazine, January 2013, pp. 70–75: available online (last access 05/2023): https://www.pv-magazine.de/archiv/optimale-dimensionierung-von-pv-speichersystemen/

[5-1] International Energy Agency; Global Alliance for Buildings and Construction. 2019 Global Status Report for Buildings and Construction; International Energy Agency; Global Alliance for Buildings and Construction: Paris, France, 2019, available online (last access 06/2023): https://globalabc.org/sites/default/files/2020-03/GSR2019.pdf

[5-2] Presse- und Informationsamt der Bundesregierung. "Generationenvertrag für das Klima", available online (last access 12/2022): https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672

[5-3] Energieeinsparverordnung: Vom 24. Juli 2007 (BGBl. I S. 1519)]; Energieeinsparungsgesetz, Energieeinsparverordnung mit Anlagen, Bekanntmachungen, Landesrechtliche Vorschriften; [Regelungen über Energieausweise]; Textausgabe mit Ausführlichem Sachverzeichnis, 1st ed.; (dtv Beck-Texte im dtv 5775); Dt. Taschenbuch-Verl.: München, Germany, 2008.

[5-4] Fassbender, E.; Ludwig, F.; Hild, A.; Auer, T.; Hemmerle, C. Designing Transformation: Negotiating Solar and Green Strategies for the Sustainable Densification of Urban Neighbourhoods. Sustainability 2022, 14, 3438, available online (last access 05/2023): https://doi.org/10.3390/su14063438

[5-5] Fassbender, E.; Claudia, H.; Natalie, M. (Eds.). Multi-Criteria Design and Decision Support for Solar and Green Envelopes: Simplicity vs. Performance; 2021. available online (last access 05/2023): https://pure.tudelft.nl/ws/portalfiles/portal/89352805/powerskin_proceedings_2021.pdf

[5-6] Severin Beucker, S.H. Einsparpotenziale aus der Optimierung von Heizungsanlagen in Wohngebäuden, available online (last access 05/2023): https://www.bmwk.de/Redaktion/DE/Publikationen/Energie/einsparpotenziale-aus-der-optimierung-von-heizungsanlagen-in-wohngebaeuden.pdf?__blob=publicationFile&v=6

[5-7] Schmelas, M. Entwicklung und Evaluierung Eines Adaptiv-Prädiktiven Algorithmus' für Thermoaktive Bauteilsysteme. Ph.D. Thesis, Universitätsbibliothek Freiburg: Breisgau, Germany, 2017, available online (last access 05/2023): https://doi.org/10.6094/UNIFR/13892

[5-8] Jungwirth, J. Lastmanagement in Gebäuden; Technische Universität München, Diss.: München, Germany, 2015. available online (last access 05/2023): https://mediatum.ub.tum.de/1221398

[5-9] Schmid, T.; Hepf, C.; Wagner, T.; Meile, S.; Bratoev, I.; Schubert, G.J. Decentralized MCT: Design of a Decentralized Measurement and Control Technology Concept for Building Services in the Context of the Internet of Things; (Forschungsinitiative Zukunft Bau F 3160); Fraunhofer IRB Verlag: Stuttgart, Germany, 2019 available online (last access 12/2022): https://www.irbnet.de/daten/kbf/kbf_e_F_3160.pdf

[5-10] Auer, T.; Hamacher, T.; Wagner, U.; Atabay, D.; de-Borja-Torrejón, M.; Dornmair, R.; Kuhn, P.; Maderspacher, J.; Sänger, F.; Laenge, J.; et al. Gebäude als Intelligenter Baustein im Energiesystem: Lastmanagement-Potenziale von Gebäuden im Kontext der Zukünftigen Energieversorgungsstruktur in Deutschland; (Forschungsinitiative Zukunft Bau F 3054); Fraunhofer IRB Verlag: Stuttgart, Germany, 2017, available online (last access 12/2022): https://www.arc.ed.tum.de/fileadmin/w00cgv/klima/Publikationen/Berichte/Endbericht_Lastmanagement-Potenziale-von-Gebaeuden.pdf

[5-11] Hausladen, G.; Auer, T.; Schneegans, J.; Klimke, K.; Riemer, H.: Lastverhalten von Gebäuden unter Berücksichtigung Unterschiedlicher Bauweisen und Technischer Systeme—Speicher- und Lastmanagementpotenziale in Gebäuden: Endbericht; (Forschungsinitiative Zukunft Bau F 2920); Fraunhofer IRB Verlag: Stuttgart, Germany, 2014, available online (last access 12/2022): https://www.irbnet.de/daten/kbf/kbf_d_F_2920.pdf

[5-12] Dornmair, R.; Atabay, D.; Sänger, F.; de Borja Torrejón, M.; Maderspacher, J. Einfluss von Gebäuden als Wärmespeicher auf das Energiesystem. In 10. Internationale Energiewirtschaftstagung der TU Wien; 2017, Vienna, Austria. available online (last access 12/2022): https://mediatum.ub.tum.de/doc/1350554/1350554.pdf

[5-13] Hausladen, G.; de Saldanha, M.; Liedl, P.: ClimaDesign: Lösungen für Gebäude, die mit Weniger Technik Mehr Können, 1st ed.; Callwey: München, Germnay, 2004, available online (last access 08/2022): https://www.baufachinformation.de/artikel.jsp?v=219634

[5-14] Deutscher Wetterdienst. "Numerical Methods". available online (last access 12/2022): https://www.dwd.de/DE/forschung/wettervorhersage/num_modellierung/01_num_vorhersagemodelle/01a_num_methoden/numerischemethoden_node.html

[5-15] Kheybari, A.G.; Alwalidi, M.; Hepf, C.; Auer, T.; Hoffmann, S. A multi-objective evaluation for envelope refurbishments with electrochromic glazing. Results Eng. 2022, 14, 100417. available online (last access 05/2023): https://doi.org/10.1016/j.rineng.2022.100417

[5-16] Energetische Bewertung von Gebäuden: 1–10, 18599 1–10; Deutsches Institut für Normung e.V., 2018: Berlin, Germany, 2022

[5-17] Wärmeschutz und Energie-Einsparung in Gebäuden: 1–11, 4108; Deutsches Institut für Normung e.V., 2018: Berlin, Germany, 2013

[5-18] Hepf, C.; Bausch, K.; Lauss, L.; Koth, S.C.; Auer, T. Impact of Dynamic Emission Factors of the German Electricity Mix on the Greenhouse Gas Balance in Building Operation. Buildings 2022, 12, 2215, available online (last access 05/2023): https://doi.org/10.3390/buildings12122215

[5-19] Statistisches Bundesamt, (Destatis), "Umweltökonomische Gesamtrechnungen: Energiev brauch der privaten Haushalte für Wohnen", available online (last access 05/2023): https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/private-haushalte/Tabellen/energieverbrauch-haushalte.html

[5-20] Rawal, R.; Shukla, Y.; Vardhan, V.; Asrani, S.; Schweiker, M.; de Dear, R.; Garg, V.; Mathur, J.; Prakash, S.; Diddi, S.; et al. Adaptive thermal comfort model based on field studies in five climate zones across India. Build. Environ. 2022, 219, 109187, available online (last access 05/2023): https://doi.org/10.1016/j.buildenv.2022.109187

[5-21] R. de Dear and G. Brager. "Developing an Adaptive Model of Thermal Comfort and Preference", available online (last access 05/2023): https://escholarship.org/uc/item/4qq2p9c6

[5-22] Energetische Bewertung von Gebäuden—Lüftung von Gebäuden—Teil 1: Teil 1: Eingangsparameter für das Innenraumklima zur Auslegung und Bewertung der Energieeffizienz von Gebäuden bezüglich Raumluftqualität, Temperatur, Licht und Akustik: 1–11, 16798; Deutsches Institut für Normung e.V., 2018: Berlin, Germany, 2022.

[5-23] Ivanova, Y.M.; Pallubinsky, H.; Kramer, R.; Lichtenbelt, W.V.M. The influence of a moderate temperature drift on thermal physiology and perception. Physiol. Behav. 2020, 229, available online (last access 05/2023): https://doi.org/10.1016/j.physbeh.2020.113257

[5-24] Keith, S.W.; Redden, D.T.; Katzmarzyk, P.T.; Boggiano, M.M.; Hanlon, E.C.; Benca, R.M.; Ruden, D.; Pietrobelli, A.; Barger, J.L.; Fontaine, K.R.; et al. Putative contributors to the secular increase in obesity: Exploring the roads less traveled. Int. J. Obes. 2006, 30, available online (last access 05/2023): https://doi.org/10.1038/sj.ijo.0803326

[5-25] Luo, W.; Kramer, R.; de Kort, Y.; Rense, P.; Lichtenbelt, W.V.M. The effects of a novel personal comfort system on thermal comfort, physiology and perceived indoor environmental quality, and its health implications - Stimulating human thermoregulation without compromising thermal comfort. Indoor Air 2021, 32, e12951, available online (last access 05/2023): https://doi.org/10.1111/ina.12951

[5-26] Schellen, L.; Lichtenbelt, W.D.V.M.; Loomans, M.G.L.C.; Toftum, J.; De Wit, M.H. Differences between young adults and elderly in thermal comfort, productivity, and thermal physiology in response to a moderate temperature drift and a steady-state condition. Indoor Air 2010, available online (last access 05/2023): https://doi.org/10.1111/j.1600-0668.2010.00657.x

[5-27] van Marken Lichtenbelt, W.; Hanssen, M.; Pallubinsky, H.; Kingma, B.; Schellen, L. Healthy excursions outside the thermal comfort zone. Build. Res. Inf. 2017, available online (last access 05/2023): https://doi.org/10.1080/09613218.2017.1307647

[5-28] Kramer, R.; Schellen, H.; van Schijndel, A. Impact of ASHRAE's museum climate classes on energy consumption and indoor climate fluctuations: Full-scale measurements in museum Hermitage Amsterdam. Energy Build. 2016, available online (last access 05/2023): https://doi.org/10.1016/j.enbuild.2016.08.016

[5-29] Koth, S.C.; Kobas, B.; Bausch, K.; Auer, T. Mitigating climate change through healthy discomfort. IOP Conf. Series: Earth Environ. Sci. 2022, 1078, 12034, available online (last access 08/2023): https://doi.org/10.1088/1755-1315/1078/1/012034

[5-30] Kobas, B.; Koth, S.C.; Nkurikiyeyezu, K.; Giannakakis, G.; Auer, T. Effect of Exposure Time on Thermal Behaviour: A Psychophysiological Approach. Signals 2021, available online (last access 05/2023): https://doi.org/10.3390/signals2040050

[5-31] Hepf Christian. “Energy optimization of a geothermal heat-pump system through dynamic system simulation: A case study for the International Airport Calgary”, Master Thesis, TUM School of Engineering and Design, Chair of Building Technology and Climate Responsive Design, Technical University of Munich, München. 2018, available online (last access 08/2023): https://mediatum.ub.tum.de/node?id=1694272

[5-32] Amato, V.; Hedegaard, R.; Knudsen, M.; Petersen, S. Room-level load shifting of space heating in a single-family house—A field experiment. Energy Build. 2023, available online (last access 05/2023): https://doi.org/10.1016/j.enbuild.2022.112750

[5-33] Bollin, E.; Schmelas, M. TABS—Thermoaktive Bauteilsysteme: Selbstlernendes und Vorausschauendes Steuern mit AMLR; Springer Vieweg: Wiesbaden/Heidelberg, Germany, 2021, available online (last access 05/2023): 978-3-658-31162-9 (ISBN)

[5-34] Gwerder, M.; Tödtli, J.; Lehmann, B.; Dorer, V.; Güntensperger, W.; Renggli, F. Control of thermally activated building systems (TABS) in intermittent operation with pulse width modulation. Appl. Energy 2009, available online (last access 05/2023): https://doi.org/10.1016/j.apenergy.2009.01.008

[5-35] Ulpiani, G.; Borgognoni, M.; Romagnoli, A.; DI Perna, C. Comparing the performance of on/off, PID and fuzzy controllers applied to the heating system of an energy-efficient building. Energy Build. 2016, available online (last access 05/2023): https://doi.org/10.1016/j.enbuild.2015.12.027

[5-36] Pistohl, W. Allgemeines, Sanitär, Elektro, Gas, 7th ed.; (Handbuch der Gebäudetechnik 1); Werner: Köln, Germany, 2009, available online (last access 05/2023): ISBN 3804146848

[5-37] Thieblemont, H.; Haghighat, F.; Ooka, R.; Moreau, A. Predictive control strategies based on weather forecast in buildings with energy storage system: A review of the state-of-the art. Energy Build. 2017, 153, 485–500, available online (last access 05/2023 https://doi.org/10.1016/j.enbuild.2017.08.010

[5-38] Oldewurtel, F.; Jones, C.N.; Parisio, A.; Morari, M. Stochastic Model Predictive Control for Building Climate Control. IEEE Trans. Control. Syst. Technol. 2013, available online (last access 05/2023): https://doi.org/10.1109/TCST.2013.2272178

[5-39] Zhang, X.; Schildbach, G.; Sturzenegger, D.; Morari, M. Scenario-Based MPC for Energy-Efficient Building Climate Control under Weather and Occupancy Uncertainty, In Proceedings of the 2013 European Control Conference (ECC), Zürich, Switzerland, 2013, available online (last access 05/2023): https://ieeexplore.ieee.org/document/6669664

[5-40] Van Dronkelaar, C.; Dowson, M.; Burman, E.; Spataru, C.; Mumovic, D. A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings. Front. Mech. Eng. 2016, available online (last access 05/2023): https://doi.org/10.3389/fmech.2015.00017

[5-41] Doda, V. Occupants Mind the (Performance) Gap, available online (last access 05/2023): https://issuu.com/climadesign/docs/20171114_brosch_c3_bcre_20cd_202017

[5-42] Lee, J.-Y.; Yeo, M.-S.; Kim, K.-W. Predictive Control of the Radiant Floor Heating System in Apartment Buildings. J. Asian Arch. Build. Eng. 2002, available online (last access 05/2023): https://doi.org/10.3130/jaabe.1.105

[5-43] Paleček, T. Controlling a Heating System Using Deep Reinforcement Learning; Bachelor Project, Faculty of Electrical Engineering, Department of Cybernetics, Technical University

Prague: Prague, Czech Republic, 2018, available online (last access 05/2023): https://dspace.cvut.cz/bitstream/handle/10467/76123/F3-BP-2018-Palecek-Tomas-Controlling%20a%20Heating%20System%20Using%20Deep%20Reinforcement%20Learning.pdf

[5-44] Nagy, Á.; Kazmi, H.S.; Cheaib, F.; Driesen, J. Deep Reinforcement Learning for Optimal Control of Space Heating. arXiv 2018, ArXiv: abs/1805.03777, available online (last access 05/2023): http://www.ibpsa.org/proceedings/BSO2018/1C-4.pdf

[5-45] Hausladen, G.; Tichelmann, K. Ausbau Atlas; DETAIL—Institut für Internationale Architektur-Dokumentation GmbH & Co. KG: Munich, Germany, 2009, available online (last access 05/2023): https://www.detail.de/de/de_de/ausbau-atlas-142

[5-46] Hopfe, C.J. Uncertainty and Sensitivity Analysis in Building Performance Simulation for Decision Support and Design Optimization. Ph.D. Thesis, TU Eindhoven: Eindhoven, The Netherlands, 2009, available online (last access 05/2023): https://doi.org/10.6100/IR643321.

[5-47] Hepf, C.; Schmid, T.; Brunet, F.; Auer, T.: Validation of a thermodynamic building model based on weather and thermal measurement; Proceedings of BauSim Conference 2022: 9th Conference of IBPSA – Germany and Austria, 2022; Weminar Germany, available online (last access 05/2023): https://doi.org/10.26868/29761662.2022.36

[6-1] 2019 global status report for buildings and construction. [Paris]: International Energy Agency; Global Alliance for Buildings and Construction, 2019.

[6-2] H. Gervásio and S. Dimova, "Environmental benchmarks for buildings: EFIResources: Resource Efficient Construction to-wards Sustainable Design," Luxembourg, Rep. JRC110085, 2018, available online (last access 12/2023): https://doi:10.2760/073513

[6-3] C. Hepf, K. Bausch, L. Lauss, S. C. Koth, and T. Auer, "Impact of Dynamic Emission Factors of the German Electricity Mix on the Greenhouse Gas Balance in Building Operation," 2022, available online (last access 12/2023):https://doi:10.3390/buildings12122215

[6-4] Lion Hirth, "The Merit Order Model and Marginal Pricing in Electricity Markets," Accessed: Nov. 16, 2023. [Online]. Available: https://neon.energy/marginal-pricing

[6-5] J. Drgoňa et al., "All you need to know about model predictive control for buildings," Annual Reviews in Control, vol. 50, pp. 190–232, 2020, available online (last access 12/2023): https://doi:10.1016/j.arcontrol.2020.09.001

[6-6] R. Jia, M. Jin, K. Sun, T. Hong, and C. Spanos, "Advanced Building Control via Deep Reinforcement Learning," Energy Procedia, 2019, available online (last access 12/2023): https://doi:10.1016/j.egypro.2019.01.494

[6-7] G. Halhoul Merabet et al., "Intelligent building control systems for thermal comfort and energy-efficiency: A systematic re-view of artificial intelligence-assisted techniques," Renewable and Sustainable Energy Reviews, 2021, available online (last access 12/2023): https://doi:10.1016/j.rser.2021.110969

[6-8] H. Thieblemont, F. Haghighat, R. Ooka, and A. Moreau, "Predictive control strategies based on weather forecast in buildings with energy storage system: A review of the state-of-the art," Energy and Buildings,2017, available online (last access 12/2023): https://doi:10.1016/j.enbuild.2017.08.010

[6-9] K. Leerbeck et al., "Control of Heat Pumps with CO2 Emission Intensity Forecasts," Energies, 2020, available online (last access 12/2023): https://doi:10.3390/en13112851

[6-10] K. Leerbeck et al., "Short-term forecasting of CO2 emission intensity in power grids by machine learning," Applied Energy, 2020, available online (last access 12/2023): https://doi:10.1016/j.apenergy.2020.115527

[6-11] B. Tranberg, A. B. Thomsen, R. A. Rodriguez, G. B. Andresen, M. Schäfer, and M. Greiner, "Power flow tracing in a simpli-fied highly renewable European electricity network," New J.

Phys., 2015, available online (last access 12/2023): https://doi:10.1088/1367-2630/17/10/105002

[6-12] European green deal: Delivering on our targets. Luxembourg: Publications Office of the European Union, 2021

[6-13] Presse- und Informationsamt der Bundesregierung. "Generationenvertrag für das Klima." Accessed: Dec. 21, 2022. available online (last access 12/2023): https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672

[6-14] C. Hepf, Schmid T., Brunet F., and T. Auer, Eds., Validation of Thermodynamic Building Model Based on Weather and Thermal Measurement Data. Weimar, Germany: Proceedings of BauSim Conference 2022 available online (last access 12/2023): https://doi.org/10.26868/29761662.2022.36

[6-15] C. Hepf, L. Overhoff, S. C. Koth, M. Gabriel, D. Briels, and T. Auer, "Impact of a Weather Predictive Control Strategy for Inert Building Technology on Thermal Comfort and Energy Demand," Buildings, 2023, available online (last access 12/2023): https://doi:10.3390/buildings13040996

[6-16] Doda, V. Occupants Mind the (Performance) Gap.,Master Thesis, not available online

[6-17] Lastverhalten von Gebäuden unter Berücksichtigung unterschiedlicher Bauweisen und technischer Systeme - Speicher- und Lastmanagementpotenziale in Gebäuden: Endbericht (Forschungsinitiative Zukunft Bau F 2920). Stuttgart: Fraunhofer IRB Verlag, 2014. available online (last access 12/2023): https://www.arc.ed.tum.de/fileadmin/w00cgv/klima/Publikationen/Berichte/Endbericht_Lastverhalten-von-Gebaeuden.pdf

[6-18] T. Auer et al., Gebäude als intelligenter Baustein im Energiesystem: Lastmanagement-Potenziale von Gebäuden im Kontext der zukünftigen Energieversorgungsstruktur in Deutschland (Forschungsinitiative Zukunft Bau F 3054). Stuttgart: Fraunhofer IRB Verlag, 2017. https://www.arc.ed.tum.de/fileadmin/w00cgv/klima/Publikationen/Berichte/Endbericht_Lastmanagement-Potenziale-von-Gebaeuden.pdf

[6-19] D. Briels et al., "Monolithic AM façade: multi-objective parametric design optimization of additively manufactured insulating wall elements," Front. Built Environ., 2023 available online (last access 12/2023): https://doi:10.3389/fbuil.2023.1286933

[6-20] S. C. Koth, B. Kobas, K. Bausch, and T. Auer, "Mitigating climate change through healthy discomfort," IOP Conf. Ser.: Earth Environ. Sci., 2022, available online (last access 12/2023): https://doi:10.1088/1755-1315/1078/1/012034

[6-21] R. de Dear and G. Brager. "Developing an Adaptive Model of Thermal Comfort and Preference." Accessed: Jan. 5, 2023. available online (last access 12/2023): https://escholarship.org/uc/item/4qq2p9c6

[6-22] Kobas, B; Koth, S.; Nkurikiyeyezu, N.; Giannakakis, G.; Auer, T.; Effect of Exposure Time on Thermal Behaviour: A Psycho-logical Approach, MDPI signals, 2021 available online (19.01.2024): DOI: https://doi.org/10.3390/signals2040050

[6-23] B. Kobas, S. C. Koth, and T. Auer, "Towards a multivariate time-series approach with biosignal datasets for the global thermal comfort database," in Proceedings of the 2022 European Conference on Computing in Construction, 2022, available online (last access 12/2023): https://doi:10.35490/EC3.2022.201

[6-24] Thermal Energy System Specialists, LLC. "What is TRNSYS?" available online (last access 12/2023): https://www.trnsys.com/

[6-25] Robert McNeel & Associates. "Rhinoceros 3D." available online (last access 12/2023): https://www.rhino3d.com/

[6-26] LADYBUG: A parametric environmental plugin for grasshopper to help designer create An envirnonmentally conscious design, 2013.

[6-27] ASHRAE Guideline14-2002: Measurement of Energy and Demand Savings, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE):Haberl, J.S., Culp, C. and Claridge, D.E. (2005). available online (last access 12/2023): http://www.eeperformance.org/uploads/8/6/5/0/8650231/ashrae_guideline_14-2002_measurement_of_energy_and_demand_saving.pdf

[6-28] Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden: Ge-bäudeenergiegesetz - GEG, 2020.

[6-29] Wärmeschutz und Energie-Einsparung in Gebäuden – Teil 2: Mindestanforderungen an den Wärmeschutz, 4108-02:2002-07, DIN Deutsches Institut für Normung e. V., Berlin, Jul. 2003.

[6-30] Nebojsa Nakicenovic, Joseph Alcamo, Gerald Davis, Bert de Vries, Joergen Fenhann, "Emission Scenarios: Special Report on Emission Scenarios," Cambridge University Press, 2000. Accessed: Nov. 16, 2023. available online (last access 12/2023): https://www.ipcc.ch/report/emissions-scenarios/

[6-31] Meteotest AG, Meteonorm (2023). Bern, Switzerland. Accessed: Nov. 16, 2023. [Online]. Available: https://meteonorm.com/

[6-32] Electricity Maps ApS. "Electricitymaps - Real-time carbon intensity of electricity." Accessed: Nov. 16, 2023. available online (last access 12/2023): https://www.electricitymaps.com/company

[6-33] DWD - Deutscher Wetterdienst. "Deutscher Wetter Dienst - Wetter und Klima aus eigener Hand." Accessed: Nov. 16, 2023. available online (last access 12/2023): https://www.dwd.de/DE/

[6-34] R. K. Pachauri and L. Mayer, Eds. Climate change 2014: Synthesis report. Geneva, Switzerland: Intergovernmental Panel on Climate Change, 2015.

[6-35] S. Alavipanah, M. Wegmann, S. Qureshi, Q. Weng, and T. Koellner, "The Role of Vegetation in Mitigating Urban Land Sur-face Temperatures: A Case Study of Munich, Germany during the Warm Season," Sustainability, vol. 7, no. 4, pp. 4689–4706, 2015, available online (last access 12/2023): https://doi:10.3390/su7044689

[6-36] S. National Environment Agency. "NEA's Annual & Sustainability Repor." Accessed: Nov. 26, 2023. available online (last access 12/2023): https://www.nea.gov.sg/

[6-37] National Climate Change Secretariat, "Climate Change & Singapore: Challenges. Opportunities. Partnerships," Singapore, 2012, available online (last access 12/2023): https://www.nccs.gov.sg/files/docs/default-source/default-document-library/national-climate-change-strategy.pdf

[6-38] B. B. Lin et al., "Integrating solutions to adapt cities for climate change," The Lancet. Planetary health, 2021, available online (last access 12/2023): https://doi:10.1016/S2542-5196(21)00135-2

[6-39] Ministry of the Environment and Water Resources; Ministry of National Development: Singapore, For a Sustainable Future: A Climate-Resilient Singapore (Climate Action Plan); 2016.

[6-40] Guatemalan National Institute for Seismology, Vulcanology, Meteorology and Hydrology (INSIVUMEH) climate change. "cambio climatico - climate change.", available online (last access 12/2023): https://insivumeh.gob.gt/

[6-41] UNIDAD DE PLANEACIÓN ENERGÉTICO MINERO, "Politica Energetica: 2019-2050," Accessed: Nov. 16, 2023, available online (last access 12/2023): https://www.mem.gob.gt/wp-content/uploads/2018/11/Pol%C3%ADtica-Energ%C3%A9tica-2019-2050.pdf

[6-42] State Meteorological Agency (AEMET). "Seville - Climate." available online (last access 12/2023): https://www.aemet.es/

[6-43] Ministerio para la Transición Ecológica y el Reto Demográfico. "PLAN NACIONAL INTEGRADO DE ENERGÍA Y CLIMA 2021-2030.", available online (last access 12/2023): https://www.miteco.gob.es/es/prensa/pniec.html

[6-44] D. Argüeso, J. M. Hidalgo-Muñoz, S. R. Gámiz-Fortis, M. J. Esteban-Parra, J. Dudhia, and Y. Castro-Díez, "Evaluation of WRF Parameterizations for Climate Studies over Southern Spain Using a Multistep Regionalization," Journal of Climate, 2011, available online (last access 12/2023): https://doi:10.1175/JCLI-D-11-00073.1

[6-45] Prairie Climate Centre. "Climate Atlas of Canada." available online (last access 12/2023): https://climateatlas.ca/

[6-46] Hepf Christian, "Energy optimization of a geothermal heat-pump system through dynamic system simulation: A case study for the International Airport Calgary," Master Thesis, TUM School of Engineering and Design, Chair of Building Technolo-gy and Climate Responsive Design, Technical University of Munich, München, 2018, available online (last access 12/2023): https://mediatum.ub.tum.de/node?id=1694272

[6-47] S. Hastings-Simon, A. Leach, B. Shaffer, and T. Weis, "Alberta's Renewable Electricity Program: Design, results, and lessons learned," Energy Policy, , 2022, available online (last access 12/2023): https://doi:10.1016/j.enpol.2022.113266

[6-48] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). "ANSI/ASHRAE Standard 55-2004 Thermal Environmental Conditions for Human Occupancy.", available online (last access 12/2023): https://www.ashrae.org/file%20library/technical%20resources/standards%20and%20guidelines/standards%20addenda/ad55_2004_i_k.pdf

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Curriculum Vitae

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Academic Education

2021-2024	Doctoral candidate and Deputy Head of Chair Chair of Building Technology and Climate Responsive Design Technische Universität München - Germany
2024 (05)	CIMNE, Polytechnic University of Catalonia, Barcelona, Spain
2023 (04-05)	Universidade de Seville – Spain - Guest Lecturer
2018-2019	Research Associate & Lecturer Chair of Building Technology and Climate Responsive Design Technische Universität München - Germany
2017	Universidad de Vigo – Spain - Exchange Student
2015-2018	Master of Science - Energy Efficient and Sustainable Building Technische Universität München - Germany
2012-2015	Bachelor of Science - Environmental Engineering Technische Universität München - Germany

Publications

Scientific Publications

2024	Gottkehaskamp, B., Hepf, C.; Miller, C; Chong, A.; Auer, T: Integration of Weather and Emission Predictive Control (WEPC) into Building Energy Simulation
2024	Lauss, L.; Hepf, C.; Schmid, T.; Romero, J.; Auer, T.: Simulation-based evaluation of thermal comfort in buildings, by mitigation of heat stress through passive measures
2024	Koth, S.; Kobas, B.; Reitmayer, A.; Hepf, C.; Auer, T.: Dynamic Cooling – A concept of time-sensitive thermal regulation to cut cooling energy demand in office buildings
2024	Hepf, C; Gottkehaskamp, B., Miller; Auer, T. International Comparison of Weather and Emission Predictive Building Control; MDPI buildings
2023	Hepf, C; Overhoff, L.; Koth, S.; Gabriel, M.; Briels, D.; Auer, T.: Impact of a weather predictive control strategy for inert building technology on thermal comfort and energy; MDPI buildings
2022	Hepf, C.; Bausch, K.; Lauss, L.; Koth, S.C.; Auer, T. Impact of Dynamic Emission Factors of the German Electricity Mix on the Greenhouse Gas Balance in Building Operation, MDPI Building
2022	Flexeder, N., Nouman, A., Hepf, C.: Measurement of Sorption Heat in Laboratory and Field Tests in Comparison with Hygrothermal Simulations; BauSIM: Weimar, Germany
2022	Hepf, C.; Schmid, S.; Brunet, F.; Auer, T. Validation of Thermodynamic Building Model Based on Weather and Thermal Measurement Data; BauSIM: Weimar, Germany
2022	Kheybari, A.G.; Alwalidi, M.; Hepf, C.; Auer, T.; Hoffmann, S. A multi-objective evaluation for envelope refurbishments with electrochromic glazing. Results Engineering
2018	Hepf Christian, “Energy optimization of a geothermal heat-pump system through dynamic system simulation: A case study for the International Airport Calgary,” Master Thesis, TUM,

Scientific Reports

2023	Realisierung eines Nearly Zero Energy Standards für die freie Waldorfschule Uhlandshhe in Stuttgart
2023	PhyTAB - Potentials of hydrothermally activated building components
2022	Adaptable wooden hybrid for differentiated expansion stages
2020	Development of a low Ug-pane with 4-chamber Heat-Mirror structure and ec pane for variation of the SHGC-value with an automatic control strategy considering the weather-predictive energy harvesting strategy and the model of glare evaluation
2019	Leasing Façade - Demonstrator Project
2018	Design of a decentralized measurement and control technology concept for building services in the context of the Internet of Things