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Development of a reduced-order thermal model to support retrofit analysis of residential building clusters

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Abstract

This study aims to introduce a method for retrofitting old buildings with different situations and help with retrofit decision-making and reduce the overall (embodied and operational) emissions during the life span of a building. For the model, several housings in a district are prepared with different options for retrofitting. Three types of housings (detached, semi-detached, and terrace) with four different dates of construction (4 different decades from 1960 to 2000) are considered. Changing windows, adding insulations, changing the source of heating, and adding solar panels as a source of energy are the strategies for retrofitting. The purpose of setting this model is to have a user programming interface to use by any non-expert person in companies and municipalities to help with fast and accurate retrofit decision-making. Moreover, the big-scale analysis can help the municipalities establish laws to push the cities to decrease the emission of the building sector. The main target of this study is the Norway context. For a more comprehensive insight, it will be a comparison between Norway and other locations with different grid emission to see if the strategies for retrofitting Norway suits other locations in Europe. As global warming is a big issue in the construction industry's future, future weather data is considered in the analysis to see the impact of retrofit decision-making in future scenarios.

Preface

This study represents the master thesis study for graduation in sustainable architecture faculty at the Architecture and Technology department of the Norwegian University of Science and Technology. The topic aims to study and suggest an analysis of retrofit decision-making in Norway.

I want to thank my supervisor, Gearóid Lydon, for his invaluable guidance, support, and expertise throughout this thesis. His dedication, patience, and insightful feedback have been instrumental in shaping this work.

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Masoud Elyasi

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AI	Artificial Intelligence
ASHP	Air source heat pumps
EPBD	Energy Performance of the Building Directive
EPD	Environmental Product Declaration
EPW	Energy Plus Weather Files
GHG	Greenhouse gases
GSHP	Ground source heat pumps
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
NVE	Norwegian Water Resources and Energy Directorate
PV	Photovoltaic
RCP	Representative Concentration Pathways
SRES	Specific Report Emission Scenarios
ZEB	Zero Emission Building

Chapter 1

Introduction

Buildings are responsible for 40% of global energy-related emissions [1]. The UN Agenda 2030 policy set a rule to combat global warming issues [2]. The Paris Agreement set a goal for global warming to be less than 2 °C until the year 2100, which leads to strategies to reduce greenhouse gas (GHG) emissions rapidly [3].

In Europe, buildings are responsible for 36% of emissions [4]. 65% of European energy consumption is related to heating energy, and 58% of this energy comes from oil, gas, and coal, which has a large amount of GHG emission [5]. Consequently, the building sector can significantly affect the Paris Agreement target and relies on large-scale electrical grid emission of the buildings and energy saving related to improvements of energy consumption, envelope, and appliances in the buildings [6].

Retrofitting is one of the effective methods to reduce the emission of existing buildings and avoid new constructions and additional emissions. By retrofitting, the emissions of the buildings can reduce significantly in the operational parts by changing different parts of the building, like windows, adding insulation, changing heating systems and distribution systems, and adding sources of energy like solar panels.

There are several studies on this topic, but when it comes to the Norwegian context, there needs to be more robust retrofit decision-making. Norway has a green power grid; most electrical energy comes from hydro-power. Consequently, having robust retrofitting strategies in Norway can reduce the emission of the building sector and make this country one of the pioneers in having low GHG emission building stocks in Europe.

The solution for having adequate and effective retrofit decision-making is to compare all the scenarios of retrofitting a case study together and make the best choice. Considering embodied emission and the lifetime of the retrofit elements are other vital points in this study.

In the first step, a case study is set with different types of housing in a district; there are three types of residential housing in this study (detached, semi-detached, and terrace houses). These houses belong to 4 different decades, from 1960 to 2000. The next step is the pre-retrofit situation, and an RC model is used for calculating the heating demand of the buildings. According to a set of scenarios, the different options for retrofitting are going to study, and a comparison of all the scenarios is to choose the best one for retrofitting with less emission in the Norwegian context (Trondheim weather). Moreover, there will be a comparison between Norway and Germany with different grid emissions to see the difference in retrofit decision-making in another European country. Also, the analysis will run for future weather scenarios to investigate the impact of global warming on retrofitting.

The thesis is separated into four main parts:

Background and review
This chapter contains the background and review of previous works, an overview of the Norwegian context, problem definition, research questions, and objectives.

Methodology
This chapter contains the primary approach of setting the model for analysis, like choosing the software, parameters of the case study, and retrofit options with emissions related to them.

Results
This chapter contains all the analysis results with different graphs and charts to represent the results.

Discussion
This chapter contains the results, answers the research questions, and discusses different options for retrofit decision-making.

Conclusion and future works
This chapter contains the conclusion of the results of this study and suggests future works.

Chapter 2

Background and review

Robust retrofitting is one of the strategies that directly impact building emissions reduction. Retrofitting and construction of a building rely on both embodied and operational emissions. Embodied emissions come from the constructional part, while the operational emissions rely on different future scenarios like global warming situation in the future, electricity grid decarbonization, and user behavior [7]. Consequently, retrofitting decision-making becomes essential to reduce the emission of the building sector.

Revising the energy performance of the building directive (EPBD) is one of the effective strategies to reduce emissions in the building sectors. It recently upgraded the existing regulations to have more ambitious targets in climate and action of society in the building stock.

These regulations push the European stocks to a zero-emission and full decarbonization of buildings toward 2050. The target is to increase the renovation rate, especially for the worst-performing buildings in Europe. It suggested better air quality and more efficient energy systems. It also indicates that EU governments should support vulnerable consumers and fight against energy poverty. The proposal included the description of zero-emission buildings and deep renovations [8].

Consequently, the building sector is going to have a significant change, emission-wise, in the following years, and Lucon et al. [9] concluded that there are three ways for emission reduction: i) improvement of technology and user behavior, ii) electrification of buildings for energy demand, iii) decarbonizing the grid.

2.1 Background

2.1.1 LCA analysis:

There are two steps for the calculation of LCA in retrofitting the buildings: i) calculation of emissions for thermal and electrical energy demands of the building in its lifespan and ii) calculation of embodied emissions of retrofitting materials. Some researchers are focused on optimizing the energy demands [11], and some of them investigate the method of profound impact assessments [12] [13]. The LCA's different stages are shown in Figure 2.1, stages from A to C show embodied emissions, operational part and replacing of materials, and C the end-of-life emissions, which refer to different stages of ZEB buildings. From retrofitting point of view, the B6 stage is often included in the analysis as the other parts have much fewer emissions than this stage. However, in this study, the embodied emission (A1 to A3) will also be considered in the emissions. PD standard files for the emission of materials and average consumption of energies are prepared by national or international organizations for simple and fast use of calculations, and deep investigations of these stages may have huge impacts on the results of retrofitting.

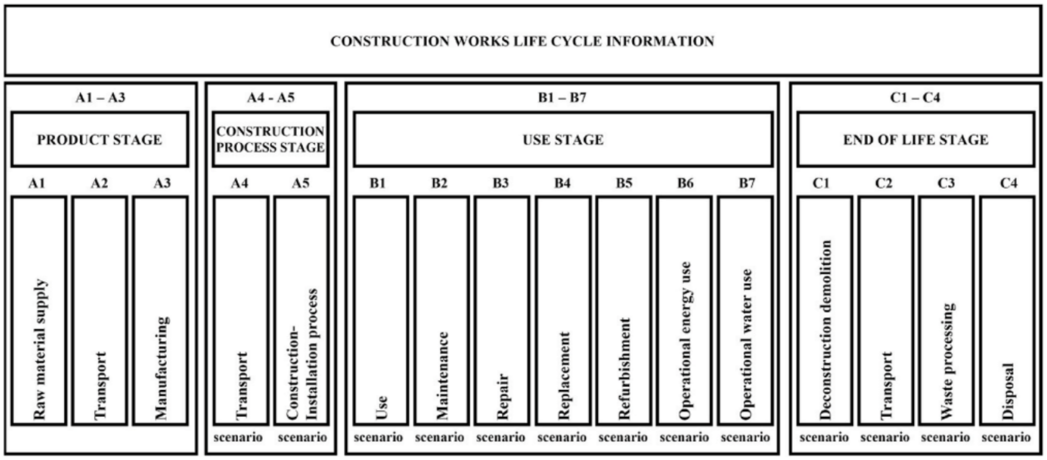


Figure 2.1: Life cycle stage according to EN 15804 2020 [10]

2.1.2 Zero emission building

The zero-emission building concept has a solution for all these emission reductions, and in recent years, there have been lots of reviews of this solution. Accelerating toward this solution needs legislative efforts by the governments, and there is a knowledge gap here between seeing how Zeb technology can be implemented and how different strategies and regulations can affect this process.

According to the Norwegian research center, zero-emission buildings can produce enough energy throughout their lifespan to compensate for the building's greenhouse emissions [32].

It defined different levels of zero emission buildings, and it can be the emission of energy use for operation except the emission of equipment (ZEB-O ÷ EQ) to the ambitious one, which is compensation for all parts of emissions from the operation, embodied emissions from materials to end of life emissions (ZEB-CPMPLETE).
The importance of energy efficiency in existing buildings with renovation is acknowledged in literature with a pathway to renovating buildings toward zero emission buildings and the economic impacts [33]. However, the studies show that cost estimation only allows large-scale renovation to zero-emission levels in the buildings.

2.1.3 Robust retrofitting

Retrofitting in the European context is one of the decarbonization strategies; in this context, assessing the different robust strategies is essential. According to Walker et al., [10], five relevant modelings have the most impact on retrofitting decision-making: (i) global warming effects and EPW files related to future scenarios, (ii) the period analysis of retrofitting and life span of materials in the buildings, (iii) decarbonization of the grid electricity, (iv) the effect of photovoltaic electricity in the buildings, (v) biogenic carbon scenarios in the building materials.

i) Global warming scenarios

The effect of global warming is a vital impact factor in retrofitting analysis. Recently some studies have been done to investigate this parameter in the analysis. Robert and Kummert suggested that future weather data should be considered for robust energy performance in buildings [14]. For instance, in future scenarios, the cooling demand will increase, and the heating demand will decrease [15]. Moreover, Galimshia et al. use different climate scenarios for analysis and claim that global warming leads to higher mean emissions, and using the current data files leads to underestimating the LCA impact [16]. Also, Roux et al. suggested that the impact of climate assumptions has significant effects on the analysis [17]. In some literature reviews, the future climate data comes from respective data providers without specific detail about how these data are collected. There are two references for climate data, older literature refers to SRES (Specific Report Emission Scenarios) [18], and new ones refer to RCP (Representative Concentration Pathways) [19].

ii) Analysis period (building lifetime)

For the analysis period of buildings, the product's expected lifetime is assumed in LCA, which is 50 to 60 years. According to the climate crisis, it is vital to have fast decarbonization in future years. The IPCC special report indicates that it is critical to decarbonize the building sector by 2030 and achieve net-zero buildings by 2050. Considering the decarbonization of GHG emissions of the source of energy and retrofit materials leads to the fact that embodied emissions of materials in the construction phase are the most important source of emissions in LCA [21]. Consequently, assuming embodied emission, the periodic assessment of the analysis becomes essential. According to the literature review, the elements that have the most lifetime uncertainty are façade, wall coverage, floor, windows, and ceiling coverage [20].

iii) Grid decarbonization

As fossil fuels are one the known GHG emission resources, and it has indirect carbon emission in the building sectors (operational stage of buildings), it has one of the most impacts on the emission calculation and scenario-based analysis. According to the previous reviews, grid decarbonization directly impacts the robust design of building systems [22]. Moreover, the local grid impact factor influences a building model in different local locations [23]. Also, the set point of time affects the analysis as the grid intensity factor can be different through different seasons [24] and [25].

Decarbonizing the electricity grid is another crucial factor in retrofitting, which is different in Europe. Some countries still use fossil fuels to provide electricity. For countries where the emission of electricity grid intensity is more than 300-400 gCO2-eq/kWh, decarbonization of the electricity grid is the most critical factor in reducing emissions. In countries with lower electricity grid emissions, the embodied emission of materials becomes more important and should be the focus of studies. In Figure 2.2, the heating demand and electricity grid GHG intensity of different countries is shown in Europe [26].

iv) Adding source of energy (PV)

Using a Photovoltaic system as a source of energy is one of the methods to help with reducing the emission of the building. The disadvantage of this technology is the low efficiency and high embodied emission of this product. On the other hand, exporting electricity produced by PVs to the grid is environmentally essential. In the definition of net zero building, the export electricity of PVs can have two options: the first option is “avoided emission” Exported electricity causes net harmful emission for the operational part of the building and avoid emission somewhere else in the grid. The second option is to compare the emission of producing electricity on-site to the export net harmful emission on the grid [28] and [29].

v) Biogenic carbon

Biogenic carbon is the amount of carbon stored previously in the materials during plant growth. Calculating the biogenic carbon in different stages of life cycle assessment is still being determined, but according to the literature, there are three different ways to consider it. The 0/0

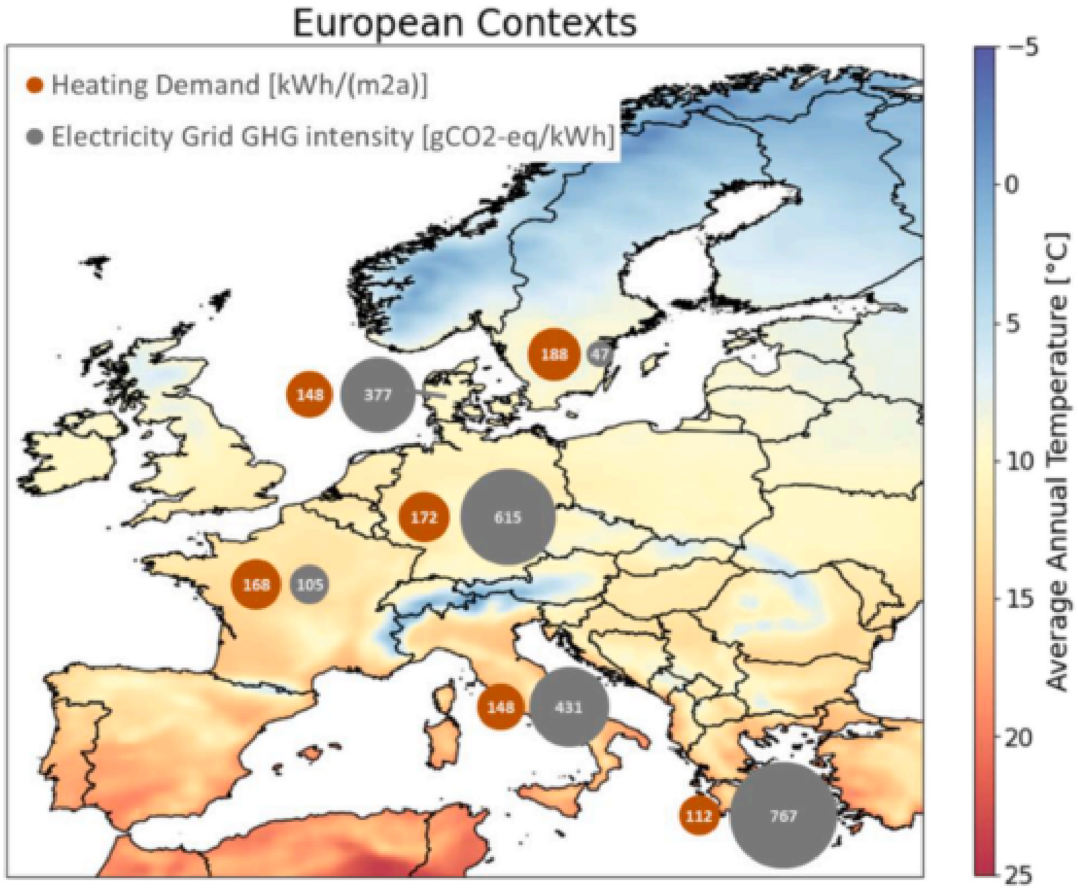


Figure 2.2: Heating demand and electricity emission of the grid in European countries [26]

approach is not included in the calculations; the -1/+1 approach includes the emission of biogenic carbon negatively in production and positively in the disposal; and the dynamic approach is based on the more detailed calculations [30]. More analysis of low-emission buildings and including biogenic carbon in the analysis have been done, and it indicates that in timber structures, it is essential to consider biogenic carbon in the calculations [31].

Walker et al. [26] have done different scenarios on retrofit strategies to see how these different strategies affect six different European countries. The scenarios vary in climate, electricity grid GHG, and building typologies. The results show that while the climate zone has less effect on the results, the electricity grid emission has the highest impact.
Moreover, Walker et al. also show that uncertainties about future operating conditions significantly affect results as traditional LCA relies on constant values in the lifetime of a building. Consequently, the emphasis is on having analysis in a shorter period to avoid misleading the prediction and be more precise. There is no specific model for robust retrofitting all European buildings but a combination of multiple possibilities that highly rely on context.

According to data and scenarios in this study, there are numerous tips that Walker et al. indicated for robust retrofitting decision-making [26]:

i) measures of retrofitting and local building typologies impact robust retrofitting; on the other hand, these two parameters have less impact on energy systems (heating and electrical).

ii) different climate is already seen in retrofitting decision-making and does not have much effect on the robust retrofitting strategies.

iii) decarbonization of the grid has a significant impact on robust retrofitting.

iv) in the situation with a low emission intensity of the electricity grid, using a heat pump as the heating system in the building has the most impact on robust retrofitting. Using high-emission material for insulating (PIR/PUR stone wool cellulose) is not robust.

v) in context with high emission intensity for the electricity grid, using pellet in the heating system, using insulation (with low or high emission), having PV with storage is the most robust retrofitting.

vi) natural gas and direct electricity systems for energy demand are not robust in any scenario. Walker et al., in another paper, [10], also indicate that retrofitting with current data without considering future scenarios is not robust. In future scenarios, lower values for emission can be reported and used, and the assumptions due to decarbonization goals and future development can be used.

2.1.4 Norwegian context

The electricity grid generator in Norway differs from other countries; 91.5% [50] of electrical energy comes from hydropower. Previously the price of electricity was low in Norway, and the buildings were heated primarily by electricity. In addition to electrical heating, direct heating, and firewood are other heating sources in the buildings. Fuel was also an energy source, but from 2020, using it as a heating source is prohibited due to reduced emissions. Consequently, Norway is already a step ahead of many countries in Europe. As the primary electricity consumption goes to building sectors for heating, recently saving energy has become vital to helping allocate hydropower electricity to other sectors. The Norwegian water resources and energy directorate (NVE) predict that the electricity demand in Norway increase by 23 TWh from 2018 to 2040. This increase comes from policies for the electrification of vehicles and petroleum sectors and the metal industry [34]. In these predictions, reducing electricity use in building sectors is not assumed, but using onshore wind power is a suggestion in the future [35].

2.2 Review

Fonseca et al. 1 [48] proposed a computational framework for analyzing the energy consumption of a neighborhood of a city. The model analyzed the energy, carbon footprint, and financial benefits of different scenarios for the neighborhood. The model is written in Python, and the case study is in Switzerland. In the optimization process, there are an average integration of 50% to 80% of buildings in the microthermal grid, and 50% to 100% buildings in solar potential and a mix of resources of solar panels, waste, and ambient heat, and using lake water for cooling systems. The results show the potential for saving energy by 45% to 60% in emission and 25% to 50% in primary energy. Lowering energy and emission costs is 14% to 44% higher than the actual buildings.

Borràs et al. [49] developed a model for assessing Energy Community potential by using the building typology as a factor for producing energy (using solar panels on rooftops). The concept of an energy community is to give the citizens control and ownership of their energy supply. Three different models were used for this analysis, i) individual self-consumption outside an Energy Community, ii) collective self-consumption with a central battery storage inside an Energy Community, iii)collective self-consumption without a central battery storage inside an Energy Community. The results show that collective self-consumption is more sufficient than individual self-consumption. Moreover, using battery storage increase 16% of sufficiency inside an Energy Community.

Walker et al. [10] proposed a model to investigate five different elements of retrofit decision-making, i) adding solar panels to the building, ii) the effect of global warming, iii) decarbonization pathway, iv) analysis period, and v) effect of biogenic carbon. The results compare GHG emissions under different scenarios for a building in Switzerland, and the results indicate that grid decarbonization has the most substantial impact on renovation strategies. On the other hand, the global warming scenarios (future weather data) do not have a significant effect on retrofit decision-making.

2.3 Problem definition and research questions

According to the literature review, there were studies about robust retrofitting in different European locations. However, there must be a study gap for retrofit decision-making in the Norwegian context. Moreover, changing windows with lower U-values, adding insulation to the walls, changing heat pumps, and adding solar panels to the house are all good choices for retrofitting a building in Norway, but do all these choices help reduce emissions? Should we consider embodied emission in retrofit decision-making? What is the compact of the grid emission in retrofit decision-making in Norway? Does the Future weather scenario have an impact on retrofit decision-making in Norway context?

This thesis topic aims to answer the above questions by having a large-scale analysis for retrofitting a district with different residential houses. The focus is on the emission of different scenarios for retrofit strategies, and both operational and embodied emissions are considered for analysis.

As Norway's grid emission is one of Europe's cleanest energies, embodied emission may significantly impact retrofit decision-making.

The final data can show which strategies fit best for a district, and these data can be a source for municipalities in different parts of Norway for retrofit decision-making.

2.3.1 Objectives

Regarding the aim of this thesis to have a large-scale analysis for retrofitting a district, the study's objectives are defined in 3 different stages.

Choose an analysis tool
There are different software for analyzing the energy in the building, like Simien, grasshopper, energy plus, and RC models in Python. The essential factor in choosing the right software is the analysis time, as numerous scenarios should be analyzed, and generating these scenarios is another critical factor that should be considered.

Set a case study
For a district in the city, there are different types of houses with different occupancies, and it is essential to have a case study that can cover all the residential houses in the neighborhood and model a realistic situation of a part of the city.

Compare all the scenarios
There is a lot of input and output in this analysis, so having a good plan for comparing these analyses and showing it is imperative to take the best results out of these scenarios and have reliable and robust retrofit decision-making according to the final data.

Chapter 3

Methodology

There are different options for retrofitting and reducing the operational emission of an old building, such as changing windows with fewer u-values, adding insulations to the wall, floor, and ceiling, changing the supply heating and cooling systems and also suitable distribution systems, and adding a source of energies like PVs and storage system for keeping and store the energy.

Each option has an embodied emission and impacts the operational emission part. Moreover, budget issues are an essential factor in retrofit decision-making. Having a model to analyze all these different options and have an optimum answer to this issue can be very helpful in both small and large case studies. The location of the building is another crucial element in the retrofitting.

Retrofit decision-making can change in different weathers, especially with the global warming issues; the impact of future weather data can impact retrofitting options. For instance, with the current weather data, it may need to use a heat pump of a particular size and no need for cooling systems, especially in the northern Scandinavian countries. However, in the future, weather data may change and impact the retrofitting options.

This proposed model aims to have a robust retrofit assessment for a district in Trondheim City in Norway. Analysis of old houses with a focus on physics, location, and type of the houses with proper software and the heating demand and heating energy (consumption of energy according to heating demand) to have an overview of the emission of the houses is the first stage of the study. The next stage is to study both embodied and operational emissions of retrofitting options and compare them to gain insight into the best scenarios in a Norwegian context.

According to the time limitations for the master thesis, some options are limited in the analysis discussed in this chapter.

3.1 Selecting the building model and model verification

There are different types of software to calculate the heating demands of buildings, and 4 of these software and tools are investigated, and one of them will chose for our purposes.

i) Energy Plus:

Energy Plus is a software for energy simulation suitable for engineers, architects, and researchers. It is a console-based program that reads data to text files. The first choice for this model was this software as it can be automated for inputs and has good accuracy for results. To use this software in Python script and have input data automation, the whole energy simulation process should be rewritten in Python. Although there is a good library including all the necessary commands for energy, it takes time to have the whole code for heating demand. Consequently, it was decided to choose another option for analysis.

ii) Honeybee tool:

Honeybee is a tool for daylight and thermodynamic modeling that creates visualized results for energy models using Energy Plus and Open Studio. It runs in the Grasshopper, one of the plugins in Rhino software. The problem with using this tool for this model was the need for more information linking it to the Python code. After lots of research, there is no accurate data for this issue, and it was decided to choose another option for analysis.

iii) Simien:

Simien is a tool that students at NTNU learn during their master's program, and it is also used in Norway for energy analysis in the industry. It calculates the heating and cooling demand according to Tek17 [39], which is the technical requirement for construction according to the Norwegian context. The limitation of this software for this task is that it is not open-source software and cannot link to Python code.

iv) RC model:

An RC model is a simplified thermal dynamic model that uses a network of resistors and capacitors to analyze the heating and cooling load of a building Figure 3.1. This model simulates the U values of different parts of the building, like windows and walls, with R's values for these elements, and the R's value represents the thermal resistance of a wall or window. This model is simple yet reliable and effective in simulating the energy consumption of the building. The advantage of the RC model is that it can easily be related to automating Python files for feeding the code with lots of input data. Another valuable advantage of the RC Model is the time of the analysis. It is a good choice for analyzing many data, like a district in a city [40]. Prageeth Jayathisa prepares the RC Model in this thesis [41].

For verification of the model, a simple geometry is generated with RC Model and Honeybee tool with the same weather file Table 3.1.

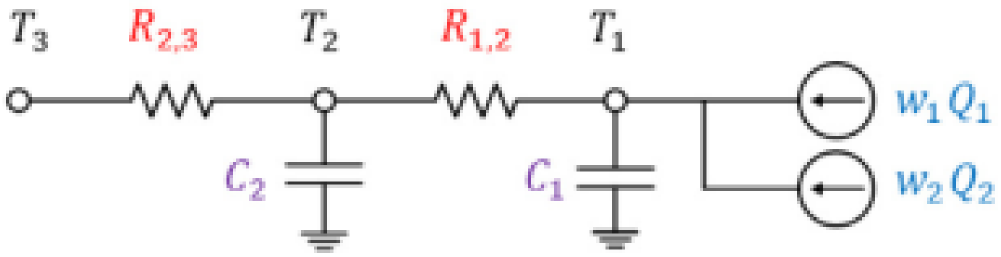


Figure 3.1: An example of model structure [40]

Type of housing	Floor area (m2)	Elavation (m)	Windows area (m2)	U-Value wall	U-Value Windows
Detached house	170	3	17	0.4	2.8

Table 3.1: Details of the model

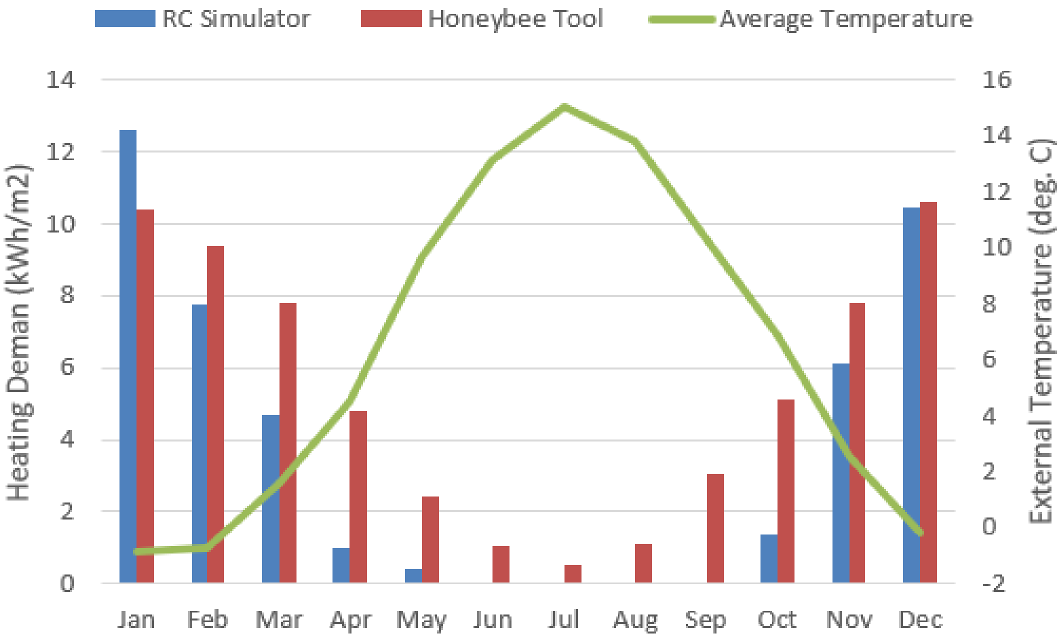


Figure 3.2: Monthly comparison of the heating demand for RC Simulator and Honeybee Tool with average dry bulb temperature of Trondheim

The yearly heating load of the detached house, analyzed with the Honeybee tool, is 64 KWh/m2; this number for the RC Model is 65.07 KWh/m2. The comparison for monthly heating demand of the two models can be seen in Figure 3.2. It can be noted that the RC model has a higher heating load during the winter period and a lower heating load during the summer period. Honeybee is a more complex tool; this difference can refer to the amount of solar gain during the year in the RC model. The speed of analysis is essential in this study, and according to Figure 3.2, the annual average of heating demand is very close to the results of the Honeybee tool. Moreover, the RC model can automate with Python script; consequently, in this case study, the RC model is a better choice for analysis.

3.2 Case study

To plan a case study, different parameters should be considered, and it is essential to set these parameters very carefully to have a good understanding of the inputs and outputs and have reliable results. Parameters like type, orientation, age, number of housings, details about the heating system, distribution system, and u- values of the walls and windows have a crucial effect on the analysis. After setting up these characteristics of the housings, the pre-retrofitting analysis can start and have the current results for the case study. The next step is to change the parameters like u-values for walls and windows and heating systems, add the energy source for a new set of analyses, and have the results for retrofitting and comparing them.

3.2.1 Type of the housings

In a district, there are different housing types, like residentials and commercials; each category has different types. For example, residential housing can be single-family, detached, semi-detached, or apartments. On the other hand, commercial housing can be an office, restaurant, hospital, etc. In this proposed model, only the residential buildings are considered for analysis, but it is possible to add and analyze other types of buildings in this model. In Table 3.2, the details of the housings can be seen. Three types of residential buildings are considered in this model.

i) Detached houses: A detached house is a kind of housing that stands alone as single-family housing and does not share walls with other houses and buildings. Figure 3.3

ii) Semi-detached houses: The semi-detached house is usually a single-family duplex house that shares one wall with another single-family house, and usually, the plan of houses mirror each other. In this case study, the semi-detached house is a two-story building with four flats. Figure 3.4

iii) Terraced houses: Terrace houses refer to houses that share more than one wall with another type of house. It is a medium-density housing that was started to build in the 16th century in Europe and a row of attached houses that share the side walls. In this case study, the terrace house is a 2-story building and contains eight flats Figure 3.5.

Housing types	Number of flats	Length (m)	Width (m)	Story	Windows area (m2)	Slope angle of roof (degree)
Detached	1	13	13	1	20	20
Semi-Detached	4	21.6	10.8	2	48	20
Terrace	8	20.2	20.2	2	80	20

Table 3.2: Details of the housings in the case study

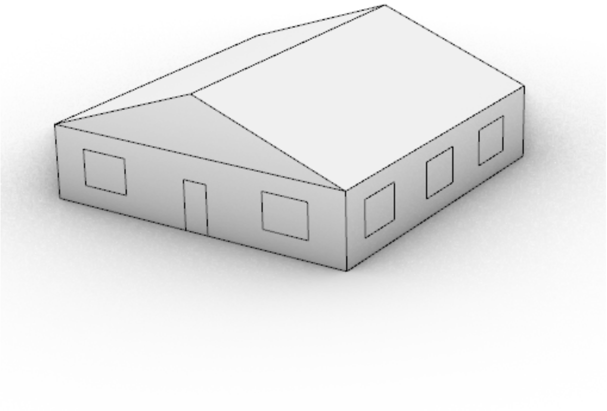


Figure 3.3: Simple model of detached houses in the case study

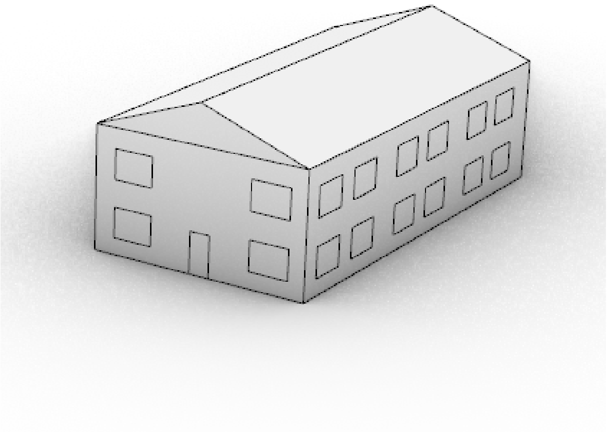


Figure 3.4: Simple model of semi-detached houses in the case study

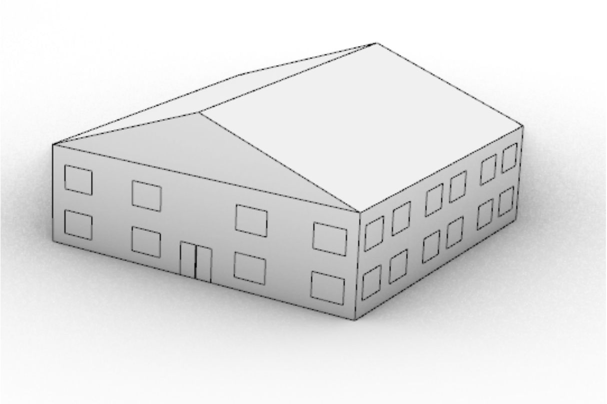


Figure 3.5: Simple model of terrace houses in the case study

3.2.2 Age of the housings

Different parameters of the housings, like u-values of walls, windows, and heating systems, may vary through different years. Consequently, for having a good case study, the different ages of the buildings should be considered; for instance, For this analysis, it is assumed that the housing from 1960 to 2000 needs retrofitting, and these houses are divided into four different decades, 1960 to 1970, 1970 to 1980, 1980 to 1990 and 1900 to 2000. All the different types of houses that belong to one decade have the same u-values for windows and walls Table 3.5.

3.2.3 Number of the housings in the district

For the case study, the number of constructions of 3 different types of housings through 4 different decades can be seen in table Figure 3.6.

According to Figure 3.6, the number of dwellings in different years is shown; for the case study, those numbers are divided by 1000 to approximate a district's housing. As the statistics of the detached and semi-detached houses are together, it is assumed that 60% of the number is for detached houses and 40% is for semi-detached housesTable 3.3.

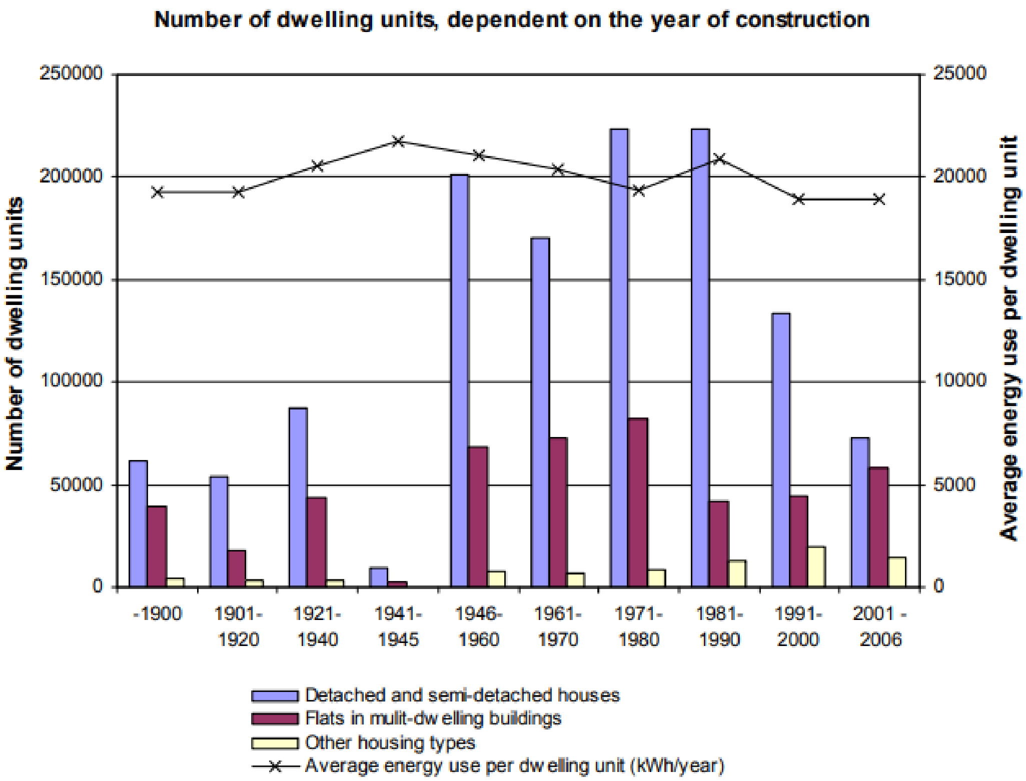


Figure 3.6: Number of Dwellings in different years,Energy Analysis of the Norwegian Dwelling Stock [42]

Decade	Number of detached housings	Number of semi-detached housings	Number of terrace housings
1960-70	102	68	75
70-80	144	96	80
80-90	144	96	40
90-2000	96	64	45

Table 3.3: Number of dwellings in the case study

3.2.4 Physical Properties of the Housings

For the case study, the physical properties of the housing are essential and should choose carefully. Size, U values for walls and windows, heating system, and distribution system are examples of the properties. In the following sections, all the assumptions are explained.

Size of the houses

The three housing types in this analysis are detached houses, semi-detached houses, and terrace housing. On the Statistic Norway Website [43], different data like dimensions of the houses and the number of these houses all over Norway can be found. For different types of housing, the dimension of the housings is distracted from this website Table 3.4.

Type of housings	Detached	Semi-detached	Terrace
Average area of houses (m2)	170	117	102

Table 3.4: Average area (square meter) of 3 different types of housing in Norway

U-values of windows and walls

As the first analysis is the pre-retrofitting situation, the u-values for windows and walls of old housing in Norway can be seen in the Table 3.5 [42].

Component	1960-1970	1970-1980	1980-1990	1990-2000
Wall	0.4	0.38	0.26	0.26
Window	2.8	2.8	2	1.8

Table 3.5: U-values of wall and window

Supply systems

The old heating systems in Norway are divided into two different systems, explained as follows.

i) Oil boiler system: The oil boiler system uses oil as a source of energy, contains a tank, and uses water for the heating system. This water, which can be liquid or steam, moves around the house with a radiator system to warm the indoor environment. The efficiency of this system is 63% [41]

ii) Pellet heating system: Pellet heating system works with heating wood, the warmup phase takes longer than fuel and oil systems, and it is used in single-family housing and large residential buildings. The efficiency of this system is 70% [41]

Distribution systems

The distribution system for all the buildings is assumed to be old radiator systems to simplify the analysis. However, other systems can be added to the code in future work and have the analysis.

Occupancies

The occupancy probability is the effective parameter of the type of buildings in the RC model. Figure 3.7, shows the occupancy of the residential building through the 24 hours of the day [41].

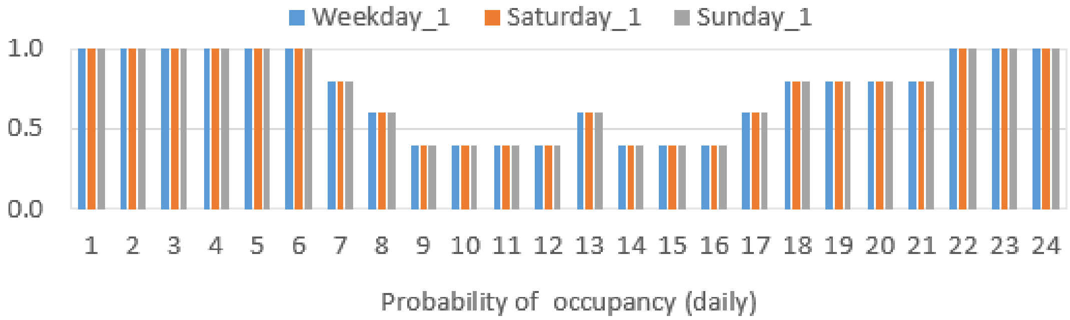


Figure 3.7: Probability of occupancy through the 24 hours [41]

As the heating and cooling demand analysis is hourly and throughout the year, these numbers repeat for all days of the year in an Excel file to feed the code for yearly analysis.

3.2.5 Weather file

The EPW file format (EnergyPlus Weather File) is standard weather data and contains essential information like latitude, longitude, time zone, sun position, temperature, etc. For this analysis, the EPW file was downloaded from the Climate One Building website [44], containing the data from 2004 to 2018.

3.3 Retrofit options and scenarios

In this section, all the retrofit options, along with their emissions, are explained. The retrofit options are changing windows, adding insulation to walls, changing heating systems, and adding a source of energy. All these options have embodied emissions while their task is to reduce the operational emissions part.

3.3.1 Changing windows

Windows are one of the surfaces that energy is lost through it. The old windows have a high amount of u-value, and in the renovation part, it is crucial to use windows with fewer u-values to keep the heat inside the house. On the other hand, windows have a massive amount of embodied emission, and the effect of this embodied emission may affect retrofit decision-making. According to the Reduzer online software, the product of the window is a double-glazed window with an aluminum frame, with a u-value of 1.5 W/m2k and emission of 117 kgCo2eq/m2 [44].

3.3.2 Adding insulations

One of the retrofit options is adding insulation to the walls of the building. Adding insulation lead to less u-value of the wall and less waste of energy through the walls. The analysis considers two types of insulation with the same u-values and different emissions. The u-value of the walls after adding the insulations is 0.14 W/m2K. In this analysis, the insulation of the roof and ground are not assumed in the model because of time limitations.

Mineral Wool Insulation: This type of insulation is fiber insulation like fiberglass, built from natural materials. There are two types of mineral wool: rock wool, made of stone, and slag wool, made of iron ore waste. In this analysis, rock wool is used with an emission of 7.12 KgCO2eq /m2 [10].

Cellulose Insulation: This type of insulation is a plant fiber used in walls and roofs. It has low thermal conductivity and is soundproof. The emission of this product is 2.57 KgCO2eq /m2 [10].

3.3.3 Changing the supply system

Old heating systems like pellet and oil boiler have low efficiency, on the other hand, the new heating system like ASHP and GSHP is very efficient and changing this part of the building with new systems may have a massive impact on the operational emission of the buildings.

Direct electricity heating system: This system converts electricity directly to heating by radiators or coils. The efficiency of this system is 100% [41]

ASHP: An air source heat pump is a system that can absorb heating from the outside and add it to the inside circle. These systems can use for both heating and cooling, and in some cases, it can provide domestic hot water. The emission of the ASHP in the analysis is 232.5 KgCO2eq/KW (without disposal [10]), and the efficiency of the system is 230% [41].

GSHP: A ground source heat pump is a source of energy that transfers heating and cooling to the ground. It helps the relatively constant temperature of the ground for heating and cooling systems. The emission of the ASHP in the analysis is 816.2 KgCO2eq/KW (without disposal [10]), and the efficiency of the system is 367% [41].

3.3.4 Adding source of energies (PV)

A photovoltaic system, often referred to as a solar power system, is a technology that converts sunlight into electricity. It is an innovative and sustainable method of generating clean energy. The solar panels are made from semiconductors, mostly silicon. The advantage of PVs is producing electricity without emitting greenhouse gases in the operational part. On the other hand, the production of PVs has many emissions, and the efficiency of PVs could be higher. According to the Reduzer online software, the product of the PV is a photovoltaic module (MAXEON 3 MONO-CRYSTALLINE), with an emission of 77.4 kgCo2/m2 [45].

The area of PVs and orientation can be seen in Table 3.6. The calculation file is set to input areas through different orientations with different angles of the roof (3 options for the

Types of housings	Orientation of the roof	Area of the PVs (m2)
Detached	East-West	40
Semi-detached	East-West	60
Apartments	East-West	120

Table 3.6: Details of the PVs for different type of housings

roof angle, 20,30, and 40 degrees). The calculations have been done according to the online calculator (Photovoltaic Geographical Information System) [46].

3.3.5 Constant parameters in the analysis

Some parameters in the model are assumed to be constant for all the scenarios, the reason for this assumption is a simplification, and it is possible to change the parameters in the input of the model and have the results Table 3.7.

ach-vent	ach-infl	ventilation efficiency	thermal capacitance per floor area	t-set heating
1.5	0.5	0.6	165000	20

Table 3.7: Constant parameters in the main analysis

ach vent: Air changes per hour through ventilation (Air Changes Per Hour)
ach infl: Air changes per hour through infiltration (Air Changes Per Hour)
ventilation efficiency: The efficiency of the heat recovery system for ventilation
thermal capacitance per floor area: Thermal capacitance of the room per floor area [J/m2K]
t_set heating: Thermal heating set point [C]

3.4 Scenarios and analysis

This section focuses on the analysis, considering all the primary data from the previous sections. Different scenarios produce, work together, and finally lead to robust retrofit decision-making.

3.4.1 Set the configuration file

The configuration file is the main input file of the analysis; in this file, all the primary data is gathered in an Excel file and fed to the code for pre-retrofit analysis, which finally leads to the heating demand as the main parameter of the retrofit analysis.

There are three different types of buildings (detached, semi-detached, and terrace housing), and each of these buildings repeats for four different decades from 1960 to 2000. For each of the housings, there are four pre-retrofit scenarios.

i) Pre-retrofit Stage: In this stage, all the elements in the building are pre-retrofit elements, like the u-value of windows, walls, and supply systems. Ultimately, the RC model gives a heating demand for this case.

ii) Changing the windows: Changing the windows with a u-value of 1.5 W/m2k and emission of 117 kgCo2eq/m2 and for the results having the heating demand of the housings.

iii) Adding insulation to the walls: There are two options for insulation, rock wool with emission of 7.12 KgCO2eq/m2 and Cellulose Insulation with emission of 2.57 KgCO2eq/m2 and, ultimately, having the heating demand of this scenario.

iv) Adding insulation and changing the windows: In this scenario, both ii and iii options work together (changing windows and adding insulation) and, ultimately, have heating demand results.

All these options lead to 48 different scenarios, which is the input of the RC model. It should be mentioned that for every single scenario, there is an hourly data analysis which leads to 8760 total hours of the year; in this analysis, the overall yearly heating demand is the target for the next stage, but having hourly data can be helpful in monthly and daily analysis.

3.4.2 Build the main scenarios

There are two old heating systems (oil boiler, pellet) and three new heating systems (ASHP, GSHP, and direct heating), so the next stage is to start changing the heating system and adding the PVs to the buildings. For all these scenarios, the emission of embodied and operational parts is calculated and compared for every scenario. You can see the process of generating all the scenarios in Figure 3.8, according to the analysis process of Walker [10]. For a detached house built from 1960 to 1970, there are four different heating demands due to the four options of pre-retrofitting, changing windows, adding insulations, and changing windows with adding insulations to the wall. It should be mentioned that two options for insulation cannot be seen in the Figure 3.8 due to the simplification of the illustration. For each of these four options, there are another five scenarios with different heating systems and two options: adding PVs or not. All these scenarios lead to 60 different options for a detached house (Figure 4.1), and the result of each scenario is the summation of embodied and operational emissions ready to compare.

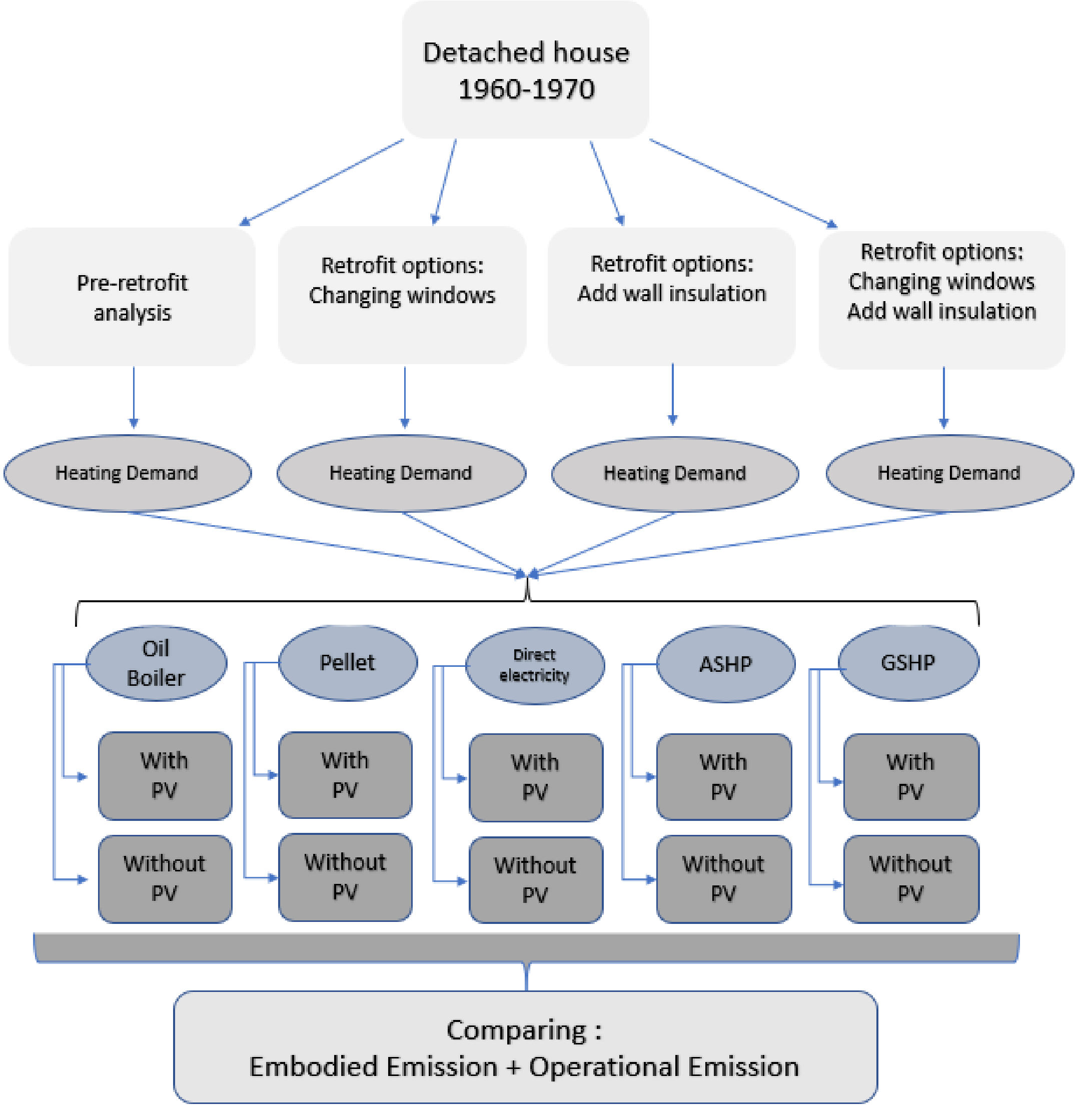


Figure 3.8: The process of generating scenarios for detached house(1960-1970), with four different scenarios (pre-retrofit, changing windows, adding insulation and both options together, five different heating systems with and without PVs

Chapter 4

Results

This chapter shows all the results of the main case study. The main result of the model is the emission numbers for different scenarios according to the model and inputs. There are extra charts to compare the different situations, like different weather files for other locations and future scenarios. Moreover, there is a chart showing the effects of different areas of PVs.

4.1 Main case study

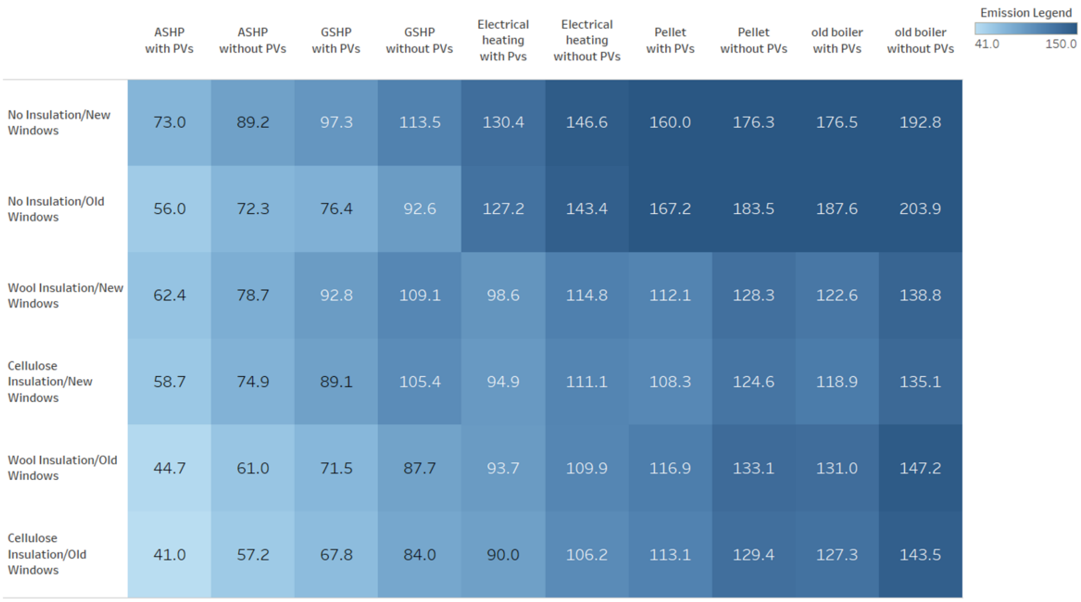
Figure 4.1 to Figure 4.12 are the case study results for each type of housing with different ages. It should be mentioned that all the emissions of charts in this chapter are the summation of embodied and operational emissions.

According to the figures, the options are pre-retrofit situation, changing windows, and adding two different kinds of insulations, which leads to 6 different options and shows at the Y-axis of the charts. In the X-axis, the different types of heating options with and without PVs are shown, and the difference in colors shows the intensity of the emissions in the scenarios; the numbers in the boxes show the exact amount of emission through 60 years.

Pellets and oil boilers are considered the old systems in the building, and electrical heating, GSHP, and ASHP heat pumps are considered new systems. For all types of buildings, the ASHP heat pump with PVs and adding Cellulose insulation without changing the windows has the minimum admission, among other options. Using PV as an energy source is favorable in all scenarios compared to not using PVs.

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	74.4	90.6	98.2	114.4	133.6	149.9	164.6	180.9	181.7	197.9
No Insulation/Old Windows	57.5	73.7	77.3	93.5	130.5	146.8	172.0	188.2	192.9	209.1
Wool Insulation/New Windows	62.4	78.7	92.8	109.1	98.6	114.8	112.1	128.3	122.6	138.8
Cellulose Insulation/New Windows	58.7	74.9	89.1	105.4	94.9	111.1	108.3	124.6	118.9	135.1
Wool Insulation/Old Windows	44.7	61.0	71.5	87.7	93.7	109.9	116.9	133.1	131.0	147.2
Cellulose Insulation/Old Windows	41.0	57.2	67.8	84.0	90.0	106.2	113.1	129.4	127.3	143.5

Figure 4.1: Emission (KgCO2eq/m2) of detached house, built in 1960 to 1970 in 60 years



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	73.0	89.2	97.3	113.5	130.4	146.6	160.0	176.3	176.5	192.8
No Insulation/Old Windows	56.0	72.3	76.4	92.6	127.2	143.4	167.2	183.5	187.6	203.9
Wool Insulation/New Windows	62.4	78.7	92.8	109.1	98.6	114.8	112.1	128.3	122.6	138.8
Cellulose Insulation/New Windows	58.7	74.9	89.1	105.4	94.9	111.1	108.3	124.6	118.9	135.1
Wool Insulation/Old Windows	44.7	61.0	71.5	87.7	93.7	109.9	116.9	133.1	131.0	147.2
Cellulose Insulation/Old Windows	41.0	57.2	67.8	84.0	90.0	106.2	113.1	129.4	127.3	143.5

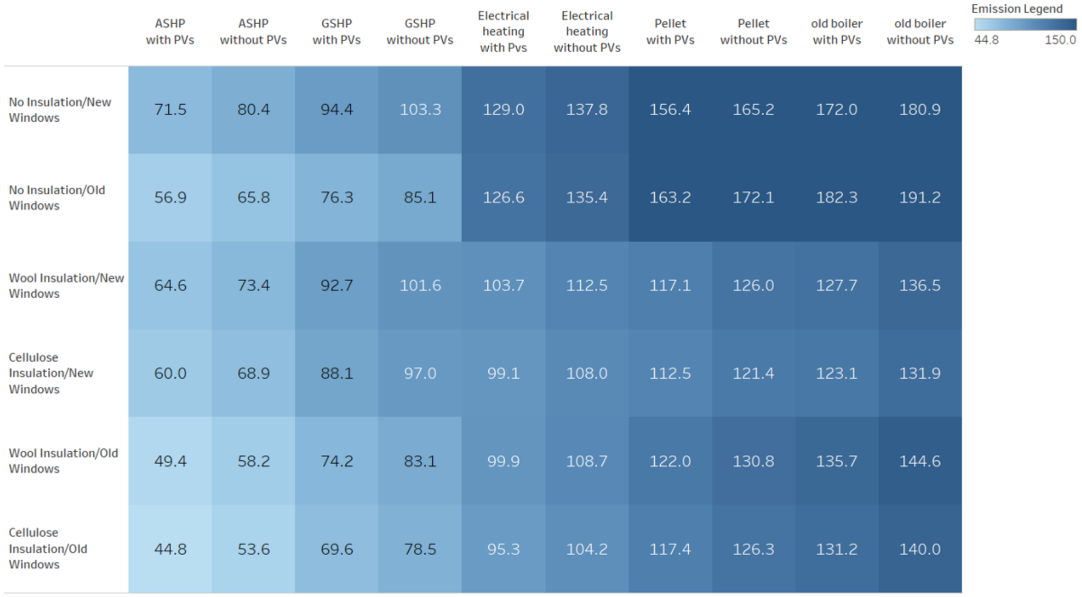
Figure 4.2: Emission (KgCO2eq/m2) of detached house, built in 1970 to 1980 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	64.7	80.9	92.1	108.3	111.3	127.6	132.8	149.0	146.3	162.5
Wool Insulation/New Windows	62.4	78.7	92.8	109.1	98.6	114.8	112.1	128.3	122.6	138.8
Cellulose Insulation/New Windows	58.7	74.9	89.1	105.4	94.9	111.1	108.3	124.6	118.9	135.1
No Insulation/Old Windows	41.0	57.3	67.0	83.2	92.7	109.0	118.0	134.2	132.9	149.1
Wool Insulation/Old Windows	38.6	54.9	67.6	83.9	79.6	95.9	96.8	113.0	108.7	124.9
Cellulose Insulation/Old Windows	34.9	51.1	63.9	80.2	75.9	92.1	93.1	109.3	105.0	121.2

Figure 4.3: Emission (KgCO2eq/m2) of detached house, built in 1980 to 1990 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	64.7	80.9	92.1	108.3	111.3	127.6	132.8	149.0	146.3	162.5
Wool Insulation/New Windows	62.4	78.7	92.8	109.1	98.6	114.8	112.1	128.3	122.6	138.8
Cellulose Insulation/New Windows	58.7	74.9	89.1	105.4	94.9	111.1	108.3	124.6	118.9	135.1
No Insulation/Old Windows	39.5	55.7	66.0	82.2	89.1	105.4	112.9	129.1	127.2	143.4
Wool Insulation/Old Windows	37.1	53.4	66.7	82.9	76.2	92.4	91.9	108.1	103.2	119.5
Cellulose Insulation/Old Windows	33.4	49.6	63.0	79.2	72.5	88.7	88.1	104.4	99.5	115.7

Figure 4.4: Emission (KgCO2eq/m2) of detached house, built in 1990 to 2000 in 60 years



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	71.5	80.4	94.4	103.3	129.0	137.8	156.4	165.2	172.0	180.9
No Insulation/Old Windows	56.9	65.8	76.3	85.1	126.6	135.4	163.2	172.1	182.3	191.2
Wool Insulation/New Windows	64.6	73.4	92.7	101.6	103.7	112.5	117.1	126.0	127.7	136.5
Cellulose Insulation/New Windows	60.0	68.9	88.1	97.0	99.1	108.0	112.5	121.4	123.1	131.9
Wool Insulation/Old Windows	49.4	58.2	74.2	83.1	99.9	108.7	122.0	130.8	135.7	144.6
Cellulose Insulation/Old Windows	44.8	53.6	69.6	78.5	95.3	104.2	117.4	126.3	131.2	140.0

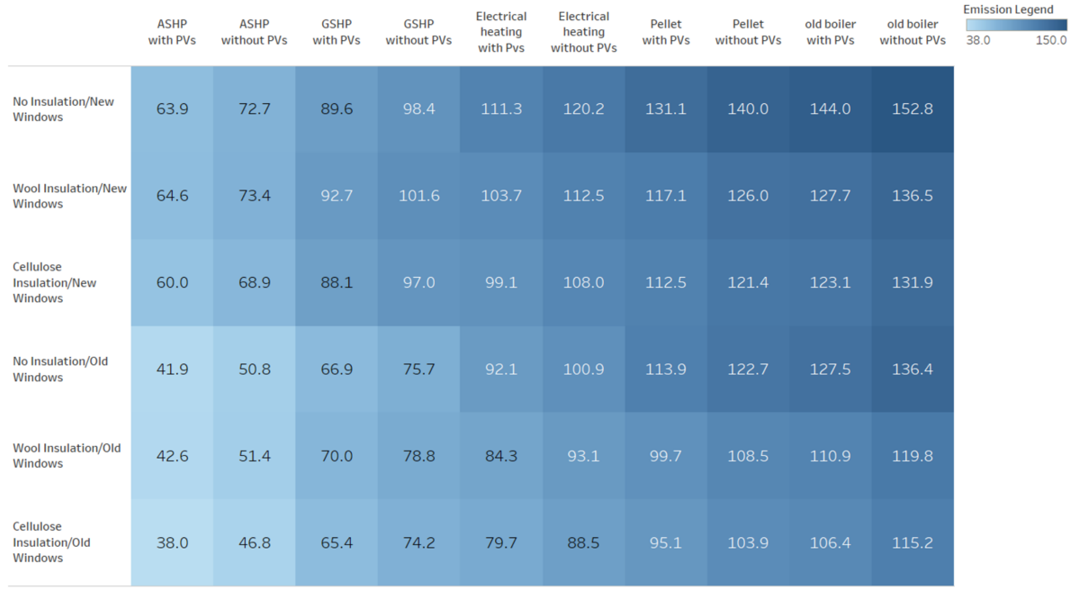
Figure 4.5: Emission (KgCO2eq/m2) of semi-detached house, built in 1960 to 1970 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	70.4	79.3	93.7	102.6	126.4	135.3	152.7	161.5	168.0	176.8
No Insulation/Old Windows	55.8	64.6	75.6	84.4	123.9	132.8	159.4	168.3	178.1	187.0
Wool Insulation/New Windows	64.6	73.4	92.7	101.6	103.7	112.5	117.1	126.0	127.7	136.5
Cellulose Insulation/New Windows	60.0	68.9	88.1	97.0	99.1	108.0	112.5	121.4	123.1	131.9
Wool Insulation/Old Windows	49.4	58.2	74.2	83.1	99.9	108.7	122.0	130.8	135.7	144.6
Cellulose Insulation/Old Windows	44.8	53.6	69.6	78.5	95.3	104.2	117.4	126.3	131.2	140.0

Figure 4.6: Emission (KgCO2eq/m2) of semi-detached house, built in 1970 to 1980 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.9	72.7	89.6	98.4	111.3	120.2	131.1	140.0	144.0	152.8
Wool Insulation/New Windows	64.6	73.4	92.7	101.6	103.7	112.5	117.1	126.0	127.7	136.5
Cellulose Insulation/New Windows	60.0	68.9	88.1	97.0	99.1	108.0	112.5	121.4	123.1	131.9
No Insulation/Old Windows	43.3	52.1	67.7	76.6	95.2	104.1	118.4	127.3	132.6	141.4
Wool Insulation/Old Windows	43.9	52.8	70.8	79.6	87.3	96.2	104.1	112.9	115.8	124.7
Cellulose Insulation/Old Windows	39.3	48.2	66.2	75.1	82.8	91.6	99.5	108.3	111.2	120.1

Figure 4.7: Emission (KgCO2eq/m2) of semi-detached house, built in 1980 to 1990 in 60 years



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.9	72.7	89.6	98.4	111.3	120.2	131.1	140.0	144.0	152.8
Wool Insulation/New Windows	64.6	73.4	92.7	101.6	103.7	112.5	117.1	126.0	127.7	136.5
Cellulose Insulation/New Windows	60.0	68.9	88.1	97.0	99.1	108.0	112.5	121.4	123.1	131.9
No Insulation/Old Windows	41.9	50.8	66.9	75.7	92.1	100.9	113.9	122.7	127.5	136.4
Wool Insulation/Old Windows	42.6	51.4	70.0	78.8	84.3	93.1	99.7	108.5	110.9	119.8
Cellulose Insulation/Old Windows	38.0	46.8	65.4	74.2	79.7	88.5	95.1	103.9	106.4	115.2

Figure 4.8: Emission (KgCO2eq/m2) of semi-detached house, built in 1990 to 2000 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.9	74.1	86.3	96.4	113.9	124.1	135.9	146.0	149.5	159.7
No Insulation/Old Windows	49.8	60.0	68.9	79.0	111.3	121.4	141.9	152.1	158.8	169.0
Wool Insulation/New Windows	61.5	71.7	87.7	97.8	98.3	108.5	110.2	120.4	120.2	130.4
Wool Insulation/Old Windows	47.0	57.1	70.0	80.1	94.7	104.8	114.8	125.0	127.9	138.0
Cellulose Insulation/New Windows	56.6	66.7	82.7	92.9	93.4	103.5	105.3	115.4	115.3	125.4
Cellulose Insulation/Old Windows	42.0	52.2	65.0	75.2	89.7	99.9	109.9	120.1	122.9	133.1

Figure 4.9: Emission (KgCO2eq/m2) of terrace house, built in 1960 to 1970 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.1	73.3	85.8	95.9	112.1	122.3	133.3	143.4	146.6	156.8
No Insulation/Old Windows	49.0	59.1	68.3	78.5	109.4	119.5	139.2	149.3	155.8	165.9
Wool Insulation/New Windows	61.5	71.7	87.7	97.8	98.3	108.5	110.2	120.4	120.2	130.4
Wool Insulation/Old Windows	47.0	57.1	70.0	80.1	94.7	104.8	114.8	125.0	127.9	138.0
Cellulose Insulation/New Windows	56.6	66.7	82.7	92.9	93.4	103.5	105.3	115.4	115.3	125.4
Cellulose Insulation/Old Windows	42.0	52.2	65.0	75.2	89.7	99.9	109.9	120.1	122.9	133.1

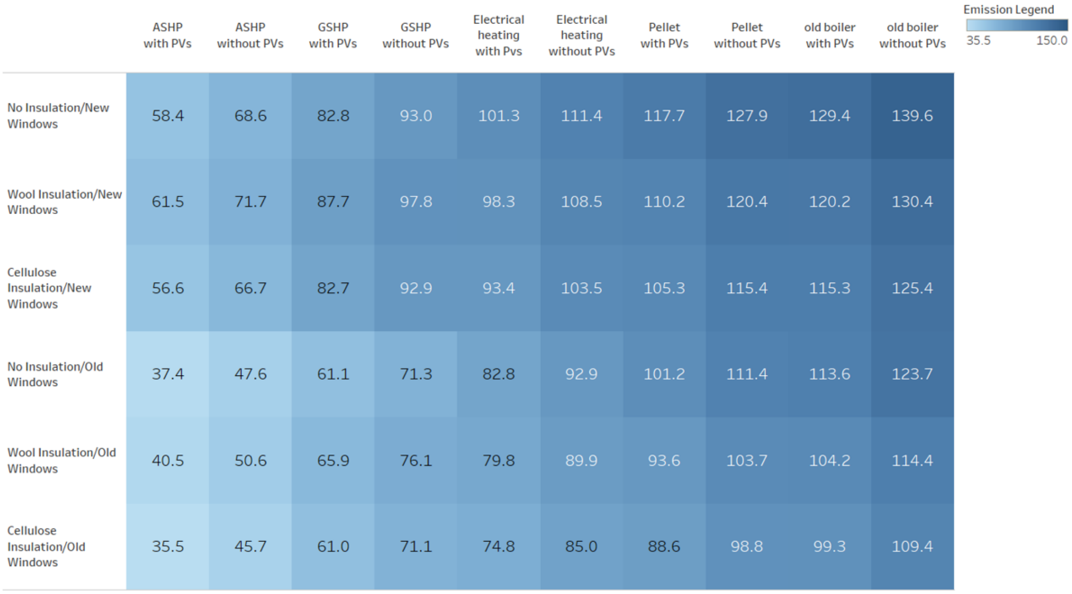
Emission Legend
42.0 150.0

Figure 4.10: Emission (KgCO2eq/m2) of terrace house, built in 1970 to 1980 in 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	58.4	68.6	82.8	93.0	101.3	111.4	117.7	127.9	129.4	139.6
Wool Insulation/New Windows	61.5	71.7	87.7	97.8	98.3	108.5	110.2	120.4	120.2	130.4
Cellulose Insulation/New Windows	56.6	66.7	82.7	92.9	93.4	103.5	105.3	115.4	115.3	125.4
No Insulation/Old Windows	38.7	48.9	61.9	72.1	85.8	96.0	105.5	115.7	118.4	128.5
Wool Insulation/Old Windows	41.8	51.9	66.7	76.9	82.7	92.9	97.8	107.9	108.9	119.0
Cellulose Insulation/Old Windows	36.8	47.0	61.8	71.9	77.8	87.9	92.8	103.0	103.9	114.1

Emission Legend
36.8 150.0

Figure 4.11: Emission (KgCO2eq/m2) of terrace house, built in 1980 to 1990 in 60 years



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	58.4	68.6	82.8	93.0	101.3	111.4	117.7	127.9	129.4	139.6
Wool Insulation/New Windows	61.5	71.7	87.7	97.8	98.3	108.5	110.2	120.4	120.2	130.4
Cellulose Insulation/New Windows	56.6	66.7	82.7	92.9	93.4	103.5	105.3	115.4	115.3	125.4
No Insulation/Old Windows	37.4	47.6	61.1	71.3	82.8	92.9	101.2	111.4	113.6	123.7
Wool Insulation/Old Windows	40.5	50.6	65.9	76.1	79.8	89.9	93.6	103.7	104.2	114.4
Cellulose Insulation/Old Windows	35.5	45.7	61.0	71.1	74.8	85.0	88.6	98.8	99.3	109.4

Figure 4.12: Emission (KgCO2eq/m2) of terrace house, built in 1990 to 2000 in 60 years

4.1.1 District results data

Figure 4.13 shows the summation of all the emissions for different types of housings for the whole district. This chart can compare with the previous charts for single housings and see if the strategies for single housings are the same for the district.

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	66,245	78,883	90,595	103,234	116,957	129,596	140,570	153,209	154,799	167,438
No Insulation/Old Windows	47,801	60,440	69,648	82,287	107,231	119,870	137,454	150,092	154,131	166,769
Wool Insulation/New Windows	61,953	74,592	90,353	102,991	98,565	111,204	111,487	124,125	121,756	134,394
Cellulose Insulation/New Windows	57,764	70,403	86,164	98,802	94,376	107,015	107,298	119,936	117,567	130,205
Wool Insulation/Old Windows	43,123	55,762	69,164	81,802	87,950	100,589	107,100	119,739	119,676	132,315
Cellulose Insulation/Old Windows	38,934	51,573	64,975	77,613	83,761	96,400	102,911	115,550	115,487	128,126

Figure 4.13: Emission (KgCO2eq/m2) of the district (the whole case study) in 60 years

4.1.2 Line charts for comparison of same houses

Figure 4.14 to Figure 4.16, compares the housing types with ASHP heat pump and 40 m2 PVs for different ages. These charts aim to understand better the effect of the embodied emission of glass related to the retrofit of windows on housings. The four colors show the different ages of the housings. Y-axis shows the amount of emission over 60 years, and the X-axis shows the different options from the pre-retrofit situation to changing windows and adding different types of insulations. Changing the windows is the worse scenario even in comparison to the pre-retrofit situation, and having Cellulose insulation and keeping windows is the best scenario among others.

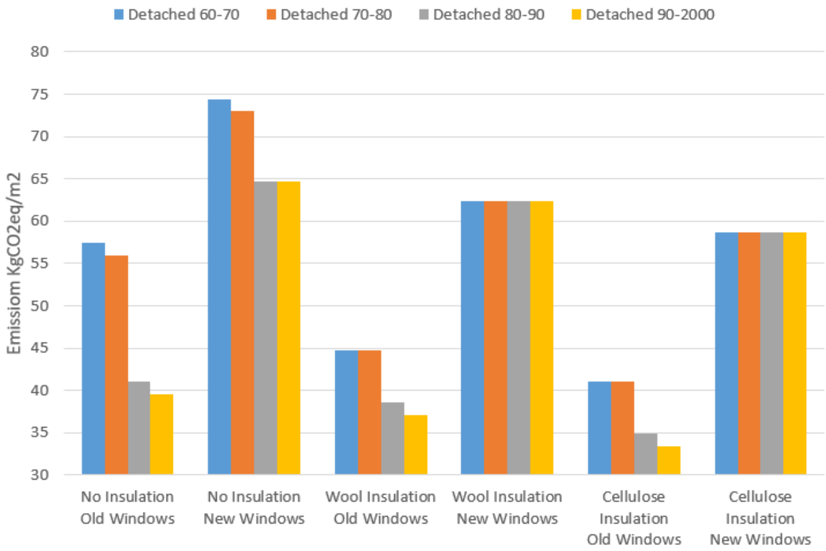


Figure 4.14: Comparison of detached housings of different ages, retrofit of heating source with ASHP and adding 40 m2 of PVs in 60 years

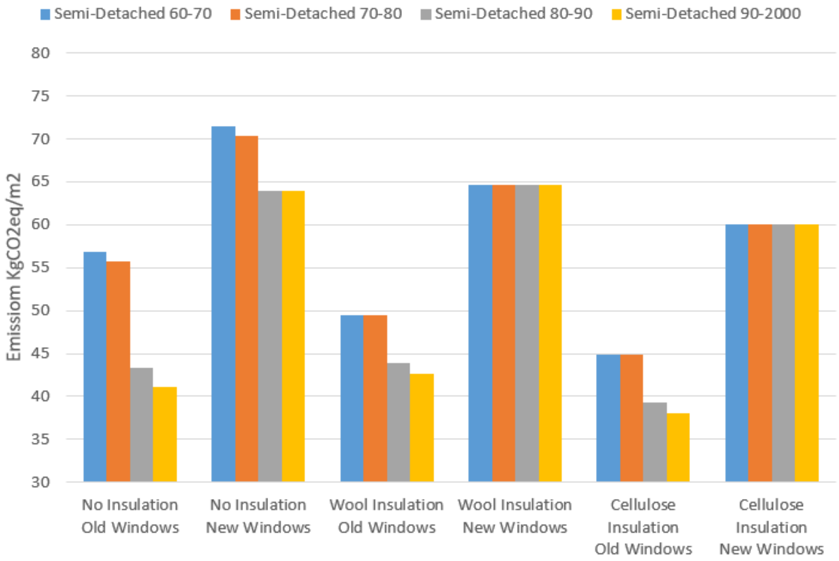


Figure 4.15: Comparison of semi-detached housings of different ages, retrofit of heating source with ASHP and adding 60 m2 of PVs in 60 years

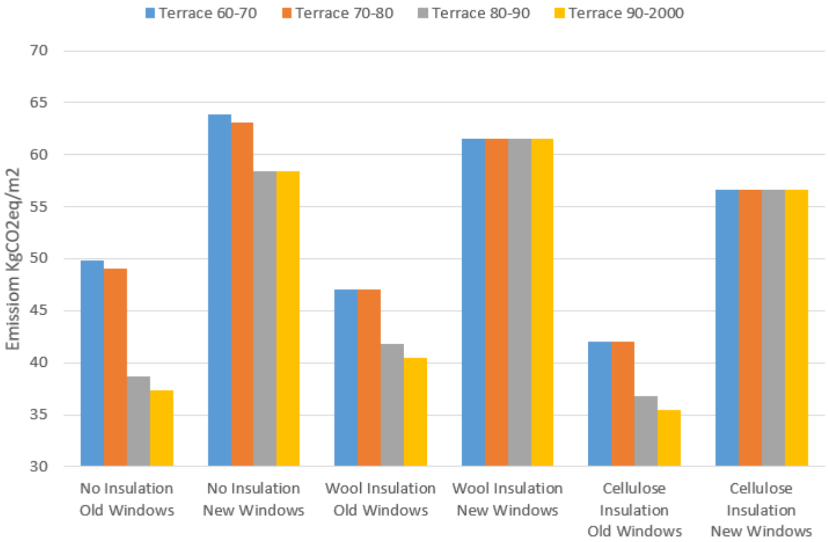


Figure 4.16: Comparison of terrace housings of different ages, retrofit of heating source with ASHP and adding 120 m2 of PVs in 60 years

4.1.3 Line charts for comparison 3 types of the houses together

Figure 4.17 compares three types of housings (detached, semi-detached, and terrace houses) with an ASHP heat pump and 40 m2 of PVs. These charts aim to understand the differences between types of houses and comparison for housing emissions. The three colors show the different types of housings. According to the chart, the Terrace houses have minimum emissions due to fewer external walls and using the shared areas in the building.

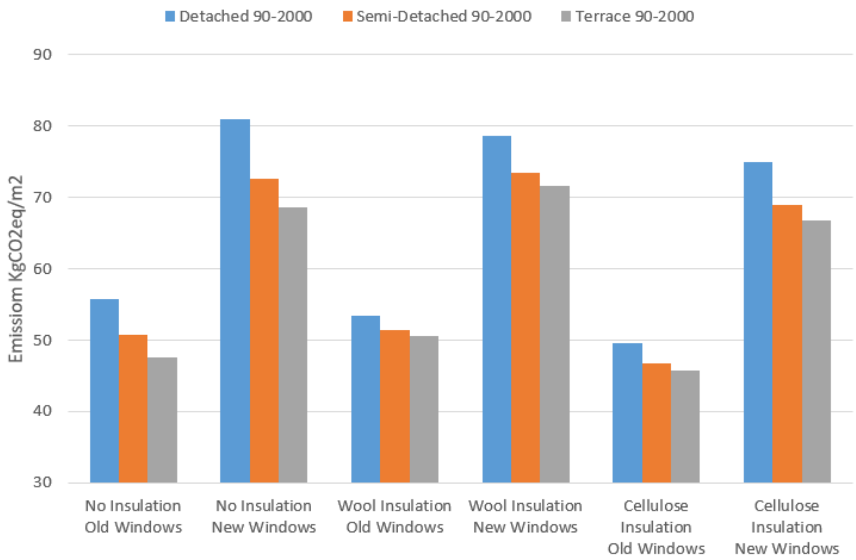


Figure 4.17: Comparison of 3 different types of housing (1990 to 2000), retrofit of heating source with ASHP and without adding PVs, emission over 60 years.

4.1.4 Neglecting the embodied emission

In Figure 4.18, there is a comparison between 3 types of building from 1900 to 2000, with ASHP heat pump and without adding PVs. In this chart, the analysis considers the operational energy (the embodied emissions are neglected in this chart). The three colors show the different types of housings. According to the chart, changing windows has a direct impact on lowering the operational emissions due to the lower U-value, which leads to less waste in energy.

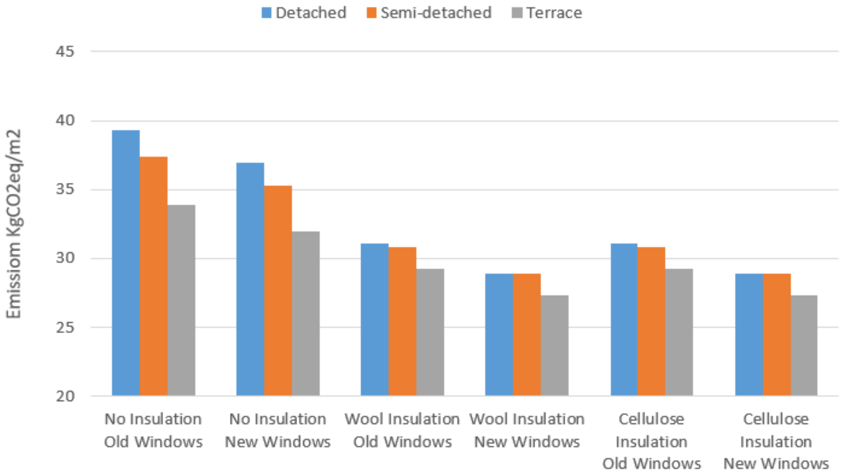


Figure 4.18: Comparison of 3 different types of the housings (1990 to 2000) for operational emission only, retrofit of heating source with ASHP and without adding PVs, emission over 60 years

4.2 Effect of different PV areas

Figure 4.19 shows the result for different areas of PVs for detached houses of 1960 to 1970 with ASHP heat pumps for five different areas, 20, 40, 60, 80, 100, and 140 m2 of PVs. The different colors show the areas of the PVs. The data for each scenario for this building can be seen in the chapter A. According to the chart, more use of PV areas on the roof leads to less energy consumption through 60 years, and even we can reach the ZEB building by using the proper amount of PVs on the roof.

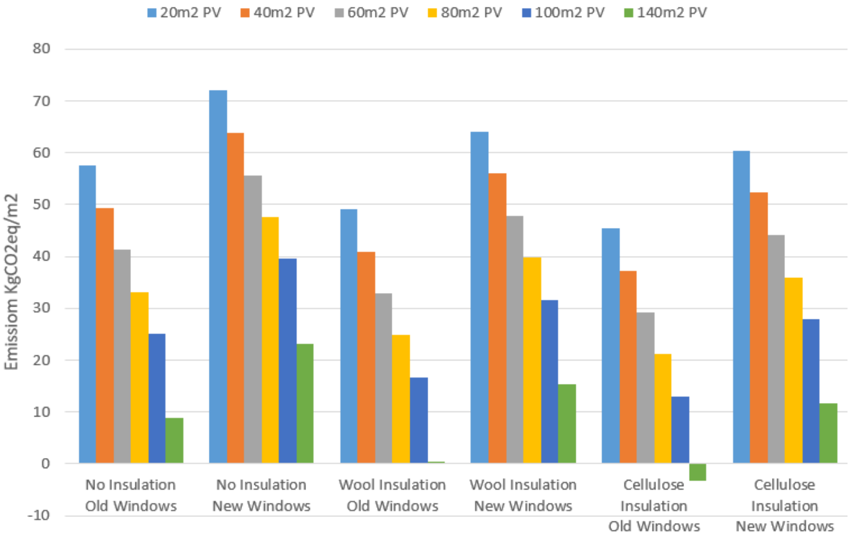


Figure 4.19: Comparison of different areas of PVs for detached house (1960-1970), retrofit of heating source with ASHP, emission over 60 years

4.3 Different weather conditions with different electricity grid emission

Berlin in Germany chose to analyze the identical houses and scenarios to compare the Norwegian context and another region. The grid emission of Germany is assumed to be 0.38 KgCO2/KWh [47], and the Berlin EPW weather file is used as an input weather file.

Figure 4.20 shows the detached house with four different ages, and the ASHP heating source of energy, with 40 m2 of PVs in Berlin and Figure 4.21 shows the difference between the Norwegian and German context. The case is the same for both kinds of weather, detached houses from 1960 to 1970, with Cellulose insulation and changing windows. It should be noted that for comparison between Norway and Germany, the grid emission is multiplied by the heating demands of each country. According to Figure 4.21, Germany has less emission than Norway in the retrofit option with GSHP heat pump because of Germany's lower heating demand. The difference between the heating demand of Norway and Germany can be seen in Figure 4.22. The data for the detached housing scenario of the German context can be seen in the chapter B. The Figure 4.20 indicates that changing windows is favorable. However, the embodied emissions are considered in the analysis, and according to Figure 4.21, by using a GSHP heat pump, the German building can reach less emission than Norway. However, Germany has much more grid emissions than Norway.

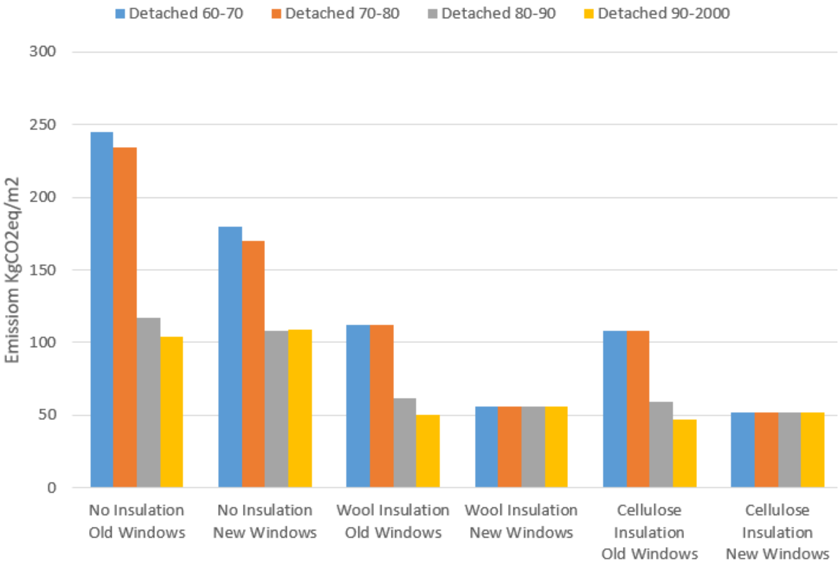


Figure 4.20: Comparison of detached housings with 4 different ages, retrofit of heating source with ASHP and adding 40m2 of PVs, emission over 60 years, Berlin weather file

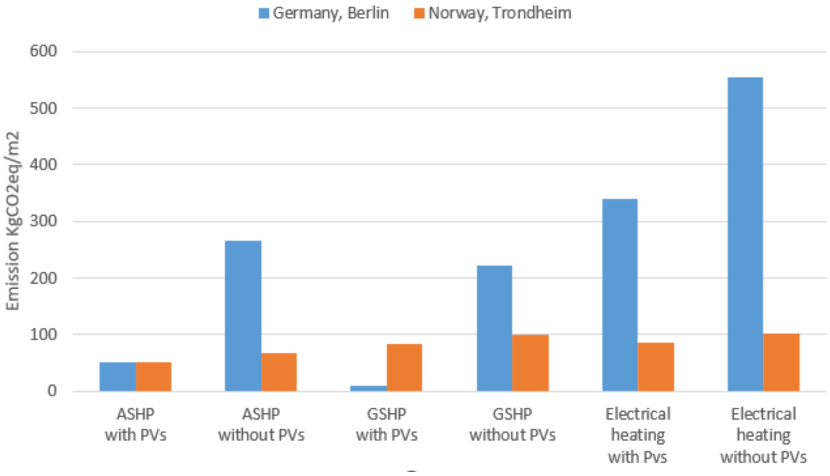


Figure 4.21: Comparison of German and Norway context, detached house (1960-1970), Cellulose insulation and changing windows, emission over 60 years

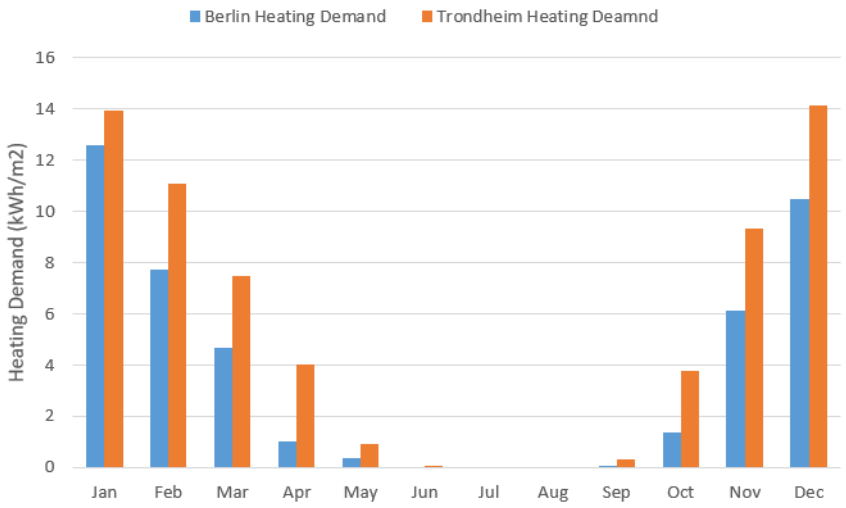


Figure 4.22: Comparison of German and Norway monthly heating demand

4.4 Future weather data

Figure 4.23 shows the analysis for future weather data for detached houses from 1960 to 1970 with Cellulose insulation and changing the windows. The future EPW file is generated in the Meteonorm 8 software. The data for the detached housing scenarios of the Future weather data can be seen in the chapter C. According to the figure, in the future scenario, the emission is less than the current data due to less operational emission for the future scenario.

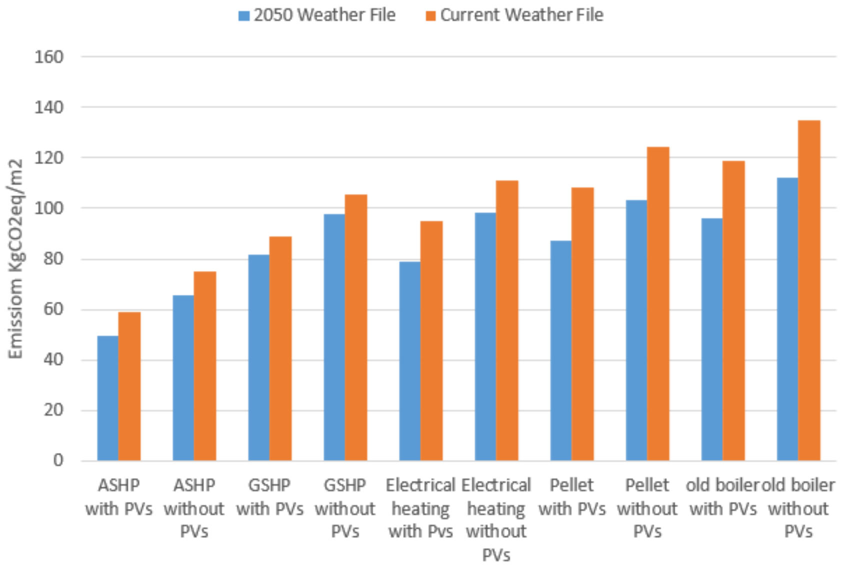


Figure 4.23: Comparison of 2050 and current weather data, detached house (1960-1970), Cellulose insulation and changing windows, emission over 60 years

Chapter 5

Discussion

In this chapter, all the analysis and results are explained and investigated to understand the model better and lead to a robust design for retrofitting. Moreover, the research questions will be answered and see if this method is solid and valuable enough for retrofit decision-making.

5.1 Robust retrofit decision-making

Figure 4.1 to Figure 4.12 show the emissions of detached houses from 1960 to 2000 for all the scenarios. The numbers in the boxes indicate the emission (KgCO2eq/m2) of each scenario over 60 years. As it is shown, Cellulose insulation choices with keeping the old windows, changing the heating system to ASHP, and adding 40 m2, 60 m2, and 120 m2 of PVs for detached, semi-detached, and terrace houses are the best scenarios with the minor emissions among other choices. (It should be noted that this is the best scenario according to the assumptions for retrofitting, with other assumptions, the emission may reduce, for instance, with using more PV area in the roof, the emission will decrease.)

5.1.1 Windows

One of the results of these figures (4.2 to 4.13) is that keeping old windows has less emission than changing them. Also, Figure 4.14 to Figure 4.16 are more visual than changing windows. Having no insulation with old windows and just changing the heating source and adding PVs has less emission than having new windows and insulations. On the other hand, changing windows with less u-value helps reduction of operational emissions due to the less heating transition. However, the high embodied emission of the glass makes it a bad choice for retrofitting.

5.1.2 Heating source of energy

The GSHP heat pump has more efficiency than the ASHP heat pump, but due to the higher embodied emission of the GSHP, the ASHP is a better choice in this case study and has less emission. Electric heating has less emission than oil boiler and pellet. However, according to the high efficiency of ASHP and GSHP, these two options are better choices with fewer emissions for retrofitting.

5.1.3 Insulation

According to Figure 4.14 to Figure 4.16, Cellulose insulation has less emission than wool insulation due to less embodied emission. It shows that embodied emission significantly affects the retrofit decision-making process in Norway.

5.1.4 Grid emission

The other important interpretation of the results is that when the emission of the grid is low, the embodied emissions are important for retrofit decision-making as here it is shown that changing windows is an issue and have more emissions, even GSHP heat pump with more efficiency, which has a significant result in operational emission part has more overall emission due to the more embodied emission in comparison to ASHP heat pump. (Also comparison between Norway and Germany Figure 4.21)

5.1.5 Most effective element in retrofitting

According to figures (4.2 to 4.13), the effects of changing the heating system are much more significant than insulation and windows due to the dominant effect of operational emission compared to embodied emission.

5.1.6 Overall district emission chart

According to the analysis method of retrofitting, this approach aims to have an application programming interface that can use by a non-expert person to have the results. For instance, Figure 4.13 is one of the main charts that can be used for different robust retrofit decision-making. Companies and municipalities can use this chart for a big-scale retrofit and choose whether they want to change windows and which heating system and insulation are more suitable for retrofitting. Moreover, the area of the PVs can change in the input file to reach the best decision.

5.1.7 Comparison of all types of buildings (detached, semi-detached, and terrace houses)

According to Figure 4.17, the terrace house has less emission than the other two types of houses as the terrace flats have fewer external walls. The patterns of retrofit decision-making are the same for all three housing types.

5.1.8 Eliminate the embodied emission

According to Figure 4.18, without considering the embodied emission, the patterns of the scenarios are decreasing (compare to Figure 4.17), and it shows that changing the windows with fewer u-values is effective and decrease the operational emission. The massive effect of embodied emission of glass can see in this chart. Also, Figure 4.18 can compare with Figure 4.20 in Berlin, and these two charts show how grid emission can impact the retrofit decision-making.

5.1.9 PV effect

Figure 4.1 to Figure 4.12 and Figure 4.19 shows the effect of the PVs. According to these figures, using PVs is effective due to the less emission through the 60 years in comparison to the scenarios without PVs; on the other hand, using more PV area in retrofitting leads to less emission, and even with a proper amount of PVs, the zero-emission building can be reachable (using 140 m2 of PVs in the detached house).

5.2 Difference between Norway and Germany

According to Figure 4.20, retrofitting in Germany differs significantly from Norway due to the high grid emission and weather conditions. Changing windows in Germany, significantly impacts retrofitting and decreases the total emissions, especially in older buildings with more u-values for windows and walls.

According to Figure 4.21, the difference between the Norwegian and German context can be seen. It is shown that although the emission of the German buildings is very high due to the emission of the grid, after retrofitting, the emission of the buildings can reduce significantly and can even be compared with Norway, with changing the heating system to ASHP heta pump the emissions are approximately equal and with GSHP heat pump the emission of the housings in Germany is even less than Norway and around zero due to the less heating demand of Germany. This shows that when the emission of the grid is high, the effect of embodied emissions are not significant, and it is worth changing the windows and using GSHP, which is different from the Norwegian context.

5.3 Future weather data

Analyzing future weather data is essential in retrofit decision-making, as the housings will be used for 60 years, and with the global warming crisis, the need for heating demand will decrease. According to Figure 4.23, it is shown that in 2050 the heating demand will decrease. In cases with less emission and using more PVs in the building, it is crucial to consider this change to have an efficient number of PVs.

Chapter 6

Conclusion and future work

This chapter concludes the summarisation of the main work in this thesis study and contains future works according to the analysis.

6.1 Conclusion

This study suggested a method for retrofitting buildings to reduce the summation of embodied and operational emissions over 60 years. An RC model is used for analysis and a district with different housing types is the model's case study. The Norwegian context is the target for this analysis, and according to the results, when the grid emission is low, the embodied emission makes differences in retrofit decision-making. Changing windows is not favorable due to the high embodied emission. Changing the heating supply system has the most effects in retrofitting; although the GSHP heat pump has more efficiency than ASHP heat pumps, the ASHP heat pump is the best choice due to higher embodied emission. Adding different amounts of PVs reduces the emission, and as the results show, with a proper amount of PVs for a detached house (140 m2), it can be a zero-emission building.

Analysis shows that in Germany, with high grid emission, the embodied emission is not critical in retrofit decision-making. Moreover, changing windows, adding insulation, and using GSHP heat pumps is the most effective strategy for retrofitting.

Using Future weather data (2050) shows the reduction in emissions due to the fewer operational emission caused by global warming in the future.

The prepared model is in the early stages. However, this model aims to be used by a non-expert user in companies or municipalities to have robust retrofit decision-making.

6.2 Future work

The suggestions for future work are as follows:

-Considering commercial buildings in the analysis like offices, hospitals, restaurants, etc.

-Working on the model to be more accurate, for example, adding u-values of roof and ground to the analysis.

-Adding costs of the materials to the code.

-Adding an AI to the model to optimize cost and emission for better retrofit decision-making.

-Improving the accuracy of the RC model.

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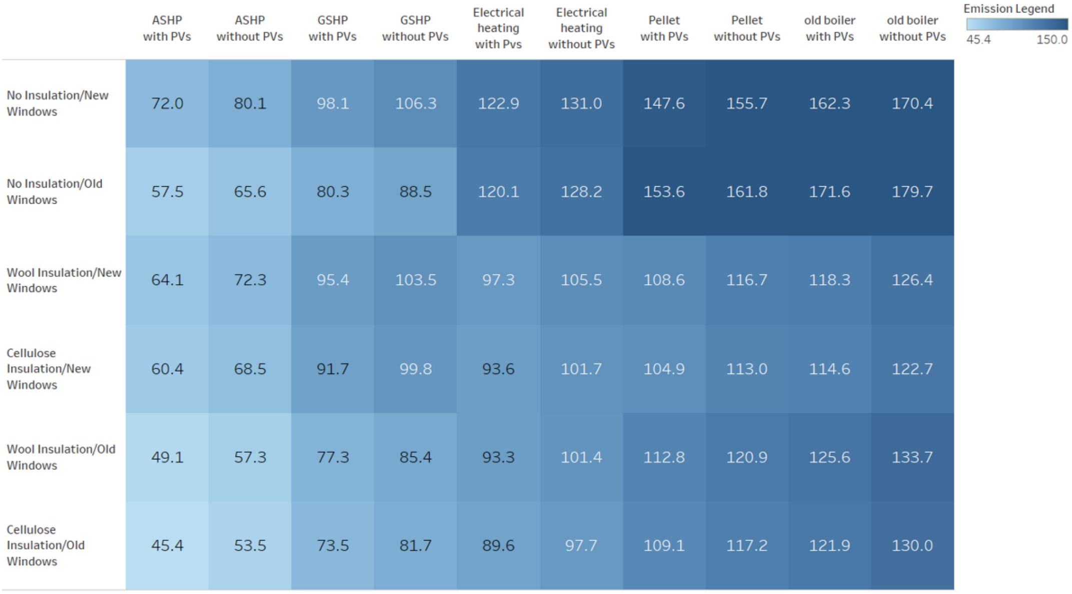
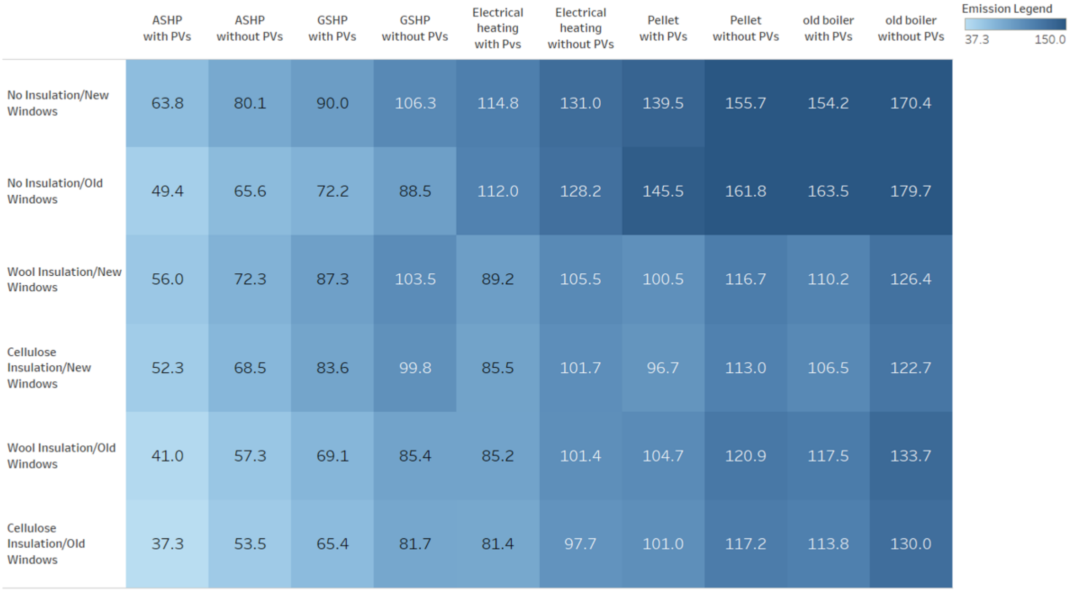
Appendix A

Emission Data for detached houses of 1960 to 1970 for 5 different areas of PVs



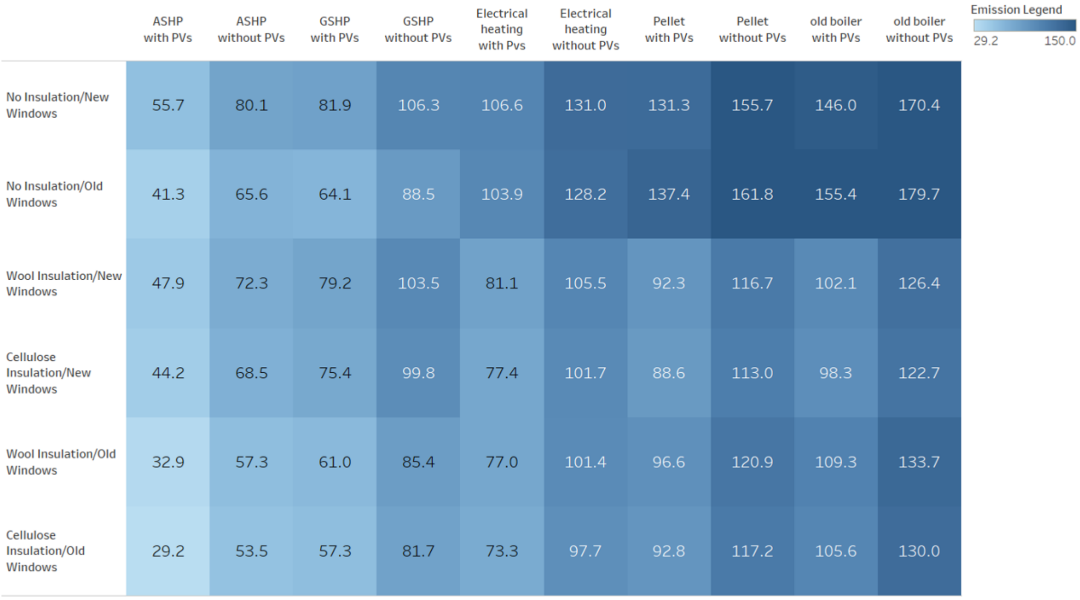
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	72.0	80.1	98.1	106.3	122.9	131.0	147.6	155.7	162.3	170.4
No Insulation/Old Windows	57.5	65.6	80.3	88.5	120.1	128.2	153.6	161.8	171.6	179.7
Wool Insulation/New Windows	64.1	72.3	95.4	103.5	97.3	105.5	108.6	116.7	118.3	126.4
Cellulose Insulation/New Windows	60.4	68.5	91.7	99.8	93.6	101.7	104.9	113.0	114.6	122.7
Wool Insulation/Old Windows	49.1	57.3	77.3	85.4	93.3	101.4	112.8	120.9	125.6	133.7
Cellulose Insulation/Old Windows	45.4	53.5	73.5	81.7	89.6	97.7	109.1	117.2	121.9	130.0

Figure A.1: Emission data for detached house (1960-1970),20 m2 area of PVs, retrofit of heating source with ASHP, over 60 years



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.8	80.1	90.0	106.3	114.8	131.0	139.5	155.7	154.2	170.4
No Insulation/Old Windows	49.4	65.6	72.2	88.5	112.0	128.2	145.5	161.8	163.5	179.7
Wool Insulation/New Windows	56.0	72.3	87.3	103.5	89.2	105.5	100.5	116.7	110.2	126.4
Cellulose Insulation/New Windows	52.3	68.5	83.6	99.8	85.5	101.7	96.7	113.0	106.5	122.7
Wool Insulation/Old Windows	41.0	57.3	69.1	85.4	85.2	101.4	104.7	120.9	117.5	133.7
Cellulose Insulation/Old Windows	37.3	53.5	65.4	81.7	81.4	97.7	101.0	117.2	113.8	130.0

Figure A.2: Emission data for detached house (1960-1970),40 m2 area of PVs, retrofit of heating source with ASHP, over 60 years



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	55.7	80.1	81.9	106.3	106.6	131.0	131.3	155.7	146.0	170.4
No Insulation/Old Windows	41.3	65.6	64.1	88.5	103.9	128.2	137.4	161.8	155.4	179.7
Wool Insulation/New Windows	47.9	72.3	79.2	103.5	81.1	105.5	92.3	116.7	102.1	126.4
Cellulose Insulation/New Windows	44.2	68.5	75.4	99.8	77.4	101.7	88.6	113.0	98.3	122.7
Wool Insulation/Old Windows	32.9	57.3	61.0	85.4	77.0	101.4	96.6	120.9	109.3	133.7
Cellulose Insulation/Old Windows	29.2	53.5	57.3	81.7	73.3	97.7	92.8	117.2	105.6	130.0

Figure A.3: Emission data for detached house (1960-1970),60 m2 area of PVs, retrofit of heating source with ASHP, over 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	47.6	80.1	73.8	106.3	98.5	131.0	123.2	155.7	137.9	170.4
No Insulation/Old Windows	33.2	65.6	56.0	88.5	95.7	128.2	129.3	161.8	147.2	179.7
Wool Insulation/New Windows	39.8	72.3	71.0	103.5	73.0	105.5	84.2	116.7	93.9	126.4
Cellulose Insulation/New Windows	36.0	68.5	67.3	99.8	69.2	101.7	80.5	113.0	90.2	122.7
Wool Insulation/Old Windows	24.8	57.3	52.9	85.4	68.9	101.4	88.4	120.9	101.2	133.7
Cellulose Insulation/Old Windows	21.1	53.5	49.2	81.7	65.2	97.7	84.7	117.2	97.5	130.0

Figure A.4: Emission data for detached house (1960-1970),80 m2 area of PVs, retrofit of heating source with ASHP, over 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	39.5	80.1	65.6	106.3	90.4	131.0	115.1	155.7	129.8	170.4
No Insulation/Old Windows	25.0	65.6	47.9	88.5	87.6	128.2	121.2	161.8	139.1	179.7
Wool Insulation/New Windows	31.6	72.3	62.9	103.5	64.8	105.5	76.1	116.7	85.8	126.4
Cellulose Insulation/New Windows	27.9	68.5	59.2	99.8	61.1	101.7	72.4	113.0	82.1	122.7
Wool Insulation/Old Windows	16.6	57.3	44.8	85.4	60.8	101.4	80.3	120.9	93.1	133.7
Cellulose Insulation/Old Windows	12.9	53.5	41.1	81.7	57.1	97.7	76.6	117.2	89.4	130.0

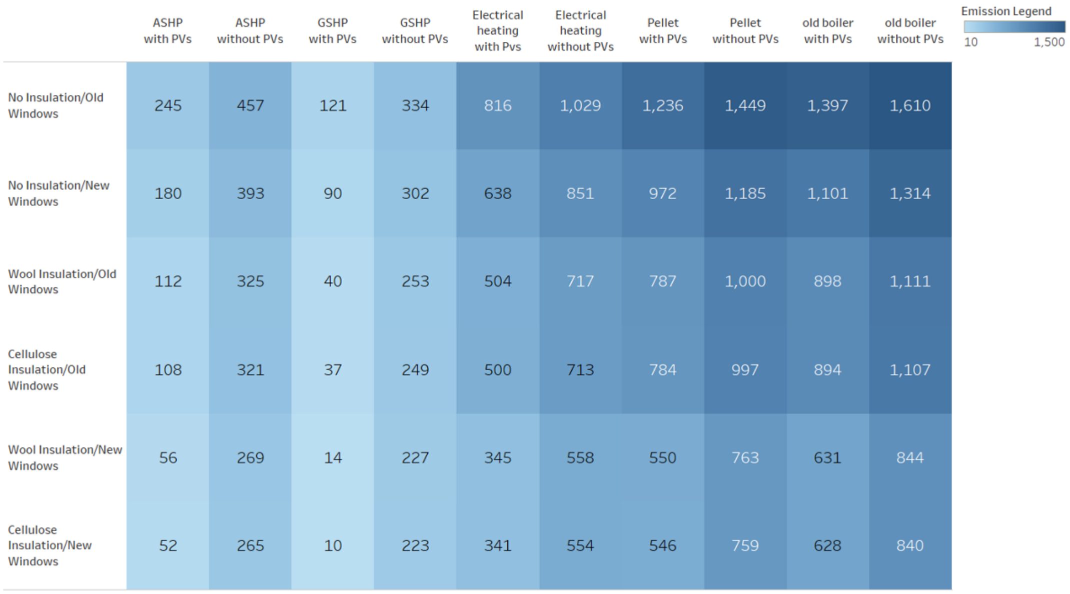
Figure A.5: Emission data for detached house (1960-1970),100 m2 area of PVs, retrofit of heating source with ASHP, over 60 years

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	23.2	80.1	49.4	106.3	74.2	131.0	98.8	155.7	113.5	170.4
No Insulation/Old Windows	8.8	65.6	31.6	88.5	71.4	128.2	104.9	161.8	122.9	179.7
Wool Insulation/New Windows	15.4	72.3	46.7	103.5	48.6	105.5	59.8	116.7	69.6	126.4
Cellulose Insulation/New Windows	11.7	68.5	42.9	99.8	44.9	101.7	56.1	113.0	65.8	122.7
Wool Insulation/Old Windows	0.4	57.3	28.5	85.4	44.5	101.4	64.1	120.9	76.9	133.7
Cellulose Insulation/Old Windows	-3.3	53.5	24.8	81.7	40.8	97.7	60.3	117.2	73.1	130.0

Figure A.6: Emission data for detached house (1960-1970),140 m2 area of PVs, retrofit of heating source with ASHP, over 60 years

Appendix B

Emission Data for all type of houses in German context

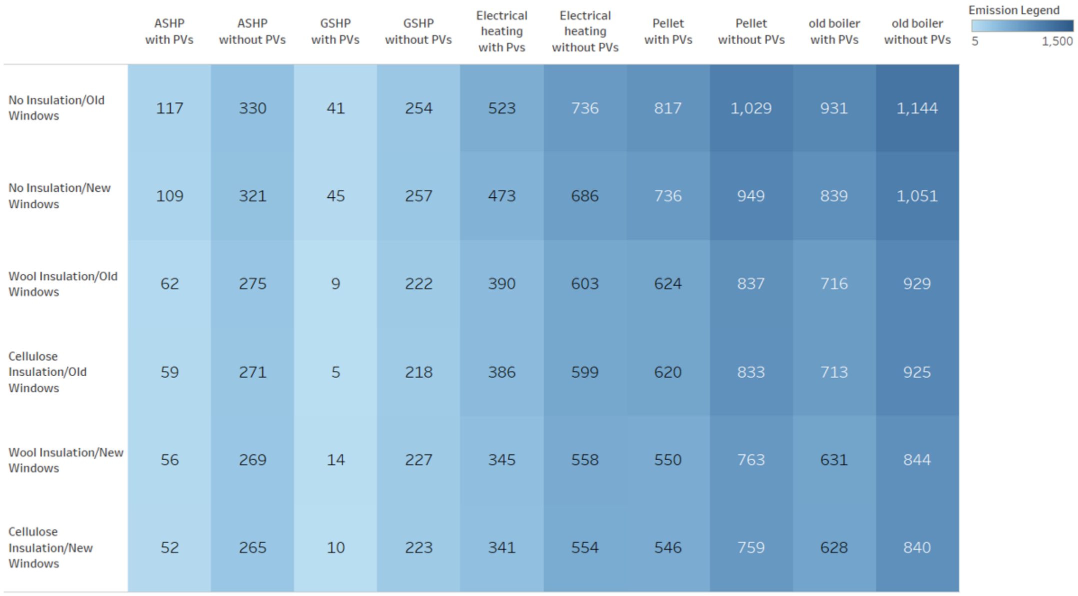


	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	245	457	121	334	816	1,029	1,236	1,449	1,397	1,610
No Insulation/New Windows	180	393	90	302	638	851	972	1,185	1,101	1,314
Wool Insulation/Old Windows	112	325	40	253	504	717	787	1,000	898	1,111
Cellulose Insulation/Old Windows	108	321	37	249	500	713	784	997	894	1,107
Wool Insulation/New Windows	56	269	14	227	345	558	550	763	631	844
Cellulose Insulation/New Windows	52	265	10	223	341	554	546	759	628	840

Figure B.1: Emission (KgCO2eq/m2) of detached house, built in 1960 to 1970 through 60 years, Berlin weather

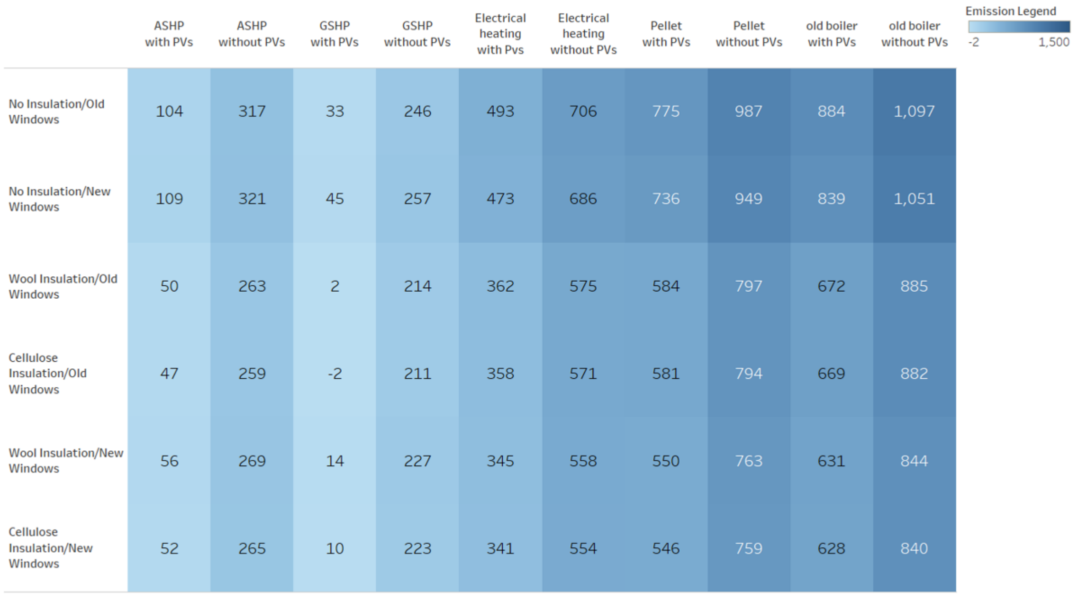
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	234	447	114	327	791	1,004	1,200	1,413	1,357	1,570
No Insulation/New Windows	170	383	83	296	614	827	937	1,150	1,062	1,275
Wool Insulation/Old Windows	112	325	40	253	504	717	787	1,000	898	1,111
Cellulose Insulation/Old Windows	108	321	37	249	500	713	784	997	894	1,107
Wool Insulation/New Windows	56	269	14	227	345	558	550	763	631	844
Cellulose Insulation/New Windows	52	265	10	223	341	554	546	759	628	840

Figure B.2: Emission (KgCO2eq/m2) of detached house, built in 1970 to 1980 through 60 years, Berlin weather



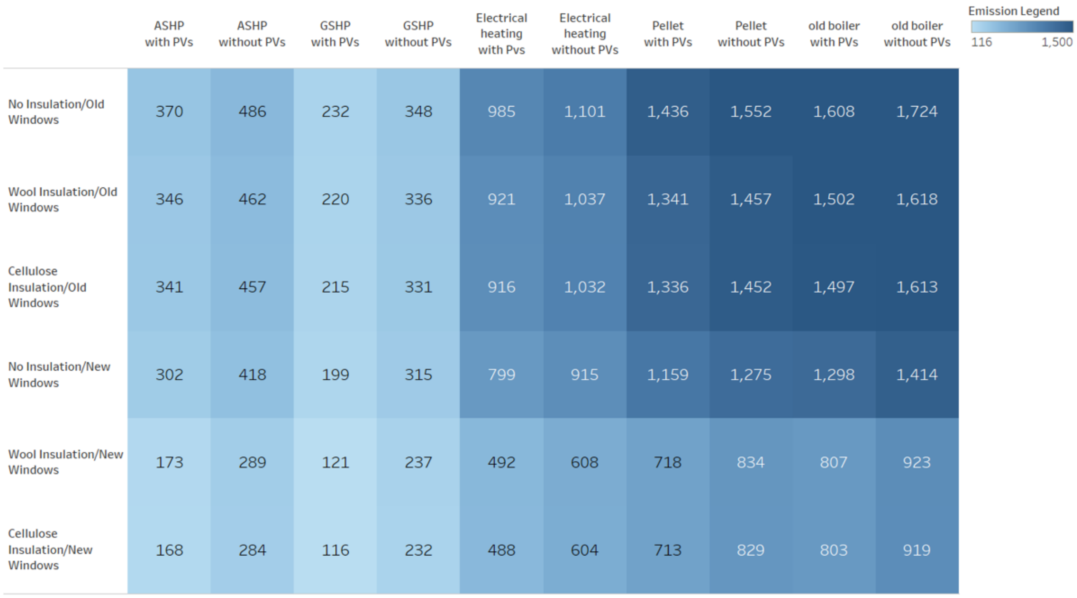
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	117	330	41	254	523	736	817	1,029	931	1,144
No Insulation/New Windows	109	321	45	257	473	686	736	949	839	1,051
Wool Insulation/Old Windows	62	275	9	222	390	603	624	837	716	929
Cellulose Insulation/Old Windows	59	271	5	218	386	599	620	833	713	925
Wool Insulation/New Windows	56	269	14	227	345	558	550	763	631	844
Cellulose Insulation/New Windows	52	265	10	223	341	554	546	759	628	840

Figure B.3: Emission (KgCO2eq/m2) of detached house, built in 1980 to 1990 through 60 years, Berlin weather



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	104	317	33	246	493	706	775	987	884	1,097
No Insulation/New Windows	109	321	45	257	473	686	736	949	839	1,051
Wool Insulation/Old Windows	50	263	2	214	362	575	584	797	672	885
Cellulose Insulation/Old Windows	47	259	-2	211	358	571	581	794	669	882
Wool Insulation/New Windows	56	269	14	227	345	558	550	763	631	844
Cellulose Insulation/New Windows	52	265	10	223	341	554	546	759	628	840

Figure B.4: Emission (KgCO2eq/m2) of detached house, built in 1990 to 2000 through 60 years, Berlin weather

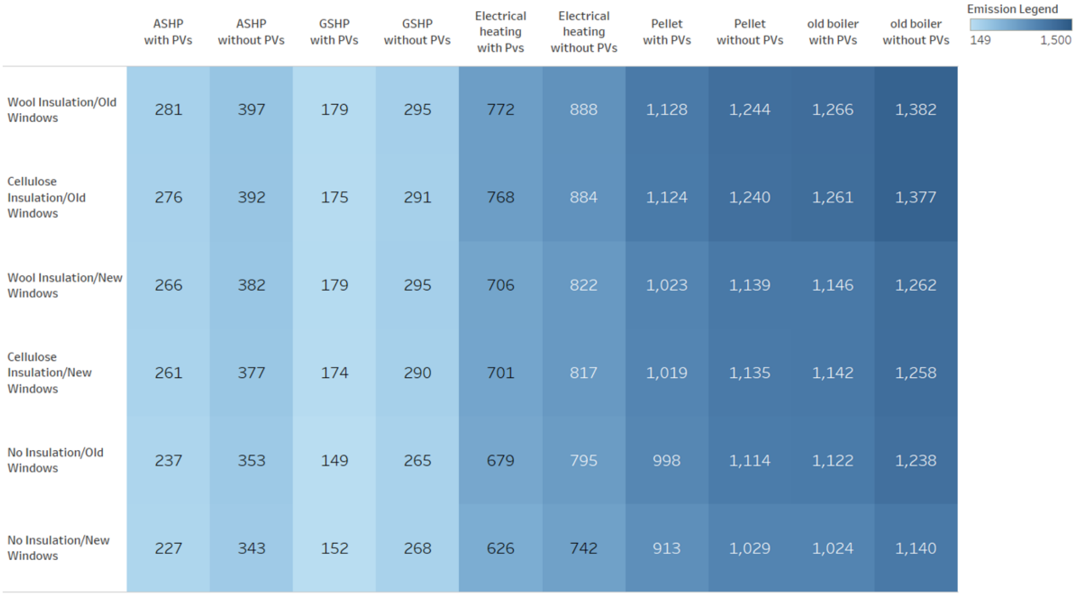


	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	370	486	232	348	985	1,101	1,436	1,552	1,608	1,724
Wool Insulation/Old Windows	346	462	220	336	921	1,037	1,341	1,457	1,502	1,618
Cellulose Insulation/Old Windows	341	457	215	331	916	1,032	1,336	1,452	1,497	1,613
No Insulation/New Windows	302	418	199	315	799	915	1,159	1,275	1,298	1,414
Wool Insulation/New Windows	173	289	121	237	492	608	718	834	807	923
Cellulose Insulation/New Windows	168	284	116	232	488	604	713	829	803	919

Figure B.5: Emission (KgCO2eq/m2) of semi-detached house, built in 1960 to 1970 through 60 years, Berlin weather

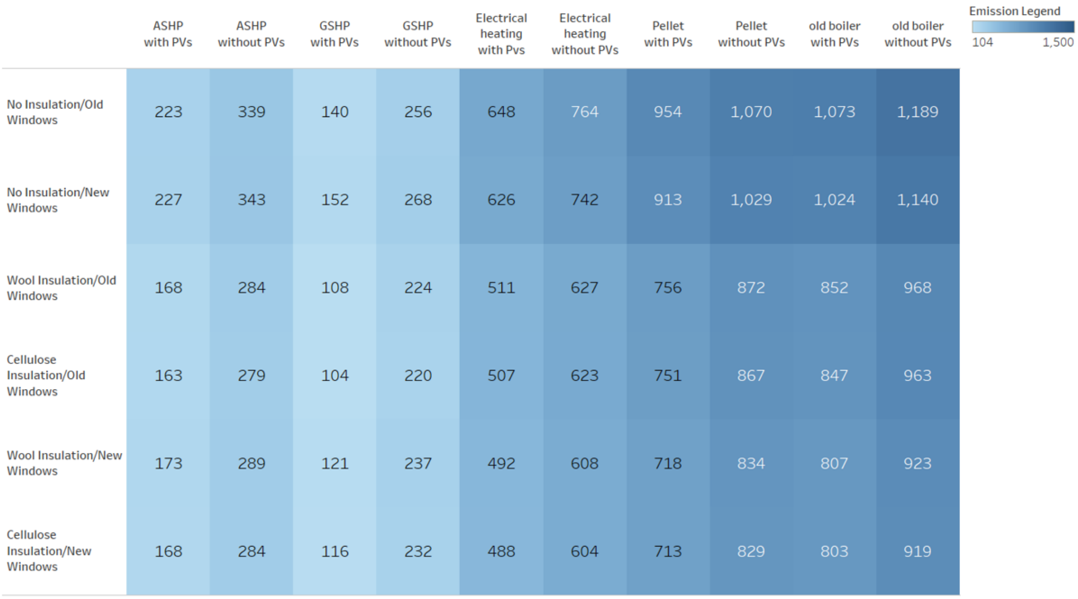
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	359	475	225	341	960	1,076	1,399	1,515	1,568	1,684
No Insulation/New Windows	291	407	192	308	774	890	1,123	1,239	1,258	1,374
Wool Insulation/Old Windows	233	349	149	265	662	778	971	1,087	1,091	1,207
Cellulose Insulation/Old Windows	229	345	145	261	657	773	966	1,082	1,086	1,202
Wool Insulation/New Windows	173	289	121	237	492	608	718	834	807	923
Cellulose Insulation/New Windows	168	284	116	232	488	604	713	829	803	919

Figure B.6: Emission (KgCO2eq/m2) of semi-detached house, built in 1970 to 1980 through 60 years, Berlin weather



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
Wool Insulation/Old Windows	281	397	179	295	772	888	1,128	1,244	1,266	1,382
Cellulose Insulation/Old Windows	276	392	175	291	768	884	1,124	1,240	1,261	1,377
Wool Insulation/New Windows	266	382	179	295	706	822	1,023	1,139	1,146	1,262
Cellulose Insulation/New Windows	261	377	174	290	701	817	1,019	1,135	1,142	1,258
No Insulation/Old Windows	237	353	149	265	679	795	998	1,114	1,122	1,238
No Insulation/New Windows	227	343	152	268	626	742	913	1,029	1,024	1,140

Figure B.7: Emission (KgCO2eq/m2) of semi-detached house, built in 1980 to 1990 through 60 years, Berlin weather



Emission Legend 104 – 1,500

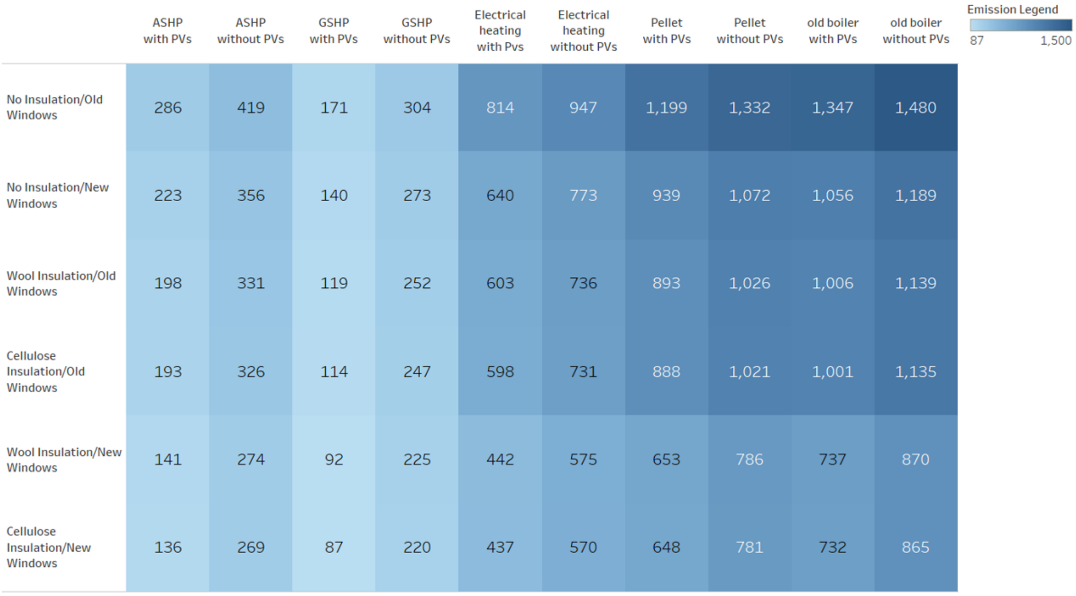
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	223	339	140	256	648	764	954	1,070	1,073	1,189
No Insulation/New Windows	227	343	152	268	626	742	913	1,029	1,024	1,140
Wool Insulation/Old Windows	168	284	108	224	511	627	756	872	852	968
Cellulose Insulation/Old Windows	163	279	104	220	507	623	751	867	847	963
Wool Insulation/New Windows	173	289	121	237	492	608	718	834	807	923
Cellulose Insulation/New Windows	168	284	116	232	488	604	713	829	803	919

Figure B.8: Emission (KgCO2eq/m2) of semi-detached house, built in 1990 to 2000 through 60 years, Berlin weather

Emission Legend 114 – 1,500

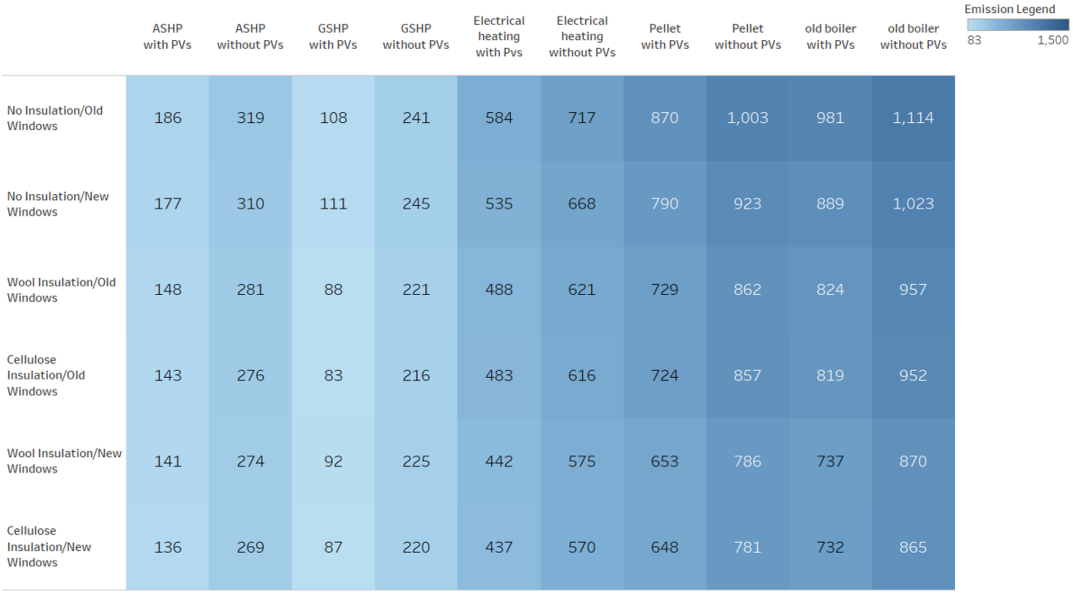
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	343	476	215	348	915	1,048	1,332	1,465	1,493	1,626
No Insulation/Old Windows	294	427	176	309	833	966	1,225	1,358	1,376	1,509
Wool Insulation/New Windows	230	363	147	281	646	779	945	1,078	1,062	1,195
Cellulose Insulation/New Windows	225	358	143	276	641	774	940	1,073	1,057	1,190
Wool Insulation/Old Windows	198	331	119	252	603	736	893	1,026	1,006	1,139
Cellulose Insulation/Old Windows	193	326	114	247	598	731	888	1,021	1,001	1,135

Figure B.9: Emission (KgCO2eq/m2) of terrace house, built in 1960 to 1970 through 60 years, Berlin weather



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	286	419	171	304	814	947	1,199	1,332	1,347	1,480
No Insulation/New Windows	223	356	140	273	640	773	939	1,072	1,056	1,189
Wool Insulation/Old Windows	198	331	119	252	603	736	893	1,026	1,006	1,139
Cellulose Insulation/Old Windows	193	326	114	247	598	731	888	1,021	1,001	1,135
Wool Insulation/New Windows	141	274	92	225	442	575	653	786	737	870
Cellulose Insulation/New Windows	136	269	87	220	437	570	648	781	732	865

Figure B.10: Emission (KgCO2eq/m2) of terrace house, built in 1970 to 1980 through 60 years, Berlin weather



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	186	319	108	241	584	717	870	1,003	981	1,114
No Insulation/New Windows	177	310	111	245	535	668	790	923	889	1,023
Wool Insulation/Old Windows	148	281	88	221	488	621	729	862	824	957
Cellulose Insulation/Old Windows	143	276	83	216	483	616	724	857	819	952
Wool Insulation/New Windows	141	274	92	225	442	575	653	786	737	870
Cellulose Insulation/New Windows	136	269	87	220	437	570	648	781	732	865

Figure B.11: Emission (KgCO2eq/m2) of terrace house, built in 1980 to 1990 through 60 years, Berlin weather

Emission Legend

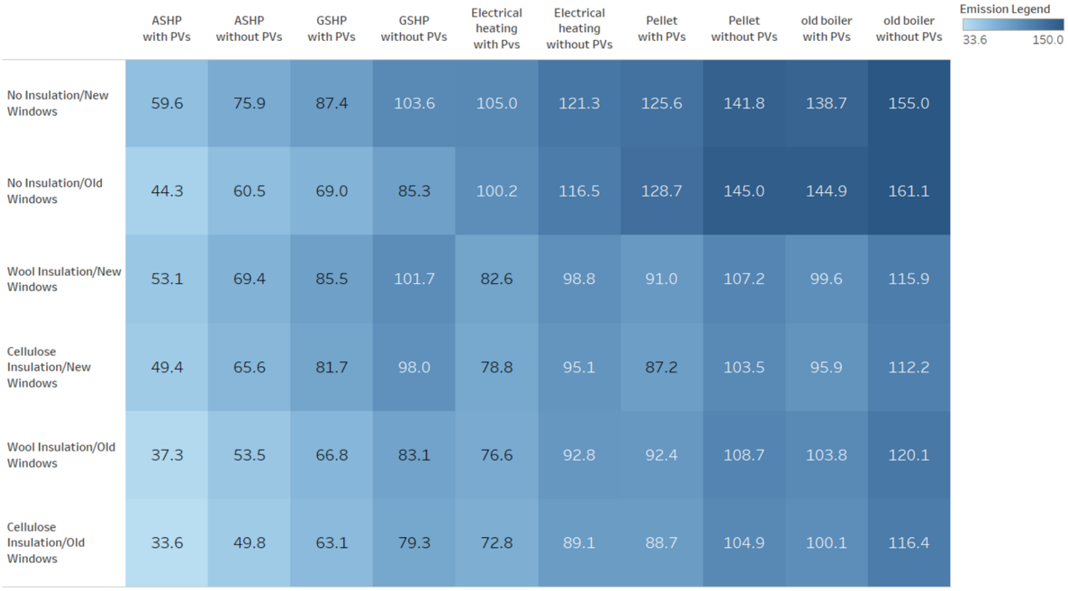
75 1,500

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/Old Windows	173.2	306.3	100.3	233.4	554.9	687.9	828.3	961.4	935.1	1,068.2
No Insulation/New Windows	177.4	310.4	111.5	244.5	534.6	667.7	789.5	922.6	889.5	1,022.5
Wool Insulation/Old Windows	136.2	269.2	80.0	213.1	459.7	592.7	688.9	822.0	779.4	912.5
Cellulose Insulation/Old Windows	131.2	264.3	75.1	208.1	454.7	587.8	684.0	817.1	774.5	907.5
Wool Insulation/New Windows	141.3	274.4	91.8	224.8	441.7	574.7	653.4	786.4	737.3	870.4
Cellulose Insulation/New Windows	136.4	269.4	86.8	219.9	436.7	569.8	648.4	781.5	732.4	865.4

Figure B.12: Emission (KgCO2eq/m2) of terrace house, built in 1990 to 2000 through 60 years, Berlin weather

Appendix C

Emission Data for all type of houses for 2050 (Future weather data)



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	59.6	75.9	87.4	103.6	105.0	121.3	125.6	141.8	138.7	155.0
No Insulation/Old Windows	44.3	60.5	69.0	85.3	100.2	116.5	128.7	145.0	144.9	161.1
Wool Insulation/New Windows	53.1	69.4	85.5	101.7	82.6	98.8	91.0	107.2	99.6	115.9
Cellulose Insulation/New Windows	49.4	65.6	81.7	98.0	78.8	95.1	87.2	103.5	95.9	112.2
Wool Insulation/Old Windows	37.3	53.5	66.8	83.1	76.6	92.8	92.4	108.7	103.8	120.1
Cellulose Insulation/Old Windows	33.6	49.8	63.1	79.3	72.8	89.1	88.7	104.9	100.1	116.4

Figure C.1: Emission (KgCO2eq/m2) of detached house, built in 1960 to 1970 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	58.6	74.9	86.7	103.0	102.8	119.1	122.4	138.6	135.2	151.4
No Insulation/Old Windows	43.3	59.5	68.4	84.6	97.9	114.2	125.5	141.7	141.2	157.4
Wool Insulation/New Windows	53.1	69.4	85.5	101.7	82.6	98.8	91.0	107.2	99.6	115.9
Cellulose Insulation/New Windows	49.4	65.6	81.7	98.0	78.8	95.1	87.2	103.5	95.9	112.2
Wool Insulation/Old Windows	37.3	53.5	66.8	83.1	76.6	92.8	92.4	108.7	103.8	120.1
Cellulose Insulation/Old Windows	33.6	49.8	63.1	79.3	72.8	89.1	88.7	104.9	100.1	116.4

Figure C.2: Emission (KgCO2eq/m2) of detached house, built in 1970 to 1980 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	52.9	69.1	83.1	99.4	89.6	105.8	103.5	119.7	114.2	130.4
Wool Insulation/New Windows	53.1	69.4	85.5	101.7	82.6	98.8	91.0	107.2	99.6	115.9
Cellulose Insulation/New Windows	49.4	65.6	81.7	98.0	78.8	95.1	87.2	103.5	95.9	112.2
No Insulation/Old Windows	32.5	48.7	61.6	77.9	73.0	89.3	89.9	106.1	101.7	117.9
Wool Insulation/Old Windows	32.6	48.8	63.9	80.1	65.7	82.0	77.0	93.2	86.7	102.9
Cellulose Insulation/Old Windows	28.9	45.1	60.1	76.4	62.0	78.3	73.2	89.5	82.9	99.2

Figure C.3: Emission (KgCO2eq/m2) of detached house, built in 1980 to 1990 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	52.9	69.1	83.1	99.4	89.6	105.8	103.5	119.7	114.2	130.4
Wool Insulation/New Windows	53.1	69.4	85.5	101.7	82.6	98.8	91.0	107.2	99.6	115.9
Cellulose Insulation/New Windows	49.4	65.6	81.7	98.0	78.8	95.1	87.2	103.5	95.9	112.2
No Insulation/Old Windows	31.3	47.5	60.9	77.1	70.3	86.5	85.9	102.2	97.3	113.5
Wool Insulation/Old Windows	31.4	47.7	63.1	79.4	63.1	79.3	73.2	89.4	82.5	98.7
Cellulose Insulation/Old Windows	27.7	44.0	59.4	75.7	59.4	75.6	69.5	85.7	78.7	95.0

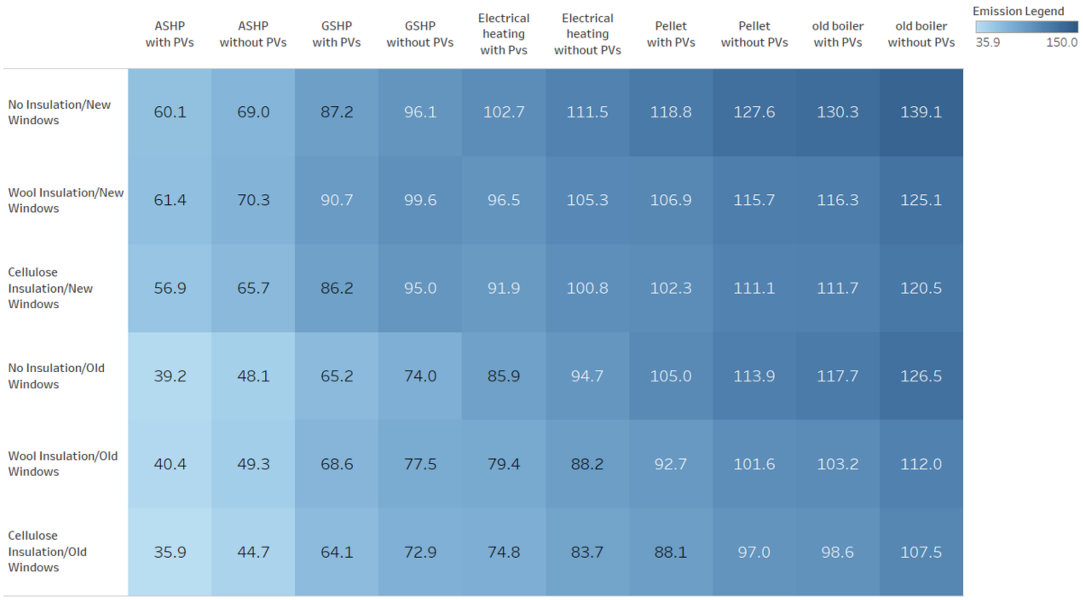
Figure C.4: Emission (KgCO2eq/m2) of detached house, built in 1990 to 2000 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	67.1	75.9	91.6	100.5	118.7	127.6	141.7	150.5	155.7	164.6
No Insulation/Old Windows	51.5	60.4	72.9	81.8	114.2	123.0	145.5	154.3	162.6	171.5
Wool Insulation/New Windows	61.4	70.3	90.7	99.6	96.5	105.3	106.9	115.7	116.3	125.1
Cellulose Insulation/New Windows	56.9	65.7	86.2	95.0	91.9	100.8	102.3	111.1	111.7	120.5
Wool Insulation/Old Windows	45.4	54.2	71.7	80.6	90.7	99.6	108.9	117.8	121.2	130.1
Cellulose Insulation/Old Windows	40.8	49.7	67.1	76.0	86.2	95.0	104.4	113.2	116.6	125.5

Figure C.5: Emission (KgCO2eq/m2) of semi-detached house, built in 1960 to 1970 through 60 years, 2050 weather data

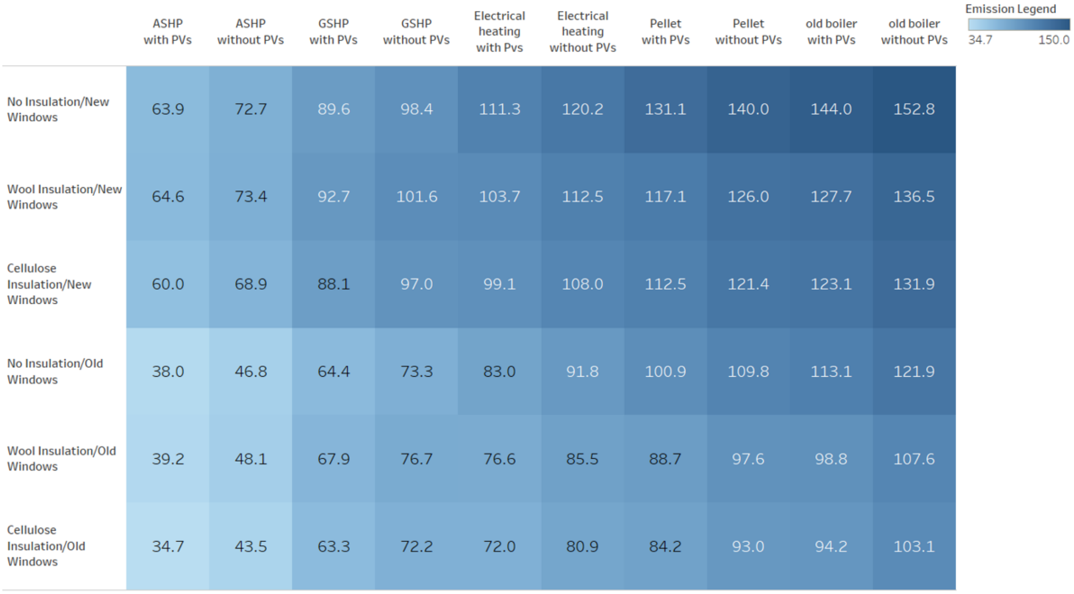
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	66.1	74.9	91.0	99.8	116.4	125.2	138.4	147.2	152.0	160.9
No Insulation/Old Windows	50.5	59.3	72.3	81.1	111.8	120.6	142.1	150.9	158.8	167.7
Wool Insulation/New Windows	61.4	70.3	90.7	99.6	96.5	105.3	106.9	115.7	116.3	125.1
Cellulose Insulation/New Windows	56.9	65.7	86.2	95.0	91.9	100.8	102.3	111.1	111.7	120.5
Wool Insulation/Old Windows	45.4	54.2	71.7	80.6	90.7	99.6	108.9	117.8	121.2	130.1
Cellulose Insulation/Old Windows	40.8	49.7	67.1	76.0	86.2	95.0	104.4	113.2	116.6	125.5

Figure C.6: Emission (KgCO2eq/m2) of semi-detached house, built in 1970 to 1980 through 60 years, 2050 weather data



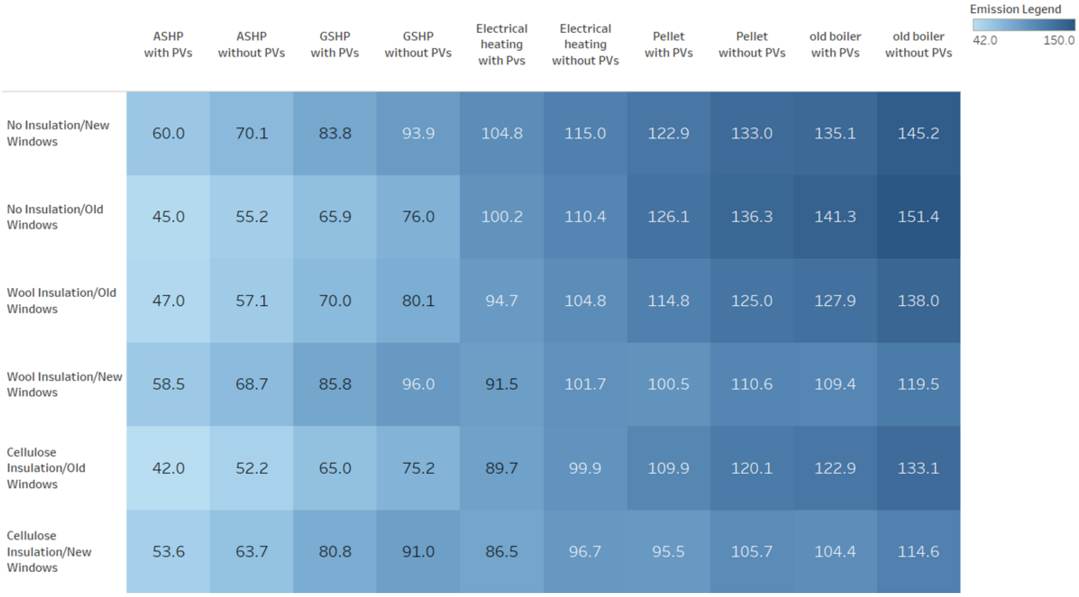
	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	60.1	69.0	87.2	96.1	102.7	111.5	118.8	127.6	130.3	139.1
Wool Insulation/New Windows	61.4	70.3	90.7	99.6	96.5	105.3	106.9	115.7	116.3	125.1
Cellulose Insulation/New Windows	56.9	65.7	86.2	95.0	91.9	100.8	102.3	111.1	111.7	120.5
No Insulation/Old Windows	39.2	48.1	65.2	74.0	85.9	94.7	105.0	113.9	117.7	126.5
Wool Insulation/Old Windows	40.4	49.3	68.6	77.5	79.4	88.2	92.7	101.6	103.2	112.0
Cellulose Insulation/Old Windows	35.9	44.7	64.1	72.9	74.8	83.7	88.1	97.0	98.6	107.5

Figure C.7: Emission (KgCO2eq/m2) of semi-detached house, built in 1980 to 1990 through 60 years, 2050 weather data



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.9	72.7	89.6	98.4	111.3	120.2	131.1	140.0	144.0	152.8
Wool Insulation/New Windows	64.6	73.4	92.7	101.6	103.7	112.5	117.1	126.0	127.7	136.5
Cellulose Insulation/New Windows	60.0	68.9	88.1	97.0	99.1	108.0	112.5	121.4	123.1	131.9
No Insulation/Old Windows	38.0	46.8	64.4	73.3	83.0	91.8	100.9	109.8	113.1	121.9
Wool Insulation/Old Windows	39.2	48.1	67.9	76.7	76.6	85.5	88.7	97.6	98.8	107.6
Cellulose Insulation/Old Windows	34.7	43.5	63.3	72.2	72.0	80.9	84.2	93.0	94.2	103.1

Figure C.8: Emission (KgCO2eq/m2) of semi-detached house, built in 1990 to 2000 through 60 years, 2050 weather data



	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	60.0	70.1	83.8	93.9	104.8	115.0	122.9	133.0	135.1	145.2
No Insulation/Old Windows	45.0	55.2	65.9	76.0	100.2	110.4	126.1	136.3	141.3	151.4
Wool Insulation/Old Windows	47.0	57.1	70.0	80.1	94.7	104.8	114.8	125.0	127.9	138.0
Wool Insulation/New Windows	58.5	68.7	85.8	96.0	91.5	101.7	100.5	110.6	109.4	119.5
Cellulose Insulation/Old Windows	42.0	52.2	65.0	75.2	89.7	99.9	109.9	120.1	122.9	133.1
Cellulose Insulation/New Windows	53.6	63.7	80.8	91.0	86.5	96.7	95.5	105.7	104.4	114.6

Figure C.9: Emission (KgCO2eq/m2) of terrace house, built in 1960 to 1970 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	63.1	73.3	85.8	95.9	112.1	122.3	133.3	143.4	146.6	156.8
No Insulation/Old Windows	49.0	59.1	68.3	78.5	109.4	119.5	139.2	149.3	155.8	165.9
Wool Insulation/New Windows	61.5	71.7	87.7	97.8	98.3	108.5	110.2	120.4	120.2	130.4
Wool Insulation/Old Windows	47.0	57.1	70.0	80.1	94.7	104.8	114.8	125.0	127.9	138.0
Cellulose Insulation/New Windows	56.6	66.7	82.7	92.9	93.4	103.5	105.3	115.4	115.3	125.4
Cellulose Insulation/Old Windows	42.0	52.2	65.0	75.2	89.7	99.9	109.9	120.1	122.9	133.1

Figure C.10: Emission (KgCO2eq/m2) of terrace house, built in 1970 to 1980 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	54.97	65.12	80.66	90.82	93.35	103.50	106.45	116.60	116.85	127.01
Wool Insulation/New Windows	58.54	68.70	85.80	95.95	91.50	101.65	100.48	110.63	109.36	119.52
Cellulose Insulation/New Windows	53.59	63.75	80.84	91.00	86.55	96.70	95.53	105.68	104.41	114.57
No Insulation/Old Windows	34.98	45.14	59.57	69.73	77.20	87.36	93.21	103.37	104.70	114.85
Wool Insulation/Old Windows	38.46	48.61	64.65	74.80	75.13	85.28	86.93	97.09	96.86	107.01
Cellulose Insulation/Old Windows	33.51	43.66	59.69	69.85	70.18	80.33	81.98	92.13	91.91	102.06

Figure C.11: Emission (KgCO2eq/m2) of terrace house, built in 1980 to 1990 through 60 years, 2050 weather data

	ASHP with PVs	ASHP without PVs	GSHP with PVs	GSHP without PVs	Electrical heating with Pvs	Electrical heating without PVs	Pellet with PVs	Pellet without PVs	old boiler with PVs	old boiler without PVs
No Insulation/New Windows	54.97	65.12	80.66	90.82	93.35	103.50	106.45	116.60	116.85	127.01
Wool Insulation/New Windows	58.54	68.70	85.80	95.95	91.50	101.65	100.48	110.63	109.36	119.52
Cellulose Insulation/New Windows	53.59	63.75	80.84	91.00	86.55	96.70	95.53	105.68	104.41	114.57
No Insulation/Old Windows	33.79	43.95	58.83	68.98	74.47	84.62	89.31	99.46	100.36	110.51
Wool Insulation/Old Windows	37.31	47.46	63.92	74.08	72.48	82.63	83.15	93.30	92.65	102.81
Cellulose Insulation/Old Windows	32.36	42.51	58.97	69.13	67.53	77.68	78.19	88.35	87.70	97.85

Figure C.12: Emission (KgCO2eq/m2) of terrace house, built in 1990 to 2000 through 60 years, 2050 weather data