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The role of building policies for long-term energy efficiency

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Abstract

Buildings consume around one third of the world final energy use, hence they have been the focus of numerous policies and programmes to reduce buildings sector emissions. In particular, the European Policy for Building Directives stands out with the ambitious long-term objective of improving the existing building stock to nearly-Zero Energy Building standards by 2050. Within this sector, very long lifespans of buildings and retrofits leads to significant lock-in risks, resulting in inertia for policies energy efficiency and pointing to the urgency of ambitious and immediate measures. This research work aims at developing a new modelling method, with the capacity to represent long lasting building structures and evaluate decision-making for improving energy efficiency of the building envelope, where benefits play out in the long-term and require farsighted strategies. The buildings vintages and thermal insulation investment module is integrated in the EDGE global buildings model, developed by the Potsdam Institute for Climate Impact Research. The contribution of this work is (1) to show how building stock and thermal insulation dynamics across regions can affect world final energy demand until 2050. (2) Investigate the current gap between the European Union buildings policy objective and the estimated future trends. (3) Analyze the amount of final energy saved if the rest of the world would follow European policies. (4) Examine the role of energy prices in improving thermal insulation levels. (5) Outline the impact that uncertainties on input parameters show on the highlighted outcomes. Model projections suggest that following current trends, final energy demand for space heating and cooling is expected to increase by 60% by 2050. Strong rise in both new construction rates and cooling demand in China and in other warm world regions is estimated, pointing to the benefit of constructing energy-efficient new buildings. European final energy demand is expected to decrease by 20% by 2050, compared to 2015, while the implementation of the European buildings Policy would lead to an additional 60% reduction in 2050. Energy price increase shows an important role in improving thermal insulation levels. Results are most sensitive to assumptions on market heterogeneity, while different assumptions on future global socio-economic development lead to similar levels of energy consumption in 2050, due to contradicting effects. The European policy targets are computed to be reachable if the best assumptions on investment cost decrease, technology choice, renovation rates and energy price increase are implemented. Further work on the improved representation of technologies and renovated buildings in the new developed model is suggested.

Keywords: Long term, energy efficiency, building stock, thermal insulation, building policies

Sommario

Gli edifici consumano circa un terzo del consumo di energia secondaria mondiale, quindi sono stati al centro di numerose politiche e programmi per ridurre le emissioni del settore edilizio. In particolare, la politica europea in materia di direttive edilizie si distingue per l'ambizioso obiettivo a lungo termine di migliorare gli stock esistenti di edifici fino allo standard di edifici a energia quasi-zero entro il 2050. In questo settore, la lunga permanenza degli edifici e dei rinnovamenti porta a significativi rischi di stagnazione, con conseguente inerzia per le politiche di efficienza energetica e sottolineando l'urgenza di misure ambiziose e immediate. Questo lavoro di ricerca mira a sviluppare un nuovo metodo di modellizzazione, con la capacità di rappresentare costruzioni durature nel tempo e valutare il processo decisionale per migliorare l'efficienza energetica dell'involucro edilizio, dove i benefici si sviluppano a lungo termine e richiedono strategie lungimiranti. Le annate degli edifici e il modulo di investimento per l'isolamento termico sono integrati nel modello globale EDGE sugli edifici, sviluppato dal Potsdam Institute for Climate Impact Research. Il contributo di questo lavoro è (1) mostrare come le dinamiche degli edifici e dell'isolamento termico in varie regioni possano influenzare la domanda di energia secondaria mondiale fino al 2050. (2) Indagare l'attuale divario tra l'obiettivo della politica europea sugli edifici e le stimate tendenze future. (3) Analizzare i risparmi di energia secondaria se il resto del mondo seguisse le politiche europee. (4) Esaminare il ruolo dei prezzi dell'energia per il miglioramento dei livelli di isolamento termico. (5) Delineare l'impatto che le incertezze sui parametri di input mostrano sui risultati evidenziati. Le proiezioni del modello suggeriscono che, seguendo le tendenze attuali, la domanda di energia secondaria per il riscaldamento e il raffrescamento degli ambienti aumenterà del 60% entro il 2050. Si stima un forte aumento sia dei nuovi tassi di costruzione che della domanda di raffrescamento in Cina e in altre regioni calde del mondo, indicando il vantaggio di costruire nuovi edifici a basso consumo energetico. Si prevede che la domanda di energia secondaria europea diminuirà del 20 % entro il 2050 rispetto al 2015, mentre l'attuazione della politica europea per gli edifici porterebbe a un ulteriore riduzione del 60% nel 2050. L'aumento dei prezzi dell'energia ha un ruolo importante nel miglioramento dei livelli di isolamento termico. I risultati sono più sensibili alle ipotesi di eterogeneità del mercato, mentre diverse ipotesi sul futuro sviluppo socio-economico globale portano a livelli simili di consumo energetico nel 2050, a causa di diversi effetti che si controbilanciano tra loro. Si stima che gli obiettivi politici europei siano raggiungibili nel caso in cui vengano implementate le ipotesi più ottimistiche sulla riduzione dei costi di investimento, sulla scelta della tecnologia, sui tassi di rinnovamento e sull'aumento dei prezzi dell'energia. Sono infine suggeriti ulteriori lavori sul miglioramento della rappresentazione delle tecnologie e degli edifici ristrutturati nel nuovo modello.

Parole Chiave: Lungo termine, Efficienza Energetica, Stock di edifici, Isolamento Termico, Politiche nel settore degli edifici

Executive Summary

Scope of the work

Climate change constitutes a great issue which calls for immediate solutions. With the Paris Agreement, the vast majority of the world nations agreed to undertake ambitious efforts to face the common issue of global warming. The objective is to keep the global temperature rise below the threshold of 2°C and to pursue efforts in order to limit the temperature even below 1.5 °C. However, the Intergovernmental Panel on Climate Change (IPCC) states that currently, anthropogenic emissions are estimated to have already caused approximately 1.0 °C of global warming above pre-industrial levels, global warming will reach 1.5 °C between 2030 and 2052, with a probability between 66 and 100%, if it continues to increase at the current rate [1]. Therefore, significant efforts are still required in order to reach the Paris target. Similarly, major gaps exist with respects to the objecties of the sustainable development goals.

The buildings sector accounts for around one third of the world final energy use and one half of the total electricity, which is linked to 20% of energy-related greenhouse gases emissions, thus playing a key role for climate change. Buildings final energy demand is expected to increase by 50% by 2050 if current trends are followed[2]. By contrast, there is a wide consensus that future final energy use in buildings may stay constant or even decline by mid-century, if today's cost-effective best practices and technologies are diffused [2, 3, 4]. Globally, 30% of buildings energy consumption is linked to space heating and cooling demand. IEA suggests that in order to achieve energy demand reductions for the highlighted end-uses, improving the envelope insulation levels must be the first step, since it also allows for downsizing of the heating and cooling equipment. Building codes are currently in place in around 40 national governments [5], with the European Policy for Building Directives (EPBD) standing out with the ambitious long-term objective of improving the existing building stock to nearly-Zero Energy Building (nZEB) standards by 2050.

Integrated Assessment Models (IAMs) and energy system models have been developed in order to analyse long-term climate mitigation strategies and have been looking at the potential of future efficiency pathways. Within the buildings sector, very long lifespans of buildings and retrofits leads to a very significant lock-in risk, resulting in inertia for policies energy efficiency. At the same time, there is a strong path dependency of choice made now for the future efficiency potential, pointing to the urgency of ambitious and immediate measures. While in OECD regions, approximately 75% of the current building stock will be still standing in 2050, economic growth in developing nations is expected to drive high new construction rates [2]. Hence, renovation of the current building stock should be made a priority in the former countries, while the most important need in the latter regions is related to urgent enforcement of stringent building codes for new buildings. Therefore, when analysing long-term climate mitigation strategies, a thorough understanding of the building stock dynamics is required. However, models used to assess long term energy and climate savings in buildings typically neglect building infrastructure. The overarching aim of this thesis is to try fill this gap.

This research work aims at developing a new modelling method, with the capacity to represent long lasting building structures and evaluate decision-making for improving buildings energy efficiency where benefits play out in the long-term and require farsighted strategies. In this way, policymakers can be informed about which building parameters are key for national carbon reduction strategies, while the construction industry could develop business strategies for sustainable refurbishment [6]. By means of scenario analyses, the impact of building policies, focusing specifically on the stringent European policy ambitions in the evolution of global energy demand until 2050 is assessed, outlining main benefits and gaps with the current trends. In particular, we address 5 main questions:

1. How can building stock and insulation dynamics across regions affect world final energy demand until 2050?
2. What is the current gap between the European Union buildings policy objective and the estimated future trends?
3. What is the amount of final energy saved if the rest of the world follows Europe policies, in the major world economies?
4. What is the role of subsidies on energy prices both at the European and at the world level? To what extent can an increase in energy prices help Europe reaching its building policy objectives?
5. To which extent will uncertainties on future discount rates, technology improvement, market heterogeneity, renovation rates, future climate change and socioeconomic drivers either hamper or help reaching these objectives?

Structure

The structure of this thesis is organized as follows. Chapter 1 introduces climate change issue and the building sector potential within this framework. Chapter 2 discusses renovation investment drivers and analyzes the most recent data on building envelope insulation levels, finally outlining the state-of-the-art and future perspectives of the current building envelope technologies. Chapter 3 provides a brief introduction on the link between IAMs and global energy models, then focusing on EDGE, which was used in this work. Chapter 4 introduces the implementation of the building stock and U-values modules in EDGE, firstly with a discussion on main concepts and input data and then through a comparison with the previous module results. Chapter 5 outlines the main results, focusing on estimated development of space cooling and heating energy demand, then providing a simulation of the EPBD policy and then discussing role of energy prices on triggering energy efficiency. Chapter 6 then provides an extensive sensitivity analysis, in order to discuss the impacts of parameter uncertainty on the final results. Finally, Chapter 7 summarizes the key findings and outlines suggestions on required future developments. The Appendices contain additional information which can be useful in order to gain a thorough understanding of the results.

Methodology

The building methodological block employed in this work is the Energy Demand GEnerator (EDGE) buildings model, developed by the Potsdam Institute for Climate Impact Research (PIK). It can be defined as a bottom-up, statistically-based simulation model, which is multi-regional and employs a long-term point of view. In this thesis, the model has been modified and significantly extended in order to include key insulation measures,as well as building vintages. This enhancements allow the model to assess the implications of energy and bulding policies on global energy demand. In order to do so, historical data on residential building thermal performance, gathered by the EU commission database [7] were analyzed, to understand the main determinants of the insulation levels over regions and time, represented by the thermal conductance of building envelope components: namely, U-value. By means of a regression analysis, the influence of several variables was tested. Moreover, an extensive literature review was performed, aiming at understanding the main drivers of renovation investments and possible policy measures to spur the improvement of energy efficiency in buildings. In addition, indications on state-of-the-art and future perspectives insulation technologies were researched. Based on the collected information, the current EDGE U-values module was reviewed and updated. First diagnostics of the results were carried out, in order to understand the sensitivity that the new module calculations showed with respect to input parameters. Then, the model had to be extended to the global level and a lack of data was encountered, compared to the wide amount of detail the European region presented. Therefore, by means of both region-specific indications from the literature and assumptions based on European trends, input data were computed for all the world regions. In order to match the 2015 historical trends, a calibration was performed. Then, comparison with the previous model results was carried out, in order to outline the impact of the new modules in the estimation of U-values development and to correct possible strong biases. In order to increase the reliability of results, a comparison with estimated past European trends of insulation levels was performed. Once the model was refined, main results were derived and discussed, with a focus on the different parameters impact across regions and time. The estimated magnitude of final energy demand trends in 2015 is compared to historical data, in order to outline possible issues that might emerge with the connection to the main model. The EPBD is then simulated both at the European and at the global level, in order to respectively quantify existing gaps with the current trends and to evaluate how the total energy demand would develop if this policy is applied to each world region. Finally, the robustness of the results is checked by means of an extensive sensitivity analysis, in order to account for uncertainties in input parameters.

Main Results and Conclusions

The data analysis shows that for the oldest vintages, U-values are spread over a wide range, mostly depending on the climate. However, especially for vintages build after the 1980 oil crisis, a steep increase in the insulation levels can be observed, with a convergence to very low U-values for the newest vintages. This shows the large impact of the implemented energy policies carried out all over Europe. U-values are found to be strongly related with climate, measured in Heating Degree Days (HDD) and Cooling Degree Days (CDD), and time. Energy prices and income are important drivers, affecting investment decision and the implementation of buildings policies. No significant differences on buildings U-values between the residential and services sub-sectors were found. The investment payback time (PBT) represents one of the major barriers for renovation, over several European regions [8]. New buildings however generally follow the cost-optimality principle, outlined in [9]. Therefore, the estimation of future buildings thermal performance was based on the optimization of the Net Present Cost (NPC). Investment costs of the available and new insulation technologies are estimated, while savings are calculated based on the insulation thermal conductivity, energy prices, energy carries shares and end-uses efficiencies and finally on the discount rate. Renovation and new construction are modelled separately as they follow different decision rules, taking into account for both of them the opaque and glazed surfaces.

Building stock and U-value modules coupling

Figure 5.5 presents the main results of the model, calibrated to current trends. At the global level, more than half of the heating energy demand currently comes from the richest countries and the regional shares do not substantially change until 2050. Renovation of the current building stock and increasing end-use efficiency will make overall final energy demand decline. Conversely, the expected income growth in low income countries and China is estimated to trigger cooling demand growth, with an 8-fold increase from 2015 to 2050. Final energy demand is eventually estimated to increases by 60%, compared to 2015 levels.

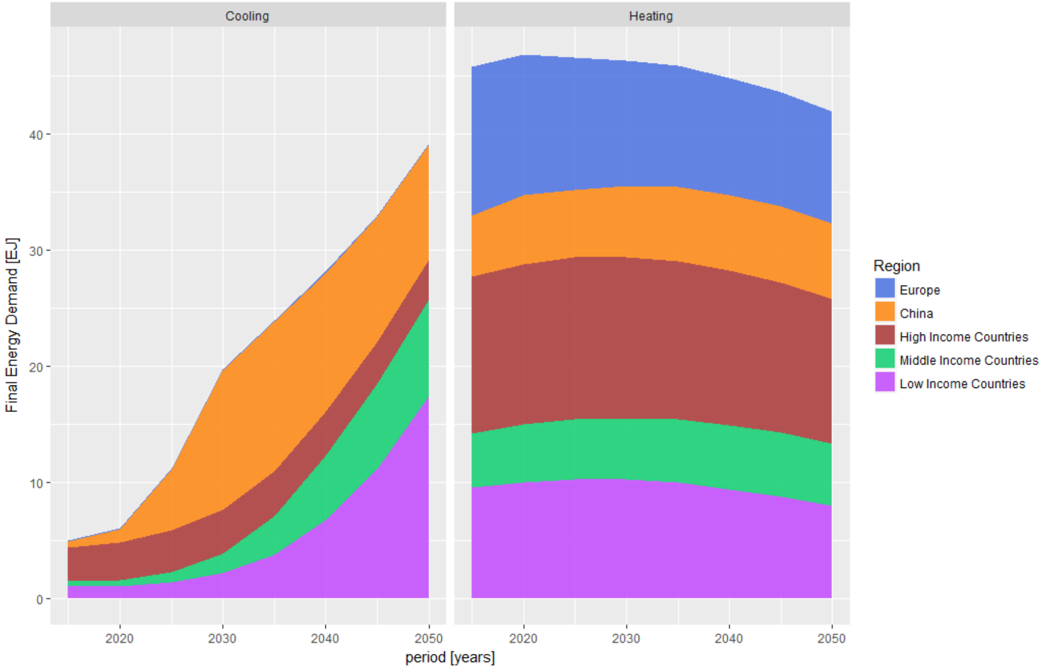

Figure 1: Heating and Cooling Final Energy Demand estimations, divided by groups of regions

European Policy for Buildings Directive objectives

In Europe, final energy demand is expected to decrease by 20% by 2050, if the current trends are followed. The implementation of the European Policy for Buildings Directive is expected to drop the 2015 levels of final energy demand by 80% in 2050. Four fifths of this 60% additional decrease comes from the renovation of old buildings. The implementation of this policy in Europe would make the 2050 total final energy demand further decrease by 10%: from 81 to 72.5 EJ. Implementing it all over the world would make the overall final heating demand decrease by 37 EJ with respect to the 2015 levels, while cooling demand would actually reach a peak and then decline, keeping in 2050 similar levels of 2015. Hence, the 2050 final energy demand would be approximately equal to 15 EJ: an overall decrease of 80% compared to the expected 2050 level. Increasing wealth and population levels in low income nations and China will similarly foster high levels of new construction as well, thus immediately implementing building codes can lead to significant energy demand reductions in the short and long term, given the long lifespan of buildings. Accordingly, China on its own would additionally save 6.5 EJ only by constructing nearly-Zero Energy Buildings from 2015 on, as figure 2 shows. A key difference from Europe is that most of the regions show that at least 50% of the 2050 final energy demand savings would be due to the implementation of a nearly-Zero Energy Buildings new construction stock, with this percentage raising to 80% in regions such as India and Africa. This means that most of the world countries would benefit on focusing mostly on new construction policies.

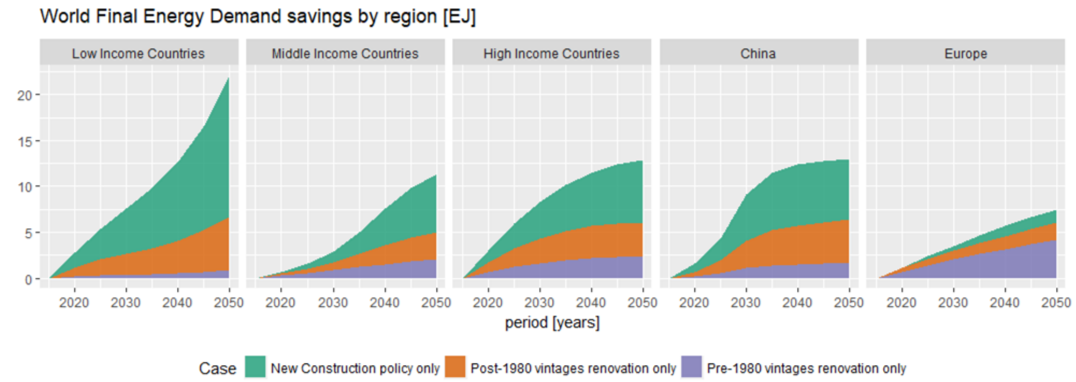

Figure 2: World final energy savings, divided by impact on the building stock

Energy price increase

Energy prices data were taken from [10], which also indicate the amount of fuel subsidies across different world regions. When implementing estimated energy price increases (+2%/y of electricity price, +2.8%/y for other carriers price until 2030 [11]) into the model, it results that additional 1.5 EJ would be saved from the 2050 final energy demand in Europe. If a stronger price increase of 4.3%/y [12] is implemented, the gap among the EPBD objectives and the expected trends decreases from 7.5 to 5 EJ, thus it is reduced by one third. Subsidies on energy prices do not basically matter in the European region: only 0.5% of the 2050 final energy demand would be saved if they are removed. This percentage instead raises much more at the global level, where around 3% of the 2050 final energy demand would be saved, with Middle East providing 55% of the additional energy savings, as can be seen from figure 5.12.

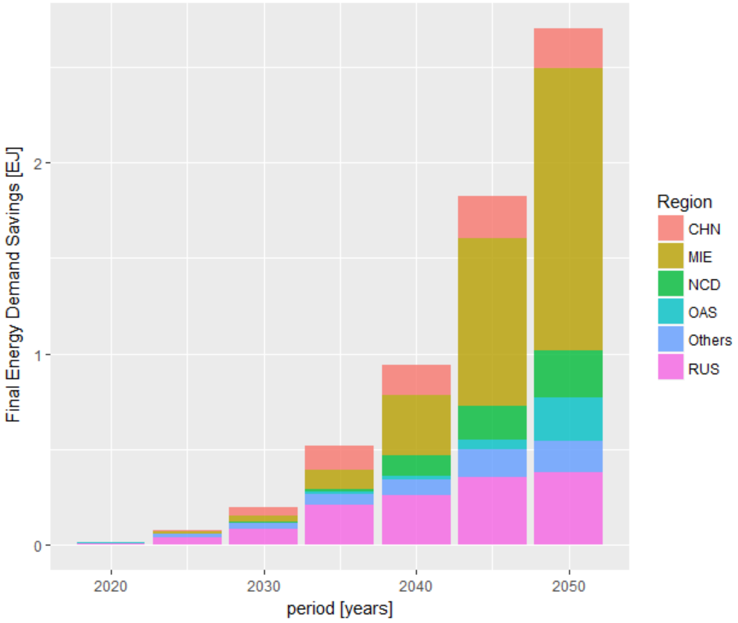

Figure 3: Final energy savings compared to the baseline, at the world level in case of subsidies reduction

Impact of parameter uncertainty

Uncertainty related to starting values of input parameters is eventually reflected in the calibration process, with the calculation of country-specific implicit discount rates, in order to match the 2015 trends. However, the development over time of such parameters is certainly not known, even if several assumptions can be found in the literature. Therefore, different tests were performed, making the most important parameters vary between reasonable ranges and accounting for the variation in results.

For reasonable ranges of technology cost decrease, every additional 1%/y reduction in cost is estimated to reduce the total final energy demand by 4 EJ in 2050. A progressive shift towards 100% market share of the best-performing technology is instead more important, eventually achieving final energy reductions of 7.9 EJ. In 2015, for the poorest regions of the world a 15% discount rate was computed. Assuming different rates of decrease of this parameter only slightly affects the results, since for instance the African income level remains really low, thus not stimulating increasing energy demand. Overall, the global 2050 Final Energy Demand increases by 2.1 EJ if no discount rate decrease is implemented, while it decreases by 2 EJ when a quicker reduction is assumed to happen. Developed countries showed an average discount rate of 5% from the calibration process. Increasing this parameter to a 7% level causes a global Final Energy Demand increase by 2.9 EJ in 2050, while convergence to a 3% level would cause it to be reduced by 3.2 EJ. Different levels of renovation rate strongly impact heating energy demand, since Europe is the region which is affected the most by this assumption. Total Final Energy Demand in 2050 changes from +3.5 EJ if no renovation happens to -2.4 EJ if renovation rates are tripled. Assumptions on the main socioeconomic drivers generate different dynamics across regions, which finally lead to similar levels of Final Energy Demand in 2050. If income levels grow and environmental awareness is raised, then developed countries will strongly reduce their heating demand, due to a less intensive use of heating equipment and to stronger technological development. However, developing nations will strongly increase their cooling consumption, due to increased wealth levels. Finally only when combining the best cases reported in the literature with increasing energy prices and renovation rates, the model estimates that the EPBD target set is ambitious but also potentially achievable.

Future Work

Further refinement of the model is required. The main points to be improved are here summarized:

- Improve the connection with the current EDGE model, in order to better match 2015 final energy demand, which is currently overestimated.

- Differentiate between renovated and non-renovated building shares within vintages, in order to improve the smoothness of transition when low U-values are reached.
- Improve the representation of available technologies, by differentiating on cooling and heating climate needs. The current model only implements increasing insulation levels in order to reduce final energy demand, which is the most suitable measure only for heating-based climates.
- Improve the representation of technologies, by differentiating on new construction and renovation costs and options, as IEA suggests [2]. For instance, it was remarked that improving energy efficiency levels of existing dwellings is generally costlier, unless it happens within a favourable opportunity, when the building is entirely renovated. Moreover, low-e coating application on existing window is the best option for renovation, compared to their replacement.

Contents

Acronyms

CDD Cooling Degree Days

EDGE Energy Demand GEnerator

EPBD Energy Performance of Buildings Directive

EPC Energy Present Cost

EPS Expanded polystyrene

EU European Union

FEC Final Energy Carrier

FED Final Energy Demand

HDD Heating Degree Days

IAM Integrated Assessment Model

IPCC Intergovernmental Panel on Climate Change

MNL Multinomial Logit

NPC Net Present Cost

nZEB nearly Zero-Energy Buildings

PLI Price Level Index

PBT Payback Time

PWF Present Worth Factor

SHGC Solar Heat Gain Coefficient

SIP Structured Insulated Panels

SSP Shared Socioeconomic Pathways

UED Useful Energy Demand

VIP Vacuum Insulated Panels

XPS Extruded polystyrene

Chapter 1

Introduction and Motivation

1.1 General context

Climate change constitutes a great issue humanity will have to face in this century. There is a wide recognition among scientists that increasing equilibrium temperatures of the planet are related to the emissions of greenhouse gases, caused by human activities. The Intergovernmental Panel on Climate Change (IPCC) states that humanity is currently estimated to have already caused approximately 1.0 °C of global warming above pre-industrial levels, this phenomenon will reach 1.5 °C between 2030 and 2052, with a probability between 66 and 100%, if it continues to increase at the current rate. Moreover, warming from anthropogenic emissions will persist for centuries to millennia, continuing to cause further long-term changes in the climate system. Risks across energy, food and water sectors could significantly overlap, spatially and temporally, thus creating new hazards that could affect increasing number of people, causing migrations and conflicts. In order to deal with this issue, two approaches should be followed at the same time, namely mitigation and adaptation. The former one is related to human intervention in order to reduce the sources or enhance the sinks of greenhouse gases. The latter one refers to undertaking actions in order to reduce vulnerability and exposure to climate change harmful effects [1].

The most relevant sources of greenhouse gases emissions are related to agriculture and land-use, industry, transport and buildings. Recent estimates of current emissions indicate that around 33-36 Gt CO_2/yr are emitted from fossil fuel industry, while land-use change accounts for an additional release of 3-8 Gt CO_2/yr. CO_2 sinks are instead related to the atmosphere, which retains one half (17 Gt CO_2/yr) of these emissions, while oceans absorb 7-11 Gt CO_2/yr and the remaining quarter (9-14 Gt CO_2/yr) is absorbed by the Earth biosphere. Global fossil CO_2 emissions have risen steadily over the last decades and the peak in global emissions is not yet in sight: projected rise in 2018 was around 1.8-3.7%. Furthermore, climate change is expected to affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere [13]. Political response to the climate change issue had not been as strong as it was required, however it has significantly raised in the recent years, particularly after the Conference Of Parties (COP) held in 2015 in Paris. In this occasion, the vast majority of the world nations agreed to undertake ambitious efforts to face the common issue of climate change. The objective is to keep the global temperature rise below the threshold of 2°C and to pursue efforts in order to limit the temperature even below 1.5 °C. In order to do so, the concept of carbon budget was created: it represents the amount of cumulated CO_2 emissions that should not be exceeded, within 2011 and 2100, in order to meet the Paris objectives. The total remaining CO_2 quota in order to limit global temperature rise to 2°C, with a 66% chance, was estimated to be 810 Gt CO_2 in 2016 [14]. Considering the current and expected future trends, significant efforts must be undertaken in order to reach this goal.

1.1.1 The buildings sector: challenges and policies

The buildings sector accounts for around one third of the total global final energy use and one half of the total electricity, which is linked to 20% of energy-related greenhouse gases emissions [3, 4, 2]. Buildings energy use is posing a primary challenge to sustainable development, due to the vast requirements of energy that current lifestyles involve. Energy consumption growth is driven by many factors, ranging from population increase, reduced household size and rising affluence, which cause increasing demands for improved thermal comfort and a wide variety of electricity-based services. Considering that increasing amenities in buildings will be required by a wealthier global population, the largest challenge will be related to satisfying future needs by means of employing sustainable energy resources. Therefore, key strategies to address these challenges are related to [4]:

1. Reduce the demand for relevant energy services while providing equal comfort;
2. Increase the efficiency, in order to reduce energy needs while providing the same service;
3. Use cleaner energy sources to fuel these needs.

Hence, buildings Final Energy Demand (FED) is expected to increase by 50% by 2050 if current trends are followed [2]. By contrast, there is a wide consensus that future final energy use in buildings may stay constant or even decline by mid-century, if today's cost-effective best practices and technologies are diffused [3, 4], with 40 exajoules that are estimated to be possibly saved in 2050 in the buildings sector through the wide deployment of best available technologies [2]. Globally, 30% of the building sector energy demand comes from heating and cooling, with this percentage raising to 50% in cold climate countries. It is recognized that in order to achieve energy demand reductions for the highlighted end-uses, improving the envelope insulation levels must be a very important step, since it also allows for downsizing of the heating and cooling equipment [2]. Looking at the thermal performance of buildings, the thermal conductivity of building envelope components (namely "U-value") is the representative parameter for the determination of energy consumption.

Worldwide, around 40 national governments have had building energy codes in place [5]. Building energy services affect a large variety of issues, such as energy security, particularly in regions where resources are imported. For instance, Europe imports most of the energy consumed in its buildings sector and each 1% increase in energy savings reduces gas imports by 2.6%. In the European Union (EU) , the main legislative texts are related to the Energy Performance in Buildings Directive (EPBD), which was established in 2010 and constitutes the major driver in policies and measures implemented in the residential and service sector, and the Energy Efficiency Directive (2012) [15]. Each member state sets the levels of energy efficiency requirements, but these levels have to be revised and updated, based on technological development [16]. The two policies aim at reaching two strict objectives for the future of the European building stock:

1. All new buildings constructed after 31 December 2020 must adhere to nearly Zero-Energy Buildings (nZEB) standards.
2. EU countries must draw up long-term national building renovation strategies, in order to transform the existing stock into nZEBs by 2050, particularly keeping an average refurbishment rate of 3% annually.

The energy consumption characteristics of the building sector are complex and inter-related [17]. Efficient and rational implementation of building stock CO_2 emissions reduction requires modelling of the most important drivers in energy demand development. Integrated Assessment Models (IAMs) were developed in order to analyse long-term climate mitigation strategies and have been looking at the potential of future efficiency pathways. Within the buildings sector, very long lifespans of buildings and retrofits leads to a very significant lock-in risk, resulting in inertia for policies energy efficiency. At the same time, there is a strong path dependency of choice made now for the future efficiency potential, pointing to the urgency of ambitious and immediate measures. While in OECD regions, approximately 75% of the current building stock will be still standing in 2050, income growth in developing nations is expected to drive high new construction rates [2]. Hence, renovation of the current building stock should be made a priority in the former countries, while the most important need in the latter regions is related to urgent enforcement of stringent building codes for new buildings. Therefore, when analysing long-term climate mitigation strategies, a thorough understanding of the building stock dynamics is required. However, while in IAMs used extensively for this purpose, energy efficiency in buildings plays an important role to meet set climate targets [18], the building infrastructure is generally neglected.

1.2 Research Questions and Methodology

This research work aims at examining a new modelling method, in order to represent the long lasting structures of buildings and evaluate decision-making in investment for improving the envelope energy efficiency where benefits play out in the long-term and require farsighted strategies. In this way, policymakers can be informed about which building parameters are key for national carbon reduction strategies, while the construction industry could develop business strategies for sustainable refurbishment [6]. The main methodological tool employed in this work is the Energy Demand GEnerator (EDGE) buildings model, developed by the Potsdam Institute for Climate Impact Research (PIK) in order to assess buildings' energy demand across the 21st century [19]. By means of scenario analyses, the impact of building policies, focusing specifically on the stringent European policy ambitions in the evolution of global energy demand until 2050 is assessed, outlining main benefits and gaps with the current trends. In particular, 5 main questions are addressed:

1. How can building stock and insulation dynamics across regions combine and affect the world final energy demand until 2050?

2. What is the current gap between the European Union buildings policy objective and the estimated future trends?

3. What is the amount of final energy saved if the rest of the world follows Europe policies? What is the relative impact of each region?

4. What is the role of subsidies on energy prices both at the European and at the world level? To what extent can an increase in energy prices help Europe reaching the EPBD objectives?

5. To which extent will uncertainties on future discount rates, technology improvement, market heterogeneity, renovation rates, future climate change and socioeconomic drivers either hamper or help reaching these objectives?

1.2.1 Methodology

In order to answer the 5 key questions, the existing global buildings model EDGE has been employed. It can be defined as a bottom-up, statistically-based simulation model, which is multi-regional and employs a long-term point of view. It has been extended with a building stock module, in order to include the representation of the development over time of building vintages. As a further step, within this work, investments on insulation measures are integrated into the existing model. In this way, the research focuses on energy efficiency dynamics that vary over time and space. Finally, the implications of the model extension on the global energy demand are assessed.

Given the scale of the issue, both in time and in space, poses several difficulties, which were solved choosing the right trade-offs between detail and complexity. Several simplifications had to be made in order to firstly keep the model simple and the results understandable. Furthermore, assumptions had to be made, due to lack of data. In order to achieve the objectives, this work has been carried out by means of:

- *Literature Review*: with the aim of understanding the main drivers of renovation investments and outlining possible policy measures to spur the improvement of energy efficiency in buildings. In addition, indications on state-of-the-art and future perspectives insulation technologies were researched.

- *Data Analysis*: historical data on residential building thermal performance, gathered by the EU commission database [7] were analyzed, to understand the main determinants of the insulation levels over regions and time. Moreover, a regression analysis tested the influence of several variables on U-values development.
- *Frequent feedback from PIK research institute*: to develop the new module in the most consistent way with the philosophy of the general EDGE model;
- *New model testing and comparison with previous version*: based on the collected information, the current EDGE U-values module was reviewed and updated. First diagnostics of the results were carried out, in order to understand the sensitivity that the new module calculations showed with respect to input parameters. Then, the model had to be extended to the global level and a lack of data was encountered, compared to the wide amount of detail the European region presented. Therefore, by means of both region-specific indications from the literature and assumptions based on European trends, input data were computed for all the world regions. In order to match the 2015 historical trends, a calibration was performed. Then, comparison with the previous model results was carried out, in order to outline the impact of the new modules in the estimation of U-values development and to correct possible strong biases. In order to increase the reliability of results, a comparison with estimated past European trends of insulation levels was performed.
- *Scenarios and robustness analysis*: main results were derived and discussed, with a focus on the different parameters impact across regions and time. The estimated magnitude of FED trends in 2015 is compared to historical data, in order to outline possible issues that might emerge with the connection to the main model. The EPBD is then simulated both at the European and at the global level, in order to respectively quantify existing gaps with the current trends and to evaluate how the total energy demand would develop if this policy is applied to each world region. Finally, the robustness of the results is checked by means of an extensive sensitivity analysis, in order to account for uncertainties in input parameters.

1.2.2 Thesis structure

The structure of the thesis report is the following:

- In Chapter 2, a literature research on renovation investment drivers is discussed. Moreover, the most recent data on building envelope insulation levels are analyzed. Then, the state-of-the-art and future perspectives of the current building envelope technologies is presented.
- In Chapter 3 a general description of IAMs is performed, focusing on the EDGE model, which was used in this work.

- In Chapter 4, improvement of the EDGE model is presented, with the implementation of the building stock and U-values module. A discussion on main parameters and input data is provided, then a comparison with the previous module results is performed.
- In Chapter 5 the main results on estimated future demand of energy for space heating and cooling are discussed. Then, a simulation of the EPBD policy and the role of energy price increase is performed.
- In Chapter 6 an extensive sensitivity analysis is discussed, with the impacts of input parameters variations on the estimated future energy demand trends.
- Chapter 7, summarizes the key findings and outlines suggestions on required future developments.
- The Appendices contain additional information which can be useful in order to gain a thorough understanding of the results. Appendix A contains information on the extensive literature review regarding insulation levels all over the world, which were eventually implemented in the new module. Finally, Appendix B explains the details of the performed regression analyses.

Chapter 2

Building Envelope State Of The Art

In Europe, the increasing share of renovation activities over the total building works from the '80s lead to a growing need of predicting refurbishment demand, especially driven by energy issues. Therefore, several studies on the evolution of the building stock were implemented. The traditional approach to gather knowledge about this topic was represented by housing surveys, for planning and assessment of state interventions. Newer engineering models have been developed in the last decade, accounting for the whole country building stock [20].

This chapter introduces the wide literature review and data analysis which was performed and constitutes the basis of this thesis work, to be employed in the following chapters. Given the importance of the already existing building stock in Europe and in general in developed countries, section 2.1 provides a deep insight on typical barriers for renovation investment decision at the household level, together with the main policy options which are available in order to trigger the improvement of energy efficiency in buildings. Section 2.2 introduces the U-value, which is one of the basic parameters employed to evaluate the building envelope thermal performance, and summarizes the current state of U-values data collection in Europe. Section 2.3 provides an investigation of the current European building stock, by means of indications from the EU main projects and data analysis, with the aim of highlighting key characteristics and the main determinants of U-values over regions and time. Based on the collected indications, a regression analysis is performed in section 2.4, in order to quantify the impacts that different predictors have on U-values improvement. Finally, section 2.5 summarizes the state of the art in building envelope technologies.

2.1 Energy efficiency drivers

The economic, technical and behavioural factors influencing investment decisions on energy efficiency improvement are not still well understood, thus policies have not been able to correctly tackle them. In Germany, between 1989 and 2006, only 30% of all the possible energy-efficient renovations were implemented in residential buildings built between 1900 and 1970 [21]. The category of drivers that can influence this type of decision is wide and the impacts of different factors show a great variability, depending on the considered study. In order to increase renovation rates, several instruments are available for the policymakers, with different advantages and drawbacks.

Drivers and barriers

Following the indications of [22], the most important renovation drivers are here classified and the main remarks are outlined. Among **technical** factors, buildings age is recognized to be a significant driver of energy-efficient retrofits, which are more likely to happen in the context of older buildings.

Location-specific drivers are also found to be important: indeed, colder and rural areas are more likely to retrofit [23, 24]. A greater ability of rural household to retrofit by themselves is a possible explanation [23]. Moreover, in the urban environment, a busy lifestyle linked to a high cost of time may result in a higher perceived hassle caused by renovation investments, therefore leading to a 3% decrease in probability to invest for London citizens. Furthermore, the proportion of flats in the cities is higher, therefore heating demand is lower compared to detached rural houses. In addition, urban households may have greater access to cheaper fuels such as gas. Finally, [24] outlines that compared to other locations in the UK, the London region has the highest percentage of gas pre-payments, and the second greatest percentage of electricity pre-payments. Since they are probably less aware of their energy consumption, they are less willing to invest as well.

Among **behavioural** factors, environmental awareness and attitudes are recognized as important drivers. Household *expectations* on energy savings and *perceptions* of comfort are more important than technical detailed information which can be provided by audits. Switching costs are associated to any change: in general, risks linked to the status quo (e.g. higher future expenditures on energy) are evaluated to a lower extent, compared to hassles related to energy efficiency improvement (e.g. high investment costs) [8].

Within **household** socio-economic characteristics, drivers impacts appear to be mixed. For instance, a higher income is associated to increased loan-taking capabilities and savings potential. However, some studies found that richer household presumably pay less attention to energy expenditures, since these constitute a lower share of their income. Other sources show significant influences of household age, with older people being less prone to investments that spread their benefits over a long lifetime, and education, which is linked to greater capabilities of gathering information. However in general, *socio-economic variables lose their explanatory power when accounting for the role of other factors relating to everyday life conditions and income.* Instead, decision-making processes really matter in this context: the *landlord-tenant* dilemma [23, 8] constitutes one of the most important barriers to insulation improvement. It is linked to the house status of occupation: rental or ownership. Indeed, in the first case, energy savings benefits would be split between the landlord and the tenant (with the former paying for the upfront costs and the latter receiving the benefits of increased energy savings, thus paying lower bills), hence reducing the probability of energy retrofits. It should be noticed that income may be linked to this dilemma: [24] states that 70% of household belonging to the two (out of a total of 5) highest levels of income are owner-occupiers. Another situation in which interests must be split over several groups is related to multi-family buildings: in this case, owners depend on each other for the renovation investment, therefore the complexity of the decision making process is higher than in single-family houses. Moreover, even when insulation retrofit measures are evaluated as convenient from an aggregate point of view, the energy savings levels may be different across stakeholders, depending on their usage patterns (i.e. households which higher energy consumption will experience greater benefits).

Finally, **economic** factors involve the most critical barriers to renovation, which are linked to upfront costs and the investment *payback time* (PBT), with the latter one being the only relevant factors across 9 European countries [8]. PBT is the amount of time required for the discounted energy savings to equalize investment costs. Therefore, calculation of the profitability of an investment requires assumptions on the households' discount rate, which is found to be decreasing with income [23] (an extensive discussion on discount rate is provided in section 4.4.3).

From the point of view of the thesis work, the most important remarks will be now summarized:

- Renovation drivers are interrelated and cause-effect relations are not always fully clear.Due to this, some drivers can be considered as proxy for others, depending on the data availability. Income data are greatly available and can be used as a proxy for house ownership and lower debt aversion.

- In general, energy efficiency improvement decisions were shown to be carried out in the context of *favourable opportunities*: in a case study in Germany [21], 46% of the energy efficiency improvement measures were taken because a renovation of the house would have been taken in any case (e.g. for maintenance issues or structural repairs). Another favourable opportunity to invest can be met by households having recently moved in the new house [23].

- The impact of different drivers on the renovation decisions varies according to the considered country and few factors (i.e. buildings age, investment upfront costs and PBT, house status of occupation) can be considered as being the most important ones whatever the case is. Indeed, different weights of the same drivers are due to the specific country situation: since energy prices in former socialist countries, as Slovenia, are low, households showed no concern about this factor [22]. As can be deduced, financial barriers represent a greater obstacle in European eastern countries, which are poorer. In Slovenia, homeowner age and financial constraints were estimated to be the most significant barrier [22]. However, [21] argues that in Switzerland, households decisions were found to be largely responsive to technical (building age) and occasional factors (building space extension) rather than income, age or education. Moreover, a study using U.S. household data found that retrofit costs, energy prices and income were the most important drivers. Moreover, while households that have to pay a loan for the house purchase were found to be less prone to energy-efficient retrofits, due to increased financial constraints, in Slovenia [22], this was not the case in the UK [24], where mortgagors showed a 4% increased probability of investment, probably due to lower debt aversion and to a presumable intention to stay in the current home for a long time. Therefore in any case, a selection of renovation drivers would always implies *omitted variables* issues.

- Renovation impacts should not only be defined in terms of extensive indicators (e.g. number of households which renovated), but also in terms of *intensity.* A smaller number of households implementing deeper renovation measures can lead to the same amount of energy savings as a higher number of shallow renovations would do [23].

- This thesis focuses on building envelope, however energy efficiency measures also imply improvement of other building components. Indeed, household can also choose several paths to reduce their energy consumption. Therefore they might respond to increased energy prices by changing their heating equipment, instead of increasing insulation levels [22].

Policy measures

Addressing the most important drivers, according to the context, can help setting up the most effective policy, in order to improve the already existent building stock thermal performance. In order to increase renovation rates, several instruments are available for the policymakers, with different advantages and drawbacks.

Information measures tackle the lack of knowledge regarding available renovation options by means of different channels, such as awareness campaigns or energy audits, yet their impact appears to be mixed, with some studies questioning their effectiveness. For instance, it can be said that energy audits favour energy-efficient retrofits. However, endogeneity issues arise, if it is forgot that households considering this type of investment are more likely to seek advice on energy savings [22]. Indeed, lower income and less educated households, with lower attitude on considering energy-efficient retrofits, are less likely to be users of audits, while they represent the group which would need the most such information.

Subsidies are designed to overcome financial constraints, but their effectiveness is often questioned, due to substantial free riding effects. In fact, in a remarkable number of cases, retrofits would have been deployed in any case, with or without policies, thus leading to low cost-effectiveness. The share of free-riders is certainly not negligible: for instance, it was found to be around 40 to 70% in France [23] during the application of the "Sustainable Development Tax Credit", while being around 50% in Mexico as well, during a national appliance replacement program and 50 to 80% in case of Canadian natural gas furnaces [15]. Even though these measures show a positive impact, there are not many conclusive evidences on the energy efficiency improvement or CO_2 emissions reduction induced specifically by the analyzed policy [15].

Regulatory policies are found to have an immediate impact on energy demand reduction. However, these can lead to dangerous side effects: if for instance the cost of new houses increases due to the implementation of stricter efficiency regulations, then the demand for existing house rises, thus their prices will increase as well. Hence, households will have less money to renovate their current homes. Moreover, the increased monetary value of existing buildings might obstacle their demolition. Another undesirable outcome is linked to the rebound effect, which is associated to a more intensive use of more efficient equipment. Overall, these effects may eventually lead to the permanence of buildings which are poorly performing in the stock.

Taxes that increase energy prices were found to be effective, since it is indicated that people respond to savings due to increased energy costs in the future. Moreover, energy prices increase helps mitigating rebound effects. The relatively low levels of energy taxation for residential use compared to automotive energy implies that there are still many opportunities to be grasped in the sector to improve energy efficiency. Indeed, in the first quarter of 2014, in the EU-28 the share of taxes on natural gas and heating oil was around 25%, while the tax share on automotive diesel and gasoline was about 55% [15]. However, energy poverty is still an issue in some European countries, such as Portugal [25]. Households which already experience low levels of thermal comfort (in Bulgaria, 40% of the population cannot afford to keep its house adequately warm [7]) would be further penalized by an increase in energy prices, therefore concerns on distributional effects have to be tackled, by means of a well-designed use of additional tax revenues. It is also important that renovations with minor energy savings are taxed, rather than subsidized, since they can induce a *lock-in* effect, represented by the permanence of buildings with rather inefficient performances. As will be further explained in section 4.6, when some insulation is already installed in a building, the PBT of further renovation investments strongly increases, thus representing an obstacle to achieving very high levels of efficiency, such as the ones envisaged by the EPBD targets (see chapter 1).

2.2 U-values

The thermal conductivity of building envelope components, namely *U-value* is one of the most important parameters for the determination of energy consumption. Thermal insulation works by resisting heat flows by conduction, convection and/or radiation[16]. The average building U-value is calculated considering the mechanisms involved in the heat transfer between an internal environment, with a controlled temperature, and the external one. These include internal and external convection, in addition to the thermal conduction across the building envelope, according to equation 2.1:

$$U[\frac{W}{m^2K}] = (\frac{1}{h_{ext}} + \frac{s}{k} + \frac{1}{h_{int}})^{-1} \tag{2.1}$$

being h $[\frac{W}{m^2 \cdot K}]$ the convection heat transfer coefficient, for either internal or external side of the wall, $s[m]$ the wall thickness and k $[\frac{W}{m \cdot K}]$ the wall thermal conductivity.

Once this parameter is calculated, yearly energy demand for space heating services can be computed, being it directly proportional to Heating Degree Days (HDD), building envelope external area and U-value. Space cooling energy consumption is determined in the same way, yet with Cooling Degree Days (CDD) instead of HDD [1]. By means of this formulation, heat transfer across building envelope is approximated. A higher detail on modeling the dynamics of building heat flows would reveal that a greater building heat capacity can delay indoor temperature variations, compared to the external environment, thus causing a reduction in energy demand. Moreover, internal gains and solar heat gains also affect indoor temperature. Finally, 25% of the most important heat transfers occur through ventilation [16]. However, according to the analysis performed in [26] across four different European countries, the building envelope properties have the second highest impact on the energy demand, being the first related to the minimum indoor temperature, which is considered in the determination of the threshold of HDDs.

In order to gather knowledge about building energy requirements, several projects were developed at the European level. In particular, the following ones focused on the building envelope characteristics, thus collecting data on U-values:

1. DATAMINE: the final report was released in January, 2009. The project starting point was related to the lack of knowledge regarding the current state of the European building stock and retrofit processes. Therefore, model projects were carried out in 12 European countries, in order to gather experience in data collection and analysis, together with harmonization of monitoring system. This project developed a common data structure across EU countries. Therefore, once representative levels of U-values for buildings, which belong to different construction year vintages, were determined for each country, both a cross-country and a cross-vintages comparison was possible [27].

2. TABULA: the final report was released in October, 2012. By means of building typology approaches used in the last decades in several European countries, a common concept was developed. This eventually resulted in the creation of national building typologies for 13 European countries (later extended to 20, with the inclusion of new nations), which contains information on several parameters related to buildings. The most important detail is related to the efficiency of the

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[1] HDDs totalize daily external temperatures below a defined threshold, assumed to be the point in which consumers turn on their heating system, over a conventional heating period. Conversely, CDDs sum up daily external temperatures above another threshold, assumed to be the point in which consumers turn on their cooling system, over a conventional cooling period. They are both expressed in [K*day]

envelope across vintages of construction [28]. A database was also developed [29], containing, among the others, information on separated components U-values (4 groups: external walls, roof, floor, windows), with indications on average components areas shares in the country building stock. Buildings are classified into several vintages, according to the year of construction: starting from a pre-1900 vintage, groups of 10 years are considered. Information on the residential sector only is available, but indications for the non-residential sector can be found in the TABULA final report [28]. 20 countries participated in this project.

3. Entranze: reports were produced in 2014. Its objective is to support policy making to achieve a fast and strong penetration of nZEB and renewable heating and cooling systems within the existing European building stock. The analyses were carried out for the EU-28 countries and Serbia.

4. Inspire: this project ended up in September, 2016. It represents a four-year collaborative research effort, funded by the European commission, with the objective of developing systemic renovation packages designed to reduce the energy consumption of existent buildings down to 50 kWh/m^2/year. Moreover, it also provided a full analysis of the current European building stock of 27 European countries, especially divided into residential and services sub-sectors [30].

5. Zebra 2020: This project focuses on tracking the market transition to nZEBs, to derive recommendations and strategies for the building industry and policy makers and to accelerate the market uptake of nZEBs. It covers 17 European countries and about 89% of the European building stock and population [31].

This led to the publications of several papers about data collection and estimations within the different nations. Moreover, a database has been developed by the European commission [7], collecting information from national agencies and the latest projects. U-values information from this source will constitute input data for the model improvement, presented in chapter 4. Table 2.1 outlines the analyzed regions.

Austria (AUT)	Belgium (BEL)	Bulgaria (BGR)	Croatia (HRV)
Cyprus (CYP)	Czech Republic (CZE)	Denmark (DNK)	Estonia (EST)
Finland (FIN)	France (FRA)	Germany (DEU)	Greece (GRC)
Hungary (HUN)	Ireland (IRL)	Italy (ITA)	Latvia (LVA)
Lithuania (LTU)	Luxembourg (LUX)	Malta (MLT)	The Netherlands (NLD)
Poland (POL)	Portugal (PRT)	Romania (ROU)	Slovakia (SVK)
Slovenia (SVN)	Spain (ESP)	Sweden (SWE)	Great Britain (GBR)

Table 2.1: European commission buildings database regions

The following list indicates the main characteristics, of the U-values section data collection:

- Data are related to both aggregated envelope and single components U-values (divided into external walls, floor, door, windows, roof, skylight), with no indication on the share of areas related to each single component;

- Buildings are classified into 7 vintages groups[2], starting from a pre-1945 group, according to the year of construction;
- Information on both the residential (from Entranze project) and non-residential (from Inspire project) sub-sectors is provided;
- Data collection was performed twice: first in 2008, then in 2014. Thus, a comparison between these two years may give indications on the evolution of the countries building stock across the years.

In addition, there is a wide range of indicators which are not only related to insulation levels. Therefore, there is a sufficient level of detail to carry out an analysis of building thermal performance over the past decades.

2.3 European building stock

Starting from the indications arising from the main projects which were previously outlined, the characteristics of the European building stock are analyzed. Moreover, the most representative charts from the EU buildings [7] and TABULA [29] databases are presented. 4 main characteristics of the EU building stock insulation levels are investigated: firstly, section 2.3.1 analyzes the evolution of U-values over time, while section 2.3.2 examines the differences across residential and non-residential sub-sectors. Then, section 2.3.3 outlines key remarks on the distribution of U-values in the building stock. Finally, section 2.3.4 explores the impact of climate on average insulation levels across countries.

2.3.1 Development over time

Data collected by European projects outline a general improvement of thermal envelope quality over the last 100 years. In particular, only a slight decrease happened until the seventies, while a remarkable drop occurred in the following decades. DATAMINE [27] outlined that strong decreases in U-values are associated to more recently constructed buildings and this holds true particularly for walls and roofs. However, the dependence for windows is actually low for all countries, probably due to the fact that these components can be more easily renovated, thus a great part of them may have already been replaced by more efficient components in 2009, when the project was executed. Warm European countries still show the presence of single-glazed windows in their building stock.

An important remark of the final DATAMINE report regards data quality, which is something that will be further discussed in 4.7 about Italy. It is outlined that the collected U-values do not always reflect the actual envelope thermal performance, since they are only sometimes calculated with detailed information on materials thicknesses and conductivities, while in other cases they may have been just assessed

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[2] The EU database vintages groups are the following: pre-1945; 1945-1969; 1970-1979; 1980-1989; 1990-1999; 2000-2009; 2010-2014

by means of default U-values depending on the construction type and building age. Hence, differences in the evaluation procedures across countries can have an effect on the data, which cannot be split from the actual differences in thermal performances [27]. Threfore, in order to confirm what emerged in this project, data on the residential sector U-values are now analyzed from both the TABULA and EU databases. Considering 2 databases leads to a more comprehensive analysis, thus increasing the robustness of the conclusions which are derived in this section. In order to facilitate the interpretation of charts, each vintage will be assigned its upper limit (e.g. buildings constructed before 1945 were assigned the 1945 value, while buildings related to the 1970-1980 period were given the 1980 value). Looking at figure 2.1, several main characteristics can be underlined, related to the development of insulation levels, for different components, over buildings construction year.

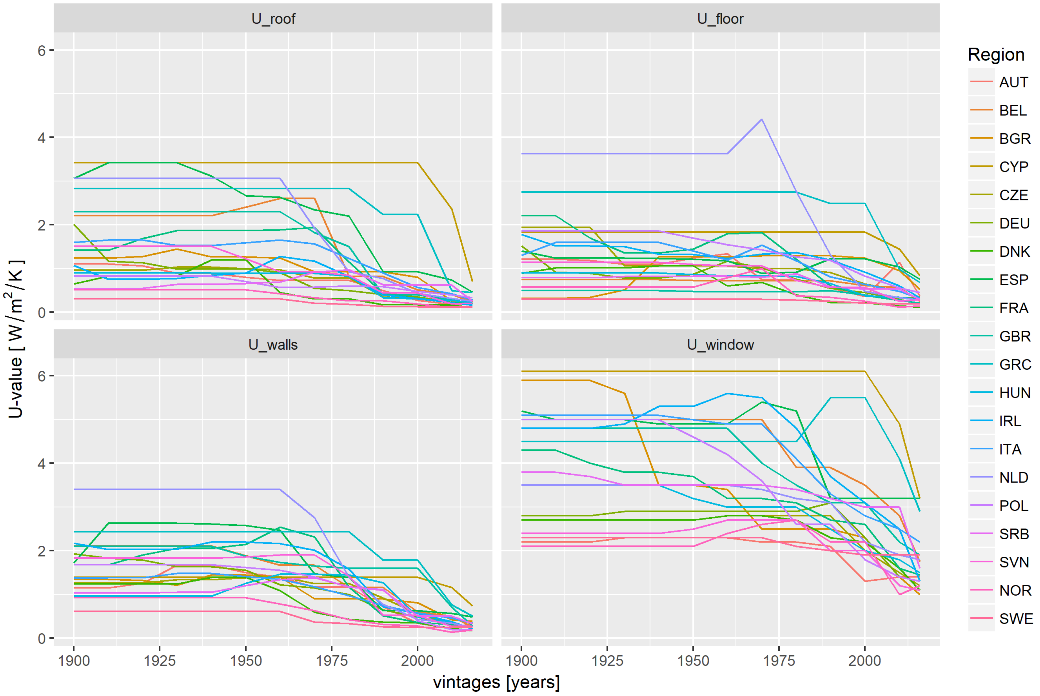

Figure 2.1: U-values development over construction year, TABULA database [29]

It can firstly be seen that insulation levels of vintages related to the pre-WWII period, show mixed results, with both increasing and decreasing trends at the regional level, but no generally significant decrease. Moreover, they are also greatly dispersed. The literature [32] indicates that the implementation of several EU policies (especially after the 1980 oil crisis) made U-values of new buildings progressively decrease in all of the considered countries. This is confirmed by the considered chart: there is a general convergence of U-values to much lower levels for the newest buildings. Moreover, this is particularly true for opaque surfaces components, that shift from an initial interval ranging from 0.5 to 3.5 $W/m^2/K$, to a much lower span of 0.1 to 0.5 $W/m^2/K$. This completely agrees to what was underlined in the DATAMINE project. For windows U-values a general decreasing trend can be observed as well, yet U-values remain higher and the convergence is less clear, with an initial U-values span of 2 to 6 $W/m^2/K$ that shifts down to 1 to 3 $W/m^2/K$. This can be also due to the characteristics of glazed surfaces, which currently present important challenges in improving their thermal performance, as will be described in section 2.5.2.

Finally, it must be remarked that non-monotonic trends also arose in the post-WWII period, with some vintages showing worse thermal performances than the previous ones. In particular, this happened more frequently for windows U-values. Possible reasons for this deviations are most probably related to different levels of renovation across vintages: replacement of window components may have caused oldest vintages to show lower U-values compared to more recently constructed buildings, as DATAMINE outlined [27]. However the general trend over construction years is decreasing, for any of the considered components and regions, with the newest vintages always showing lower U-values than the pre-WWII ones.

After this analysis, data from the European commission database can be examined from figure 2.2. At a first look, general decreasing trends still hold true, yet the U-values convergence over time results to be less clear, compared to the previous chart. As in figure 2.1, glazed components show a higher degree of dispersion, which in this case can be referred to as a divergence, since the U-values span actually increased over time. Reasons behind these differences can be firstly found in the analyzed regions: Malta is present only in the European commission database, for instance. This country shows very high U-values even in the newest vintages, especially because single-glazed windows are still being installed, again confirming the indications from DATAMINE [27]. The remaining nations actually present the convergent trend that has already been outlined. Some increasing trends can be noticed again, even if they are only related to a few countries.

2.3.2 Residential and services sub-sectors

The EU building stock is quite heterogeneous. Across all countries the majority of the floor area is composed by residential buildings, but the share varies considerably, going from 60-65% in Romania, Lithuania or Czech Republic to around 85% in southern countries such as Cyprus, Malta and Italy [33]. The Inspire project provided data for the European commission database, regarding sectors other than residential. Looking at its final report, it is only stated that the office sector is generally younger than the residential one, with no indications regarding differences of thermal envelope performances [30]. The TABULA report also presents a small chapter on non-residential buildings. It actually highlights the difficulties arising when trying to classify this sector, due to the variety of uses and characteristics. It is outlined that data from official statistics are generally poor, therefore once again, knowledge regarding the European building stock is small.

A closer insight into the available data actually confirms that no noticeable differ-

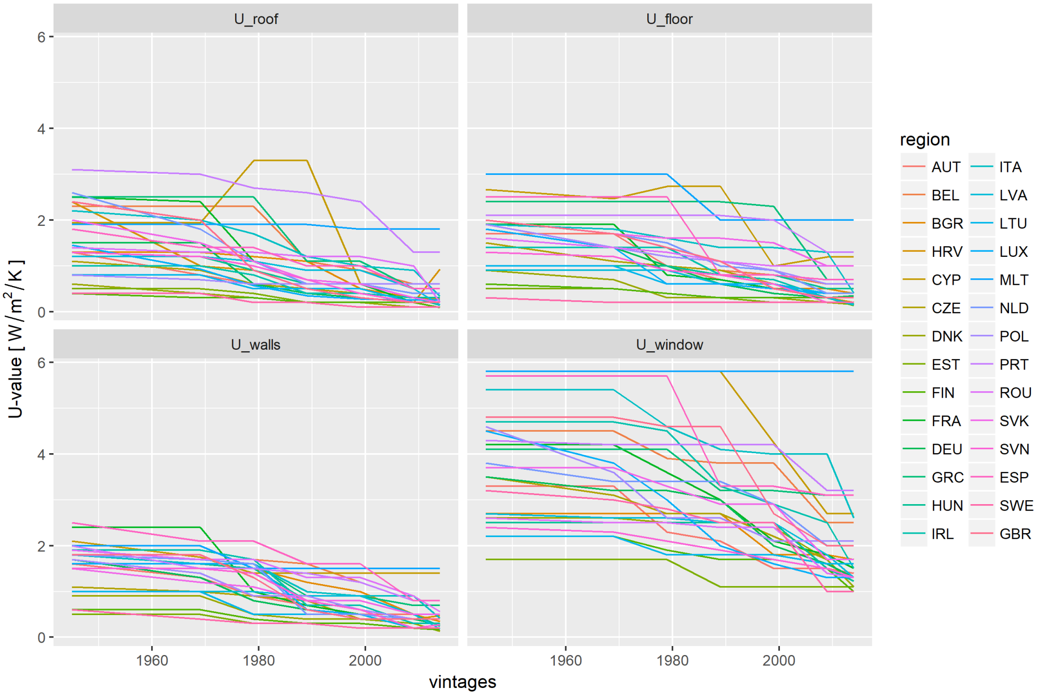

Figure 2.2: U-values development over construction year, European Commission database

ences arise from the comparison of U-values related to different sub-sectors, as can be seen from figure 2.3. A comparison at the envelope level is also required, since,

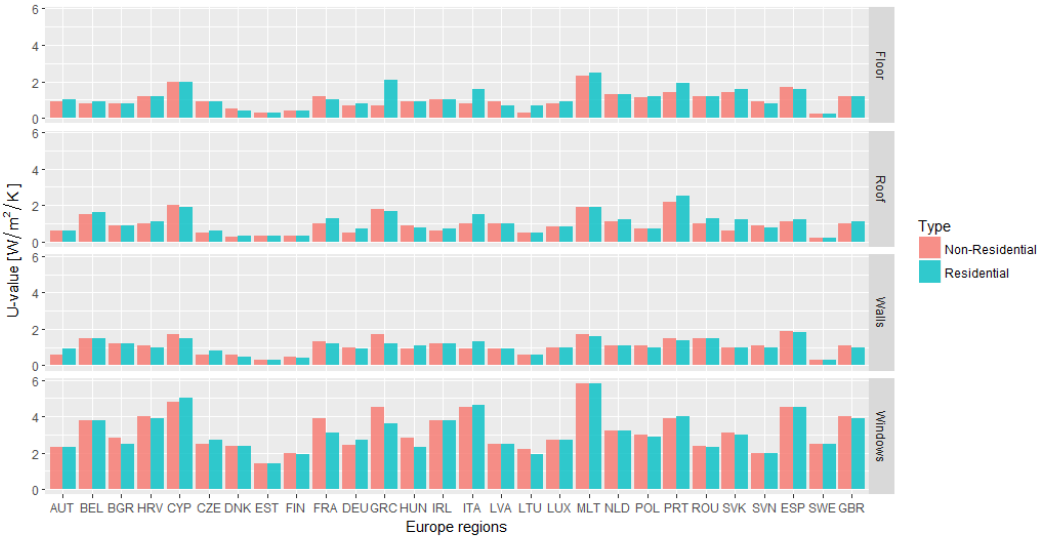

Figure 2.3: Country-level U-values of different envelope components, for the residential and non-residential sector (European Commission database)

for instance, it might happen that non-residential buildings present higher levels of window-to-wall ratios. However, figure 2.4 outlines no difference again, in the U-values of buildings belonging to these sectors.

Continuing the discussion, one last check has to be performed. Indeed, even if the

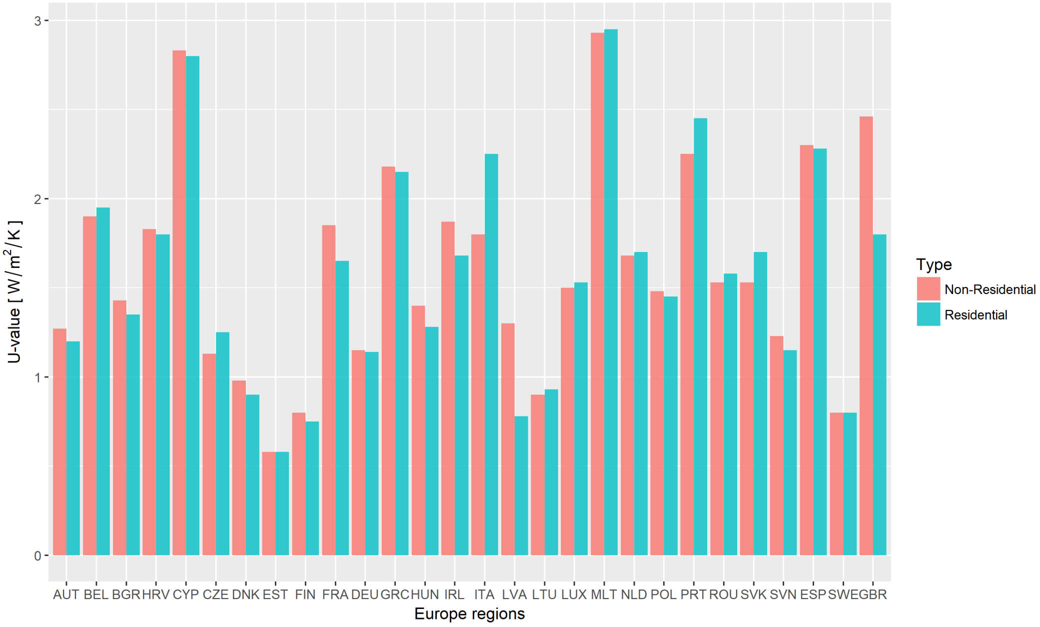

Figure 2.4: Country-level envelope U-values, for the residential and non-residential sector (European Commission database)

aggregated country U-values are similar, both at the components and at the envelope level, some differences across vintages may arise. For instance, it might happen that in the non-residential sector, older vintages get higher levels of insulation, while having lower thermal performances in the newest one. Figure 2.5 seems to confirm that no differences arise between these sectors, even across vintages. A regression analysis was performed and further justified the conclusions that have been drawn. Details on the procedure and results can be found in appendix B.

2.3.3 Buildings frequency distribution

Many reported data report average U-value levels, yet the distribution affects also the renovation potential, since it gives indications on the fractions of buildings that have already a good level of insulation. As can be seen from figure 2.6, in some databases a small range of U-values occurs, while in others a broad spectrum with two peaks occurs. The latter aspect is basically related to the presence of two types of surfaces: with and without insulation.

The resulting U-values depend on the initial thermal performance of the wall, named U_0 in equation 2.2, which in turn depends on the geometric and thermal characteristics of the different layers which constitute the envelope, according to 2.1. This is related to the construction types of the selected country, therefore it can be the reason why Germany and Poland show distribution peaks at different U-values levels. Since insulation material is applied with a minimum thickness, there are certain ranges of U-values which are not commonly found. This is due to equation 2.2, which outlines the functional form of the relation between the resulting U_{value} and the added insulation

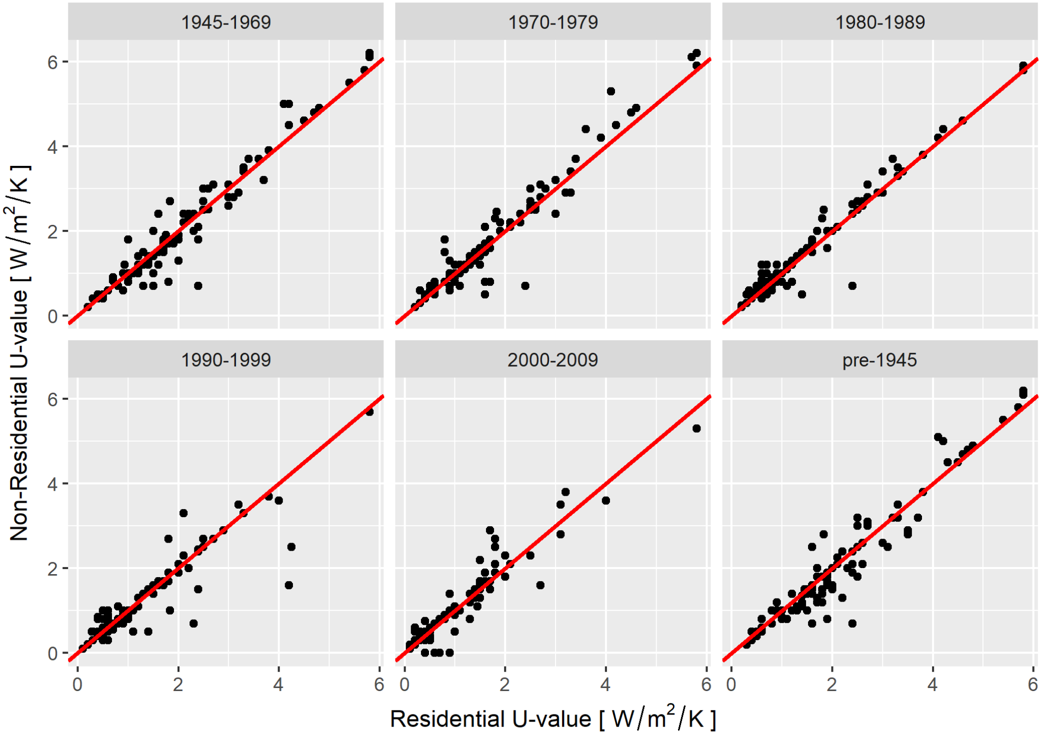

Figure 2.5: U-values related to different vintages, for the residential and non-residential sector (European Commission database)

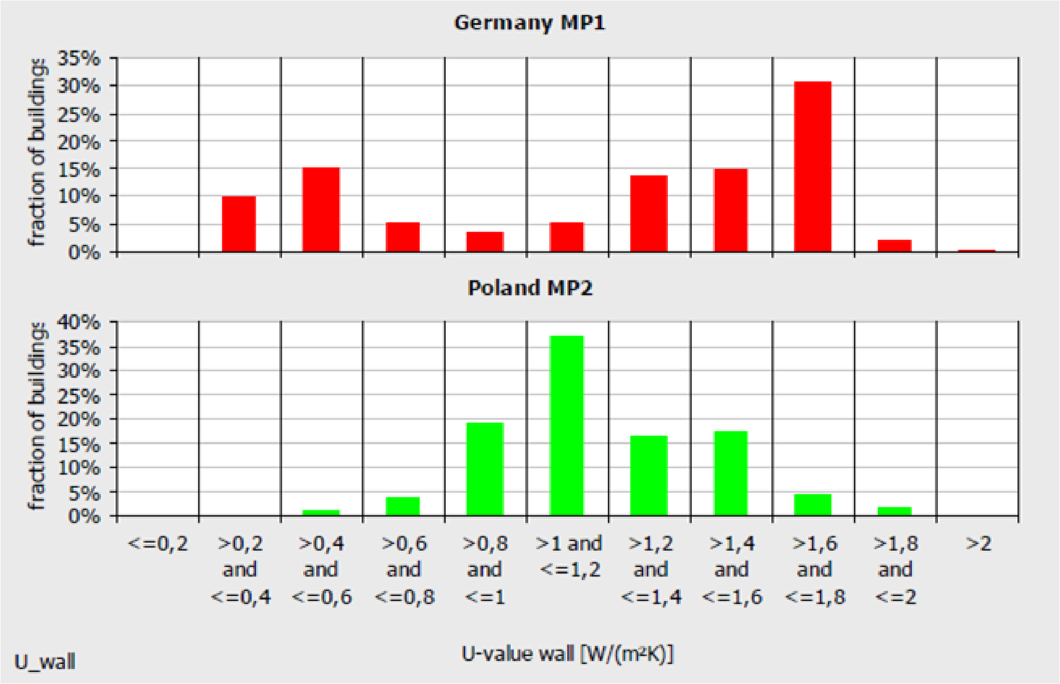

Figure 2.6: Frequency distribution of walls U-values [27]

thickness s [m] and thermal conductivity k [W/m/K].

$$U_{value} = \frac{1}{\frac{1}{U_0} + \frac{s}{k}} \tag{2.2}$$

It can be seen that s and U_{value} are inversely proportional. Moreover, k is around 0.03 W/m/K, for conventional insulation materials. Therefore, the ratio of k to s, which represents the added insulation U-value, can be quite small even for a few centimeters of thickness, considering that surfaces with no insulation show U-values in the range of 1.8-2 W/m^2/K, as can be seen for Germany. This is clearly highlighted in figure 2.7, which was computed for a wall with an initial U-value of 2 W/m^2/K, to which is added an insulation layer of variable thicknesses. According to the added U-value, different levels of U-new are reached for the considered wall. What this figure firstly outlines is that once some insulation is added, even for small thicknesses, the U-value undergoes a steep decrease, becoming one fourth of the initial value for 5 cm only of new layer. Adding 5 cm more contributes to further halving the wall U-value, while from 10 to 20 cm of added insulation no significant improvement of the thermal performance is reached. Therefore, the first remark is related to the noticeable U-value improvement for only 5 cm of added insulation. Due to the function steep decrease, Germany, does not show many buildings with U-values of around 1 W/m^2/K. This is then linked to the two peaks distribution, as already said. Moreover, it will represent an important feature of the model, as discussed in chapter 4. The second remark is related to costs. They were computed assuming a basic expenditure of 1.2 $\$/\mathrm{m}_w^2 all/\mathrm{cm}_i nsulation$, which is common for conventional materials currently in the market, as will be seen in section 2.5.3. Since costs are shown to be linearly increasing with the layer thickness, it can be deduced that decreasing marginal benefits are associated to higher expenditures on insulation, as every additional unit of material leads to lower and lower improvement in overall U-value. This is linked to the final conclusion. In order to reach significantly low

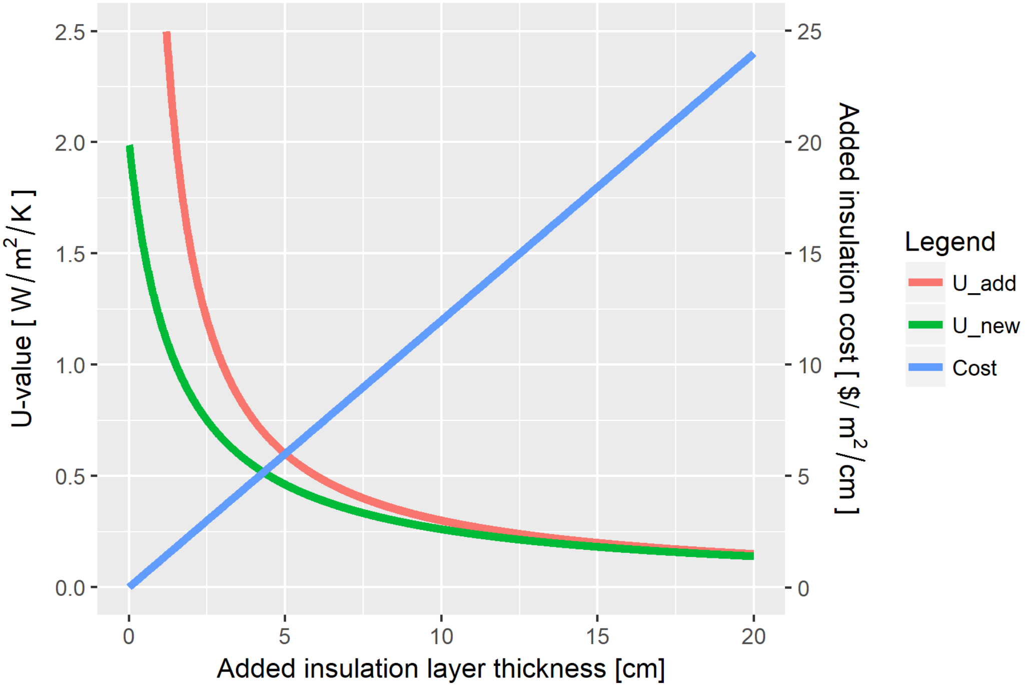

Figure 2.7: Costs and performances of added insulation

energy demands, the required U-values should be around 0.1 $W/m^2/K$, as the “Code for Sustainable Homes” [9] or the Passive House concept [34] outline. In order to reach such low levels without installing cumbersome insulation layers, new technologies with lower thermal conductivities are needed. This will be further discussed in section 2.5.1.

2.3.4 Climate impact

A first insight into regional distribution of insulation levels reveals that U-values are clearly related to HDD, as can be seen in Figure 2.8. This is one of the main aspects that is related to the U-values dispersion within each vintage. Therefore, the colder the climate, the lower the U-values.

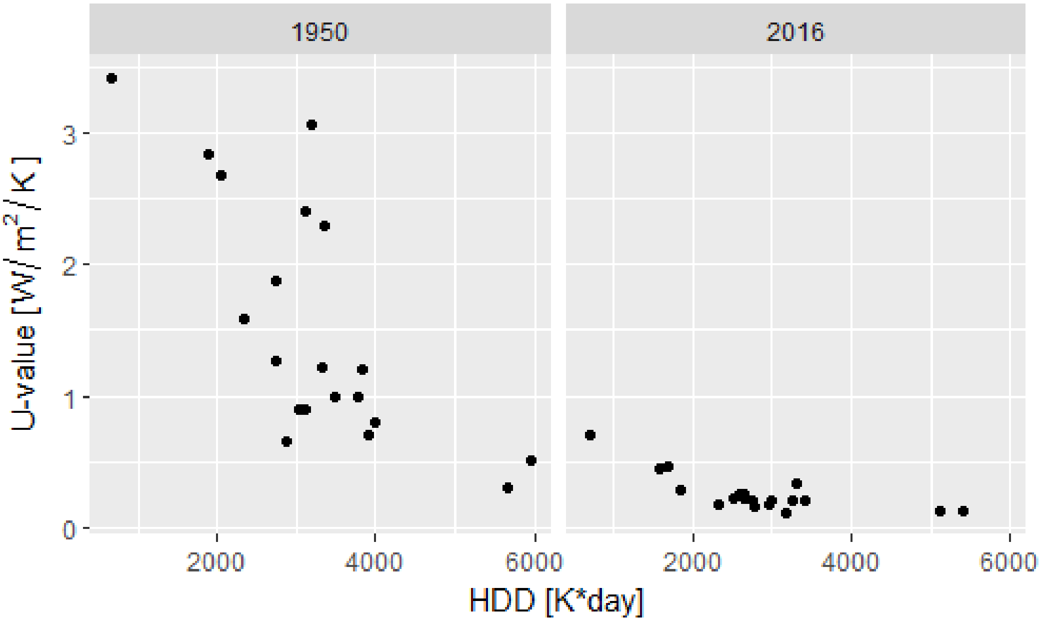

Figure 2.8: Correlation of Roof U-values [29], selected for pre-1950 and 2010-2016 vintages, with HDD [35]

As already shown by figure 2.1, the above chart clearly shows the convergence to very low U-values in the newest vintages, across all countries. Certainly, given the wide range of insulation levels that the oldest vintages show, it can be stated that climate was a fundamental driver of U-values regional distribution in the past. This is probably due to a matter of thermal comfort. Concerning the newest vintages, it can be seen that apart from a further increase of insulation levels in very cold regions, U-values in warmer countries decreased by a very significant amount, compared to 1950. HDD levels have not dramatically changed within the last 60 years, yet the levels of insulation now cover a much more narrow span. Therefore, different drivers impacted on the U-values regional distribution over time, and the importance of climate is now lower, compared to the past. Possible reasons might be due to technology development. It can yet be remarked that the 2016 graph follows a trend which was already outlined in the recommended U-values for different climate zones, in an Ecofys technical report [34]. Therefore, the impact of policies can be clearly be seen here, since no thermal regulation was implemented in 1950, while very strict requirements have been recently put in place in Europe. Another paper [26] confirms what discussed: comparing insulation levels of 4 European countries, it is highlighted that despite France and Spain have a similar climate, the latter ones show much higher U-values on average (respectively 1.1 W/m^2/K against 1.9 W/m^2/K). Therefore it is concluded that climate is not the only driver of insulation levels. However, other factors can also be considered. A better insight into energy efficiency drivers is given in section 2.1.

In any case, based on this chart and on figure 2.7, it can be concluded that the greatest room for low-cost improvement of the building stock thermal performances can be found in warmer countries, especially for the oldest vintages.

2.4 Regression analysis

Three tests are performed in this section. Firstly, the weight of single components U-values on the computation of the envelope U-value is investigated. Then, the significance of the impact of several possible energy efficiency drivers on U-values levels has been examined. Finally, differences across the 2008 and 2014 analysis of the EU database were explored.

Components U-values weight

The envelope thermal performance can be calculated from the single components U-values, weighting them on the share of their area over the total envelope surface, according to equation 2.3. The effect of thermal bridges (i.e. components that easily conduct heat and cold, especially across the connection between different envelope components [2]) across different components is here neglected.

$$U_{envelope} = \frac{A_{window} \cdot U_{window} + A_{wall} \cdot U_{wall} + A_{roof} \cdot U_{roof} + A_{floor} \cdot U_{floor}}{A_{window} + A_{wall} + A_{roof} + A_{floor}} \tag{2.3}$$

The TABULA evaluation report [29] outlines indications on average areas of the single components. Looking at figure 2.9, which shows the mean surface shares of the 4 components across different countries, it can be stated that the ratio of wall area over the total is dominantly higher than the others, being its average around 50%. Instead, roof and floor represent on average around the 18% of the total area each, while windows show the lowest shares: 15%. In order to confirm this indication, the EU database has been employed. Since it outlines both aggregated and disaggregated data on the envelope thermal performances, the weight of different components on the determination of the envelope U-value is regressed, determining the coefficients outlined in equation 2.4, given that the functional form is linear.α is the intercept, while ϵ represents the random error term. Thus, the β_i coefficients thus represent the ratio of the area of each component to the total.

$$U_{envelope} = \alpha + \beta_1 \cdot U_{wall} + \beta_2 \cdot U_{roof} + \beta_3 \cdot U_{floor} + \beta_4 \cdot U_{window} + \epsilon \tag{2.4}$$

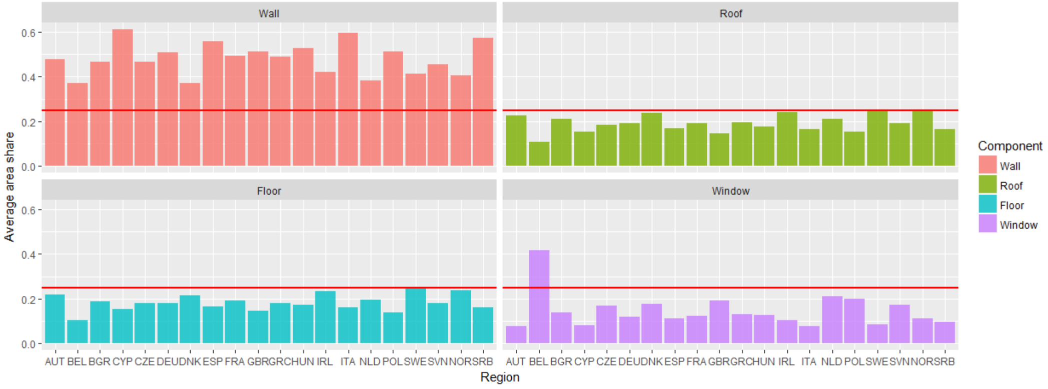

Figure 2.9: Average area of the components over the total, variations across regions [29]

However, the regression results outlined that the shares of each components are quite similar to each other. Moreover, the intercept α was found to be negative, even though with a low significance. Furthermore, the β_3 coefficient is equal to 24% if the 2008 data are regressed, while it decreases to 14% for the 2014 data collection. Further details on the results can be found in appendix B.

In conclusion, the two databases suggest strongly differing indications and even switching from the 2008 to 2014 data of the EU database, results are shown to change. Therefore, no clear conclusions can be drawn on the weight of each component on determining the total envelope U-value.

Energy Efficiency drivers

Based on the analyses of the previous sections, possible drivers of U-values development are selected and tested. Firstly, time and climate should be certainly included in the determination of U-values. Moreover, since the 1980 oil crisis spurred insulation policies, a variable related to oil prices has been added to the investigated ones. Policy impacts are also considered. Moreover, urbanization trends might also affect the development of U-values, since the probability of renovation is higher in rural regions. Furthermore, a variable related to income was added as well. Therefore, the tested regression, for a generic country i and vintage t is summarized in 2.5.

$$U_{i,t} = \alpha + \beta_1 \cdot Oil + \beta_2 \cdot Policy + \beta_3 \cdot Urban + \beta_4 \cdot Income + \beta_5 \cdot Climate + \beta_6 \cdot Time + \epsilon \quad (2.5)$$

Regarding data collection, the annual average crude oil price, in \$/barrel, with the inflation adjusted to July 2017, was taken from [36]. Impacts of policies for space heating are indicated in the MURE (Mesures d'Utilisation Rationnelle de l'Energie) database [37]. Concerning β_3, both urbanization rates and population density were taken from [38] and tested. Income was represented by the GDP per capita from [35]. Climate could be represented by both HDD and CDD, downloaded from [35]. Finally, the time dimension is the average vintage value. Details on the implementation of the regression are explained in appendix B. Both the TABULA and the EU commission database were employed.

Looking then at the results, Time and HDD were found to be the most significant predictors, in both databases, with very low levels of p-value, whatever the considered U-value is (if either envelope or single component U-value are considered, the results do not substantially change). Among the other variables, urbanization rates were found to be more significant than population density, yet running the final regression their p-value strongly increases. The oil variable becomes slightly significant only in come cases in the European commission database (with a p-value in any case ranging from 0.1 to 0.01). If the time dimension is removed, then income and oil variables become significant, with p-values lower than 10^{-2}. This trend happens due to the correlation of income and oil prices with time. Hence, it can be concluded that only HDD and time are significantly linked to U-values, as it already emerged in section 2.3. The β_5 and β_6 results represent a useful tool that will be used for the estimation of U-values levels in other regions of the world, in case of lack of data. Numeric values are shown in appendix B.

2008-2014 analyses

Since some differences generally arose among the coefficient estimates of the previous analyses related to the European commission database, in 2008 and 2014, possible reasons for this discrepancy were investigated. In fact, looking at the evolution of U-values related to the same vintages across these two years might hold some indications on renovation measures. Considering the most important drivers of U-values development, from 2008 to 2014 HDDs generally showed a decrease. One might wonder if the 2008 economic downturn might have had an impact on the buildings thermal performances, yet regressing the differences in U-values against variations in GDP per capita holds no significant results. Therefore, it can be concluded that no clear indication arises on variations of the thermal performance of the same vintages over time, since having only 2 data points does not represent a solid base for analysis. Regarding the performance at the aggregated building stock level, country-level U-values decreased by 0.1 $W/m^2/K$ on average across different nations. However, this might be also due to both demolition of the oldest vintages, together with new construction. There are several mechanisms involved in these trends and it is very difficult to separate out the impacts of each of them.

Regression summary

Given the complexity of drivers involved in the determination of U-values across countries and vintages, few indications could be outlined by means of the regression analysis, in addition to what was discussed in the previous sections. The complexity and multitude of the drivers involved in this topic, together with data collection issues, makes very difficult to draw conclusions that can be generally valid over different nations. Quoting [26] again, climate is not the exclusive determinant of U-values. However, the effects of other drivers are quite mixed and may be relevant for some countries, but not for others. Moreover, non-linearities may arise in the real world, especially when looking at such complex drivers. Even considering the first analysis, on the weights of different components U-values, in which the real function is known to be linear, some inexplicable trends emerged. Therefore, within this section, the complexity and uncertainty in the determination of insulation levels was outlined.

2.5 Technology

Advanced envelope design can reduce the capital costs of heating and cooling equipment, since it can lead to a reduction of 40-60% of energy loads. In any case, space heating and cooling accounts for 30% of overall buildings energy consumption at the global level, and these loads can be reduced by employing a wide array of available technologies [2]. The most important heat losses occur through roofs (30-35%), walls (25-30%), windows (15%) and ventilation (25%). The first three mechanisms can be tackled by increasing building envelope thermal insulation levels, while the fourth one can be suppressed by reducing air infiltration, by means of increased envelope airtightness. Both work well in reducing overheating and thus cooling loads in warm countries, given that adequate solar shading is provided [16]. Therefore, the main elements related to the improvement of the envelope thermal performance can be summarized in the following points:

1. Opaque surfaces (i.e. floor, walls and roof): high insulation levels are crucial especially in cold countries, whereas highly reflective surfaces can be very effective in warm climates;

2. Glazed surfaces (i.e. windows): high performance windows with low thermal transmittance and an appropriate Solar Heat Gain Coefficient (SHGC), depending on the country climate. Sunlight is free and should be harvested as much as possible in cold countries, while in warm climates appropriate shading would be needed;

3. The minimization of thermal bridges (such as high thermal conductive fasteners and structural members);

4. Proper sealing of the building envelope, in order to reduce external air infiltration rates;

5. Passive solar design: optimization of the building orientation and placement of windows and shading, allowance of natural ventilation.

Given the wide range of available technologies, three main characteristics of the specific country or region should be considered, in order to choose the most effective solution. Firstly, 45% of buildings end-use energy usage in cold countries is due to space heating, while this percentage decreases to 13% only in warm nations, in which space cooling and overheating prevention are more important. Furthermore, the type of economy of a country also plays a role in the determination of the most effective policies. Finally, refurbishment should be the main priority in developed nations, in which approximately 75% of the current building stock will be still standing in 2050 and most of the buildings were constructed before 1970, thus when no energy policy was applied. Conversely, developing countries are in particular need of stringent codes for the new construction, since the buildings lifespan is currently low (around 25-35 years) and the stock growth rate is very rapid. Therefore, the selection of technologies should take into account [2]:

- Country climate: heating and cooling loads reductions can be achieved by means of different technologies: for instance, high insulation levels are required especially in cold countries;
- Country economy level: low costs solutions, which guarantee significant performance improvements should be privileged in poorer countries, while richer nations should employ a higher level of technology solutions, with higher costs but also greater thermal performances;
- Distinction between tackling either renovation or new construction. Concerning the former one, insulation and coating layers can be applied over an already existing building. Regarding the latter one, integrated building design represents an additional degree of freedom, which allows for the optimal choice by keeping into account both architectural and technology features. For instance, in order to optimize seasonal heat flows, passive designs with proper orientation that allows sunlight to enter only in winter are the ideal option, yet clearly feasible only for new construction.

Keeping in mind what has been outlined here, sections 2.5.1 and 2.5.2 provide a deeper insight into the available technologies performances and limits, respectively for opaque and glazed surfaces. Even if section 2.5.2 only discusses windows, the majority of inefficient doors are glass doors that can really be considered as a type of window for energy efficiency. Also, many countries combine windows and doors as a common “fenestration” product category [2]. Moreover, doors U-values in the EU buildings database show much less data than the others [7], therefore no detail on doors will be discussed. From now on, glazed surfaces will be only referred to as ”windows”, keeping in mind that glass doors can also be included in this group. Finally, section 2.5.3, a wide research concerning technology perspectives indication from the literature has been performed, in order to then understand which may be the feasible options for the short and long-term future of building envelope technologies. Technology and cost choices will be discussed in section 4.4.1, related to the implementation of the model.

2.5.1 Opaque surfaces

Walls, roofs and floor constitute the largest share of external area of most buildings, therefore they represent one of the most important source of heat losses. The Zebra 2020 project collected data on existing high thermal performance buildings, outlining that opaque surfaces of both renovated and new constructed nZEB show U-values ranging from 0.1 to 0.24 $W/m^2/K$, depending on the component and especially on the country climate [31]. Such low levels of insulation are actually reachable with the current technologies, but some issues such as space constraints arise from the utilization of conventional technologies. Recalling figure 2.7, it can be seen that great savings potentials are available even adding thin layers of insulation, with increasing marginal costs for each unit of decrease in U-value level. As already remarked at the end of section 2.1, even if immediate efficiency improvements at low costs are available, they can create a *lock-in* effect in the building stock, hampering further decrease in U-values to the very low levels required by nZEBs.

Conventional insulation materials

In order to clarify the current status of insulation technologies, a brief background on thermodynamics is provided. The most important property that must be considered is the thermal conductivity k of the material, which is the result of several mechanisms of heat transfer that happen across the medium, according to equation 2.6.

$$k_{tot} = k_{gas} + k_{solid} + k_{rad} + k_{conv} \tag{2.6}$$

Four terms are outlined in the above calculation, being them respectively related to gas molecules colliding with each other (k_{gas}), heat transfer by means of lattice vibrations (k_{solid}), radiation emittance in the infrared wavelength (k_{rad}) and finally thermal transport through movement of air and moisture (k_{conv}) [39]. Traditional thermal insulation materials hamper heat flows by means of pores filled with still air, in order to suppress the convection term. However, this class of technologies finds a lower limit in their thermal conductivity due to the k_{gas} term, being it equal to around 0.025 W/m/K for immobile air. Inorganic fibrous and organic foamy materials belong to this group. These products show values of thermal conductivity that range from 0.029 to 0.055 W/m/K. The lower value is due to the already remarked lower limit of still air, while the dependence of these materials on temperature, moisture content and density may change their thermal performance, leading to such a wide range. A better performing technology can be found in Polyurethane, which is considered as a transition material between conventional and superinsulation technologies, since it shows values of thermal conductivity ranging between 0.02 and 0.03 W/m/K, again depending on temperature, moisture and density.

An important characteristic of all the presented materials is related to the possibility of cutting and perforating them, without any loss of thermal performance. Several requirements must be satisfied by insulation materials, as for instance fire resistance, but in this section they will not all be discussed. Overall, the indicated materials basically summarize current insulation technologies status, since they offer the best performance per unit cost, thus they almost completely dominate the market. Indeed, inorganic fibrous materials, such as glass wool and stone wool, own 60% of the market, while organic foamy materials like expanded polystyrene (EPS) and extruded polystyrene (XPS) constitute the 27% of the market [40]. As will be better outlined in section 2.5.3, there are not huge cost differences across these materials: for instance, XPS costs 10 to 30% more than EPS [41].

Improvement of envelope components thermal performance

Insulation layers are typically prepared by making blankets out of flexible fibres, which are available in different sizes and can be applied in roof insulation, stud walls and under suspended timber floors. Fibres can also be sprayed in place after being mixed with adhesive foam, in order to adhere to the surfaces. Moreover, insulation can become part of the building structure by creating forms for concrete to be poured into. Furthermore, foam boards are made of polymers, foamed with a low-conductivity gas: these can be either pressure-sprayed into wall cavities, where they expand and harden, or they can be produced as structured insulated panels (SIP), which are prefabricated elements to be used in building walls, floors and roofs[16]. The latter type of systems is yet mostly related to new construction [2]. A wide range of options are available for decreasing heat transfer through all the opaque components of a building:

- Starting with walls, external insulation is represented by attaching insulation layers to the external façade of a building. This possibility represents the most effective approach, since the insulation layer thickness is not limited by any constraint. However, it is hardly economically convenient due to the required infrastructure, especially for retrofit options, unless it is considered in the occasion of a major renovation, or maintenance, of the building walls. Therefore, the latter sentence can be linked to the concept of the favourable occasion for energy efficiency improvement, which was outlined in section 2.1. Another possibility is given by filling cavity walls by blowing high thermal performance material. This represents a valid low-cost retrofit option, yet achievable U-values are limited by the cavity width, which usually ranges from 5 to 15 cm. Then, another viable option is represented by attaching an insulation layer to the inner surface of exterior walls. Interior insulation thus represents another cheap possibility, however the added layer thickness must be limited to 10 cm, due to the disadvantage of living space reduction. Unfortunately, this last issue represents a binding constraint in cold countries, where very low U-values are needed.

- Foundations and floor insulation presents the same options of walls, with the preferred option being again the addition of external insulation layers. However, adding insulation while performing a foundation backfilling represents again a labour-intensive option. Therefore, there is a vast need for retrofitting floors and especially in cold climates, mandatory building codes imply restrictions for the thermal performance of these components [2].

- Regarding attic insulation, high thermal performance layers can be applied either between and beneath rafters, or over the external surface, after being covered with a waterproof layer [16]. Concerning this component of the building, air leakage is particularly an issue due to the chimney effect: hence, proper insulation levels must be coupled with effective air sealing. The greatest advancements in roof energy performances are represented by the integration of thin film photovoltaic cells within this component. Challenges are related to heat rejection of the cells, which must be accurately tackled. This mechanism is necessary to avoid a decrease in photovoltaic electricity production, however it may lead to an increase in the building cooling loads if heat is rejected through a badly insulated roof[2]. Finally, in cooling-based climates, the most interesting option to cheaply reduce energy consumption is represented by reflective coatings, applied over the roof surface in order to reflect sunlight. They can decrease cooling loads by 13 to 25% [42], depending on the building level of insulation: some authors actually outlined reductions until 93% [43]. Indeed, the solar reflectivity of building surfaces is generally around 0.2-0.35, but can be as low as 0.05 for dark roofs. Treating these components with light coloured paints can increase this term to 0.7, thus decreasing the solar absorptivity (linked to cooling loads) to 0.3 [3]. Bright white paints have solar reflectances around 85% [16]. Cool roofs are currently being extensively studied for applications in Asia-Pacific economic cooperation (APEC) countries [45]. Due to their cheap costs and significant cooling loads reduction, especially for non-insulated buildings, cool roofs represent the first option to immediately tackle overheating issues in developing countries with hot climates [2].

In general, when applying insulation layers, the optimal thickness is predominantly driven by the climate, heating system type and efficiency, and installation costs [2]. In this last paragraph it has been remarked that some constraints may arise on the achievable thermal performance of added insulation layers, due to limitations on their maximum thickness. Given the EPBD objectives of reaching an nZEB stock in 2050, this constitutes a problem. Recalling equation 2.2, in order to reach U-values as low as 0.05 W/m^2/K with conventional insulation materials, the required thickness is around 50 cm [16], which is certainly not always feasible, since it greatly overcomes the constraints that were previously outlined. Therefore, in order to drastically improve the building stock insulation levels in a feasible way, superinsulation is needed. This term is referred to material with thermal conductivity lower than 0.02 W/m/K.

Superinsulation materials

Two options are already available, despite still experiencing high costs:

1. **Aerogel**: with a thermal conductivity ranging from 0.012 to 0.02 W/m/K, it is believed to be one of the materials that will dominate future global markets [40], while other authors outline that they are unlikely to reach high market penetration [16]. Indeed, the main barriers for this technology are related to high costs, due to the complexity of the manufacturing process, and brittleness. Even if due to the latter aspect, the flexibility of this technology is not as high as

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[3] The irradiation interacting with a surface can be divided into 3 terms: defining reflectivity the fraction of irradiation that is reflected, absorptivity the fraction that is absorbed and transmissivity the fraction that is transmitted, the sum of these three components must be equal to one. Indeed, all the irradiation must be either reflected, absorbed or transmitted. An opaque medium experiences no transmission, thus in this case the sum of absorptivity and reflectivity is equal to one. [44]

conventional materials, perforation does not represent a problem for aerogel, too [39]. Lower density, compared to conventional insulation materials, is another advantage [40]. Some applications in which it represented feasible solutions are related to highly constrained spaces and thermal bridges [2].

2. **Vacuum Insulated Panels (VIP)**: they show extraordinary low thermal conductivity levels, down to 3-4 mW/m/K at the center of the panel in fresh conditions. Such low values are reached by creating an open porous structure which is evacuated, in order to decrease the k_{gas} term in equation 2.6 to a negligible value. A gas barrier is then wrapped around the panel. However, air and vapour diffusion through the VIP envelope make ageing one of the main weaknesses of this technology, since after 25 years the thermal conductivity inevitably reaches values of 8 mW/m/K. Moreover, puncturing the VIP envelope would reset all its advantages, since the thermal conductivity would immediately increase to 0.02 W/m/K. Therefore, VIPs cannot be cut for adjustment at the building site and since a simple nail can strongly decrease their thermal performance, this class of technologies does not definitely offer the same flexibility advantages of aerogels and conventional materials. Indeed, their introduction in the market will put new demands on building planners regarding how to plan and handle VIP [æs2013VIPproblems]. Moreover, the gas barrier represents a dangerous thermal bridge, thus increasing the overall conductivity of the VIP, with respect to the center-of-the-panel value [46]. Insulation solutions with VIP wrapped in EPS are currently in use, yet in this configuration the loss of vacuum is not easy to detect (while with no additional covers, damages can be detected by a simple visual inspection), therefore increases the probability of installing panels with no vacuum [39]. High cost also represents a barrier for the wide-scale adoption of VIPs [47]. However, due to the achievable levels of thermal performance, it is claimed that their contribution to the near future should not be neglected, even if they may not represent the ultimate solution [39].

Some studies claim that these new technologies are already convenient when the space saving benefits, due to a much lower thermal conductivity, compensate for higher material costs (e.g. in a city apartment, where the economic potential of increased floorspace is high [48]). Therefore they might represent important options especially for retrofitting applications [40].

Other technology possibilities are related to Gas-filled panels, which work on the same principle as VIP but do not have to withstand vacuum, being them filled with a noble gas, which has lower thermal conductivity than air. However, their overall performances are lower than VIPs [39]. Modified atmosphere insulation (MAI) is another vacuum technology, which is similar to VIPs but employs fewer processing steps. Since manufacturing can account for 75% of the VIP price [49], critical paths are currently being developed to produce MAI at 40% lower cost than VIP [50]. Finally, a new concept of insulation technologies may be represented by phase change materials, which are able to absorb and release heat while keeping a constant temperature, thus stabilizing heating and cooling loads. However, this class of materials has still not been used as envelope insulators [39].

Looking at the long-term future, several new concepts of insulation materials may arise, yet they mainly constitute pathways of research and development rather than technologies already present in the market, hence few indications are available on their feasibility and costs. The main concepts are [39]:

- Vacuum insulation materials: the concept is similar to VIPs, but vacuum is created within a closed pore structure. Since pores are not connected each other, perforations do not cause air penetration and loss of vacuum, thus they can be cut and adapted at the construction site with no loss of thermal performance, overcoming one of the VIPs main limits.

- Nano insulation materials: thermal conductivity is decreased without any need of a vacuum. Indeed, when pores size is decreased below a certain threshold (i.e. 40 nm for air), the main free path of the gas molecules becomes larger than the pore diameter (Knudsen effect), thus strongly decreasing the k_{gas} term in equation 2.6, leading to a thermal conductivity of 4 mW/m/K even with air-filled pores. Therefore, not only these materials can be cut and perforated, but they also do not suffer by air and moisture penetration. With nanotechnology, materials having the same construction properties of concrete, but with substantially lower thermal conductivity may be created, thus having a huge impact on the buildings sector.

- Dynamic insulation materials: their advantage is linked to the possibility of controlling the thermal conductivity within a desirable range, by modifying the terms outlined in equation 2.6, thus allowing heat transfer only when it is needed.

2.5.2 Glazed surfaces

Most of the technologies outlined in the previous section cannot be implemented in windows, since these components must allow light transmission. The only material that is interesting both in terms of low thermal conductivity and translucency properties is aerogel [51, 40].

Basic classification

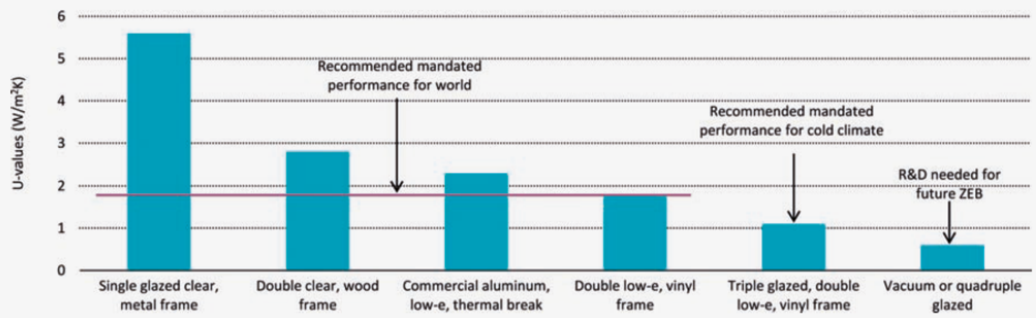
The easiest way to introduce these components is to classify them according to the number of glazed surfaces that are applied, which ranges from single to triple-glazed windows for currently available technologies, but in the future quadruple glass components may get into the market. However, it must be remarked that wide ranges of U-values are linked to each class, due to the different quality of components that can be used. Indeed, coatings can be applied over the glasses, while different framing materials and technologies can be implemented in order to obtain the desired structural and insulating properties. Moreover, small variations can be also due to different glass thicknesses. Finally, since windows constitute quite complicated systems, in which components with different thermal properties interact, appropriate calculation codes must be followed in order to determine the corresponding U-value. Depending on the ISO code which has been used, some variations in the results may also happen [2].

Single-glazed components: their U-values range from 7.9 W/m^2/K for aluminium frame, clear glass technologies to 2.9 W/m^2/K, for coated, timber-framed windows [52]. Firstly, low-emissivity coatings are represented by thin transparent metal film, which are able to both reduce the window thermal loss and also reflect solar energy. Indeed, [2] outlines that U-values can be reduced by up to 42 % when low-e coatings are applied on single glazed, clear glass windows. Secondly, non-metallic frames can be employed in order to reduce thermal bridging, but then some drawbacks in the window structural properties arise. Indeed, due to high structural requirements for many services sub-sector buildings, an aluminium frame must be chosen. However, even in this case, thermal breaks can be implemented within the frame, in order to hamper heat transfer and accordingly reduce U-value.

Double-glazed windows present a new degree of freedom in their implementation, since they present a gap between the two glasses, which is generally filled with air. Inert gases can be employed, to further reduce heat transfer between cavities. The gap width is also another important parameter to be optimized, considering the thermal properties of the filling gas, in order to reduce convection heat flow. Considering all of these variables, [52] outlines that double-glazed windows U-values range from 6.2 to 2.5 W/m^2/K. However, IEA indicates that aluminium framed windows with low-e coatings and thermal breaks, which are used in the services sub-sector, reach U-values of 2.3 W/m^2/K. Moreover, non-metallic frames windows with low-e coating and inert gases are used in cold OECD countries and reach interesting U-values of 1.8 W/m^2/K [2].

Triple-glazed windows generally show very high thermal performances in any case. Indications from the literature show U-values ranging from 2.9 W/m^2/K for clear glass and aluminium frame elements [53], down to 1.1 W/m^2/K, which is related to building codes requirements in some European countries [2]. However, very high-performance windows are generally not economically viable and great research effort is still required. Future goals are related to U-values around 0.6 W/m^2/K. A key economic perspective for policy makers is represented by assuming a point of view beyond the simple energy savings of the windows components, thus considering overall system efficiencies. In this way, reductions in heating and cooling equipment size due to lower energy loads can be accounted and included in the profitability calculation.

More advanced window technologies are available, thus not always showing an improvement in terms of both costs and performances compared to the groups that were discussed. An interesting option is represented by vacuum glazing, which is seen as a way to achieve significant U-values reduction while keeping a thin glazing unit. However, due to thermal expansion issues they cannot be implemented in severe cold climates, where they would presumably be needed the most, and show limitations on size. Moreover, they do not exceed triple-glazed windows in terms of thermal performance [2]. Another very interesting option is represented by aerogel glazing. Mounting an aerogel sheet between two low-e coated glass panes and using krypton as a filling gas, U-values lower than 0.4 W/m^2/K were reached. Figure 2.10 finally summarizes the state of the art in window technology diffusion.



Notes: ZEB = zero-energy building, performance in accordance with ISO 15099 standard.

Key point *Low-e double glazed window performance levels are recommended for worldwide application, and advanced windows for cold climates.*

Figure 2.10: Typical window U-values for common products in the market place [2]

Current technology diffusion

Despite many options being available in the window technology market,it was already outlined in section 2.3.1 that single-glazed windows are still present in warm European countries building stocks. Moreover, [2] highlights that many products that are currently being sold in the world are single-glazed, with inefficient frames. Indeed, two differences from opaque surfaces insulation technologies arise. Firstly, in the latter field, conventional materials have been used for decades, while in window technologies the most significant advancements occurred in the last 20-30 years only. Indeed, high performance windows with U-values around 2.4 W/m^2/K came into the market only in the 2000's. Moreover, it must be remarked again that window replacement for the only scope of energy savings is hardly profitable, while this is not the case for opaque surfaces efficiency improvement. Looking at the world level, in China there has been a global effort in order to push high performance windows diffusion, due to the prospected high construction rates. India is also promoting low SHGC windows for cooling loads reduction.

Other requirements

Windows are required to dynamically change their interactions with sunlight, either hampering or allowing heat flow depending on the season and climate. For cold countries, let in as much radiation as possible is crucial, especially in the heating season, while in warm zones the priority is related to avoiding overheating, keeping out heat from the sun. The former requirements is much more difficult to be implemented than the second, since solar light can be reflected by means of shutters and in general shading options. Again, low-e coatings represent an useful option, either for retaining heat or reflecting sunlight. However, only OECD countries implemented mandatory codes for their utilization, while in other regions the adoption of such technologies is still far to be forced. Moreover, very low SHGC windows may result to be too dark when solar light is not directly hitting the surface, thus causing an increase in the use of artificial light, with an overall increase in energy consumption. Therefore, the most interesting solutions are represented by automatic shade control and dynamic SHGC control [2]. Among the latter solutions, electrochromic glazing technologies are able to vary SHGC by means of applying a DC voltage. They show interesting perspectives, with expected cooling loads reductions of 19-26% for office buildings [54] and their reliability has been proven, even if little is known about their performance in cold climates [55].

Finally, air sealing constitutes an important requirement for windows. Especially in older buildings, glazed components are responsible for a major portion of air leakage. Technologies such as storm panels are proven to reduce whole-building infiltration by 5.7-8.6%, but concerns are raised about their performance degradation over time, due to thermal cycling.

2.5.3 Technology cost summary

Indications on opaque conventional technology prices are found to be quite abundant and do not range over wide intervals of values. However, this is not the case for windows: due to the complexity of these systems, the relation between costs and components U-values showed important variations across different sources. Another issue that has to be faced was related to properly separating cost components, that means determining the right shares between materials, labour, taxes and business profits in the final price. In several cases, a lack of clarity emerged when looking for which components were actually included in the considered analysis. Furthermore, costs are usually normalized by a unit of surface (i.e. cost per square meter) and it has been studied that such expenditures decrease with the size of the living area [56]. It should also be remembered that for opaque surfaces, insulation costs depend on both the considered building envelope component (wall, roof or floor) and the type of measure that is implemented (e.g. cavity fill is cheaper than external wall insulation), as outlined in section 2.5.1. In addition, costs are sometimes indicated either per m^2 of envelope surface, or per m^2 of living area, and it is not always specified which unit was considered. In the following paragraphs, costs will be always normalized to the unit of component surface. Finally, cost differentiation across European and world regions further creates difficulties in determining what could be the correct cost to be assigned to each technology.

Opaque technologies

Application of insulation layers over a surface requires defined amounts of labour, linked to the installation, equipment and ancillary works, and finally materials. Regarding conventional insulation materials, clear indications emerged from several studies regarding the share of these components into the final cost. Firstly, an Italian study outlined that *the final cost is only slightly affected by the insulating layer thickness* [57]. This is in line with the outcomes of an analysis performed in Switzerland, which highlights that within the estimations for compact façade thermal insulation, material cost weight is around 15-20%, while assembly costs, linked to labour, get a 60% share of the total price, with auxiliary equipment having the remaining 20% [58]. This is further confirmed by a study performed in Sweden, where out of a total cost for renovation of 100000 Euros, the span of variation due to added insulation material was around 15000 Euros [59]. Moreover, several reports outlined insulation costs divided into a variable component, which increases with the thickness of the added insulation layer, and a fixed component, meaning that it just depends on labour, taxes, and equipment [60]. It could be outlined that variable costs are thus not important and should not be analyzed: however, this statement only holds true for conventional insulation materials, with VIP and aerogel showing much larger costs per added cm thickness. Therefore, both cost components will be investigated.

Variable costs

Conventional materials costs were found to vary within a quite small range, depending on the considered source. Studies on aerogel and VIP technologies show accordance in the estimations of material costs. The reviewed indications are summarized in table 2.2. Costs are given per unit of surface and added material thickness (in Euro/m^2/cm) and they were translated to a common currency, when possible, from the outlined data. Thermal conductivity k is given in W/m/K. The "notes" column indicates why certain cost ranges were found in the analysed source.

This table shows that for conventional materials, a reasonable range of costs would be from 1 to 2 Euro/m^2/K, with some sources outlining even higher prices, referred to low thermal conductivity materials. The two sources from China and Korea outline quite low costs. Moreover, two websites were analyzed, outlining that in the U.S., insulation is cheaper than Europe: [61, 62] indicate ranges among 0.2-0.6 Euro/m^2/cm, with higher costs for foam boards and SIPs (2-4 Euro/m^2/cm). VIP and aerogel currently show too high costs to be competitive with conventional materials. However, [63] indicates that aerogel costs could be more than halved by 2020, with [40] outlining that costs might even get down to 500 Euro/m^3 by 2050. Regarding VIP, few information was found on future perspectives. Considering MAI objectives [50], achieving a 40% reduction compared to VIP would mean reaching approximately 20 Euro/m2/cm, optimistically speaking.

Another approach which is often followed is to consider the net installation expenditure related to a measure, meaning that costs are presented in Euro/m^2 without information on the added insulation layer thickness. In [16], the required expenditures for roof, cavity wall, interior and floor insulation are similar, being them around 20-45 Euro/m^2. However, in the same report it is outlined that costs for external wall insulation are much higher, with ranges of 70-150 Euro/m^2 which drop down to 30-80

Technology group	Country	Material	Cost	k	year	Source	Notes
Conventional technology	Sweden	Mineral wool, EPS	1	0.034-0.037	2017	[59]	
	Germany	-	1.1-2.7	-	2016	[12]	different envelope components
	Europe	-	0.9-1.9	-	2012	[60]	different European regions and envelope components
	Poland	Mineral wool, polystyrene, ecofibre, polyisocyanurate	0.9-1.8	0.028-0.041	2011	[64]	Costs vary according to insulation material
	Cyprus	polystyrene	0.6	-	2002	[65]	
	Italy	Insulation materials used in the italian market	0.2-1.2	0.038-0.045	2005	[66]	
	Belgium	Mineral wool	1.1-1.8	0.04	2010	[67]	different envelope components
	Portugal	Cork, EPS, XPS, polyurethane	1.4-3.2	0.02-0.05	2012	[68]	Costs vary according to insulation material
	Finland	Mineral wool, EPS, polyurethane	0.6-3.4	0.025-0.05	2007	[69]	different insulation materials
	UK	EPS	0.5-0.6	-	2014	[70]	
	China	EPS, XPS, polyurethane, polyvinyl chloride	0.3-1.2	0.03-0.05	2011	[71]	different insulation materials
	Korea	Styrofoam insulation panel	0.8	0.036	2013	[72]	
Advanced technologies	UK	VIP	17.9-28.8	0.007-0.017	2017	[48]	different core materials
	Korea	VIP	21.2	0.0045	2013	[72]	
	UK	VIP	28-82	-	2014	[70]	different VIP thicknesses
	-	VIP	40	0.008	2014	[40]	
	-	Aerogel	30	0.015	2008	[63]	
	-	Aerogel	27	0.015	2014	[40]	

Table 2.2: Summary of reviewed literature sources

Euro/m^2 when the work is combined with other maintenace of the façade. Therefore, probably auxiliary equipments and scaffolding costs are also included in this source, since the cost of the insulation layer should vary from 15-30 Euro/m^2, assuming thicknesses of 10-20 cm and a 1.5 Euro/m^2 cost per cm of added material. The same report outlines that in the U.S., insulation costs are much lower, compared to Europe, for all kind of measures, being them around 10-25 Euro/m^2, thus confirming what was previously outlined. Another report outlines slightly lower costs (10 to 20% less) for new construction buildings compared to the renovated ones [9].

Fixed costs

This is the most important cost component, in opaque surfaces insulation. An Ecofys report outlines that for cavity wall, roof and cellar insulation, fixed costs are quite similar, being them around 15-25 Euro/m^2, depending on the considered European region. Installation costs for external façade insulation are yet much higher and show a greater span of variation across regions: from 48 to 15 Euro/m^2. Nordic countries show the highest expenditures per m^2, while south-eastern nations present the lowest [60]. Another report highlights that in Germany, labour costs and taxes add 80 Euro/m^2 up to the final cost of roof refurbishment, while this amount is equal to 40 Euro/m^2 for wall refurbishment, probably because either interior insulation or cavity filling measures were considered. A value added tax equal to 19% of the total cost of labour + material is assumed. Poland and Spain are also included in this report and show lower costs [73].

One of the Entranze project deliverables considers insulation costs divided by several components, for 9 European countries. Business profits and professional fees are expressed in terms of percentage of (labour+material costs) and they show different values: from 5% in France to 35% in Czech Republic for the former component, while the latter varies across 10-15%. In the considered report, material costs probably include both insulation and auxiliary equipment, since they show high shares in the final expenditures, being them approximately equal to 30-50% for roof insulation (which makes sense compared to the percentages outlined by [58]). Regarding façade insulation, shares of expenditures on materials vary from 30 to 80%, presumably depending on the type of measure that was considered in each country (either external or internal insulation).

Concerning reflective coating technologies for cooling-based climates, [16] reports that costs vary from 6 Euro/m^2 for acrylic paints to 25 Euro/m^2 for PVC single-ply membranes.

Window technologies

According to [16], the total replacement cost of windows in office buildings is around 300 Euro/m^2 (for U_{window}=2 W/m^2/K) and 400 Euro/m^2 (for U_{window}=1 W/m^2/K), with demolition and removal of old components costing 13 Euro/m^2, thus the latter represents a negligible fraction. This report assumes labour costs of 100 Euro/m^2, independently from the window efficiency level. Window replacement costs for residential buildings range from 140 Euro/m^2, for single-glazed components, to 430 Euro/m^2, for the most efficient elements. However, these expenditures may drop down to 60-130 Euro/m^2 when windows are installed as part of a general renovation or in new construction [16]. This is in accordance to what was outlined in [2], that is, windows replacement for the only purpose of energy savings is rarely convenient, moreover it further remarks the importance of the *favourable occasion* for implementing energy efficiency measures in buildings [21]. This will be reflected in the model as well (see section 4.6). Indications from [60] also fall within this range, with double-glazed windows costing 400 and 160 Euro/m^2 respectively in nordic countries and south-east urope, implemented in renovated houses. Triple-glazed elements are instead installed in new construction buildings and their cost vary from 480 to 190 Euro/m^2 across EU regions. Moreover, expenditures for multi-family buildings are assumed to be approximately 25% less than single-family houses. A technical report performed in Belgium outlines windows replacement costs, without taxes, which are even higher, ranging from 450 Euro/m^2 to 650 Euro/m^2, for U-values that are respectively equal to 2 and 1.64 W/m^2/K [74]. From the Entranze project, costs of replacement with the most efficient windows instead remain high across different European countries, and fall within a range of 350-500 Euro/m^2, with high shares of material expenditures, varying from 50 to 80% of the total cost [75].

Indications from the literature are therefore quite mixed. For all the reasons discussed at the beginning of this section, the relation between costs and U-values shows great differences across studies. A noticeable example is given by figure 2.11. Looking at two different sources [76, 53], single-glazed window cost vary between 110 and 180 Euro/m^2, while double-glazed clear show prices of 200-240 Euro/m^2. Double-glazed windows with thermal break and low-e coatings cost around 230-320 Euro/m^2 and finally triple-glazed windows cost vary across 330-380 Euro/m^2. It can be therefore stated that costs increase with the complexity of the component, yet finding the correct expenditures range is definitely not easy. What can be also noticed is that cost increase appear to be linearly related to U-value decrease, especially in [53], which is definitely not the case for opaque surfaces insulation costs, as can be deduced from figure 2.7. In the same study, additional costs related to improved frames and glazings (i.e. respectively adding a thermal break and a low-e coating) can be estimated to be respectively around 15 and 35 Euro/m^2. However, [42] outlines that coatings price can decrease to 2.5 \$/m^2 when this technology is available in a mature market.

Finally, a last remark concerns aerogel glazings. IEA outlines this technology to be in a pre-market viable status [2]. One study outlines costs for improving a double-glazed window (U=2.86 W/m^2/K, which presumably costs 200-300 Euro/m^2) with an aerogel layer, stating that in order to reach U-values of 1.19 and 0.6 W/m^2/K, additional expenditures of 56 and 121 Euro/m^2 can be respectively calculated, depending on the required filling thickness and assuming a cost of 4000 Euro/m^3 for aerogel material [51]. If expectations on aerogel future cost decrease are respected, this technology might become cost-competitive. However, this is not in line with [40], which outlines that the cost of this technology is around six times higher than that of a conventional double-glazed window. Concerns on the durability of this technology is still an issue [51], therefore several uncertainties are related to the future development of aerogel glazings.

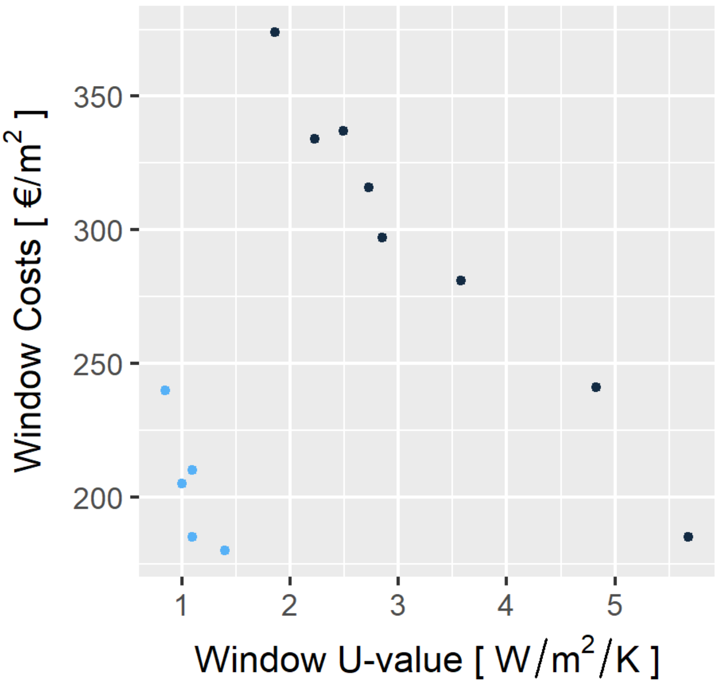


Figure 2.11: Relation between window costs and U-values according to different sources: dark blue dots [53] and light blue dots [69]

Costs across regions

The costs of construction vary per country, as can be seen in figure 2.12. Indeed, [60] outlines that costs were calibrated according to an Eurostat study which outlined price level indices (PLI). These are the ratio of purchasing power parities to exchange rates. Purchasing power parities are in turn the ratio of prices in national currencies for an identical or comparable good or service in different countries [77] for different European countries, related to the European average. If the PLI is higher than 100, it means that the considered country is relatively more expensive than the EU27 average. Indeed, figure 2.12 outlines that the highest prices can be found in nordic countries, while the lowest are related to south-east nations.

Moreover, in the same study, PLIs are distinguished between residential, non-residential and construction works. It results that the first two subgroups show the highest price dispersion, thus it is really important to account for these variations. Differences across countries are due to the high labour content in the construction sector and the wide spread of salaries in various countries.

Final summary

Starting from opaque surfaces, installation costs for opaque surfaces insulation are outlined to be higher than 100 Euro/m^2 for nordic countries, while they generally remain below this threshold in other nations. The relevance of insulation layer expenditure is negligible compared to the other cost components unless superinsulation materials are

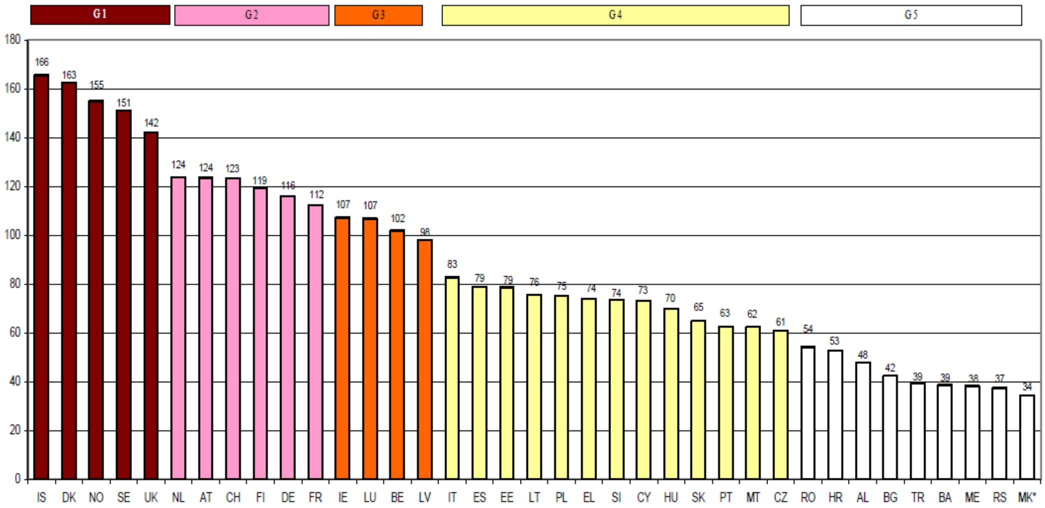


Figure 2.12: Price level indices of construction in 2007 (EU27=100) [77]

installed. Concerning glazed elements, costs for the most efficient window technologies (i.e. double-glazed components with low-e coating and thermal break, triple-glazed windows) generally fall within a range of 300 to 400 Euro/m^2, with single-glazed elements costing approximately 150 Euro/m^2. Therefore, costs per m^2 of window surface are generally much higher than expenditures for opaque components, being them always above 100 Euro/m^2. Costs are also indicated to decrease in case of a general envelope renovation or in new construction in several sources [9, 16]. Finally, the high labour content in the residential and non-residential sub-sectors represents the most important cause of cost variations across countries.

Chapter 3

Methods

This chapter is organized as follows. Section 3.1 provides a brief introduction on the link between IAMs and global energy models. Then, section 3.2 will introduce the EDGE buildings model, firstly presenting a general overview and then further deepening the analysis is on the insulation module current state and improvements.

3.1 From IAMs to Global Energy Models

IAMs have been developed in order to analyse long-term climate mitigation strategies. Efficient and rational implementation of building stock CO_2 emissions reduction requires modelling of the most important drivers in energy demand development. Therefore global energy models for buildings were developed, with 3 main objectives: [6]:

1. Estimate and predict the baseline energy demand of the existing building stock, at several levels (e.g. cross-country, national, regional, and so on);

2. Explore the impacts of different policies and technology development over time, again with different points of view (e.g. short, medium, long term);

3. Identify the effect of emission reduction strategies on indoor environmental comfort.

Hence, IAMs could be then used by both policymakers, in order to gain a deeper understanding of the key building parameters for emissions reduction and main challenges associated to future developments, and by the construction industry, aiming at developing new business models for sustainable approaches. Energy consumption modeling aims at quantifying energy requirements as a function of input parameters. Two distinct approaches can be mainly identified [17]:

- **Top-Down approaches**: They utilize the estimate of the buildings sector energy consumption and other important variables to *attribute* the energy consumption to characteristics of the analyzed sector.

- **Bottom-Up approaches**: In contrast with the top-down models, they *calculate* the energy consumption of single units (which may be represented by either groups of houses, households, or even regions or nations) and aggregate the results to compute the energy demand at the desired level.

The EDGE model belongs to the second category, thus the state-of-the-art of bottom-up models will be now analyzed. This approach can be implemented in two different ways [17]:

- *Statistical Methods*: they rely on historical information and regression analysis, in order to firstly relate dwelling energy consumption to particular end-uses, then estimate the future levels of energy demand according to changes in inputs;
- *Engineering (building physics) Methods*: they explicitly account for the energy consumption of end-uses, based on either power ratings, use of equipment or heat transfer relations.

Uncertainty in Modeling

Given the complexity of interrelations between variables, which may vary across regions and time, global models must deal with several sources of uncertainty. Increasing the level of detail would allow for a more comprehensive investigation of dependencies, however the model complexity would grow as well and especially at wider levels (both in space and time), data unavailability and uncertainty would cause the results too uncertain. In that case, instead of gathering great amounts of data, accurate assumptions would provide reasonable results as well, moreover they would ease the modeling process. Regarding the residential sector, the difficulties in understanding general drivers impact have already been outlined in section 2.1. Indeed, this sector can be seen as very difficult to model [17], since:

- This sector involves a large variety of structure sizes, materials and technologies;
- Occupant behaviour is very important and can influence the energy demand up to 100%;
- Privacy issues limit the successful collection of data;
- Detailed data assessment would lead to prohibitive costs.

Regarding the second point, situated approach studies constitute an attempt to include a detailed description of influences on household decision-making processes. However, analyses are confined to specific cases, thus making generalization to other contexts difficult [15]. If it is also considered that uncertainty may derive from a wide array of sources (see [78] for an extensive discussion on this topic), the challenge of obtaining reasonable results becomes hard to be overcome. To better capture this uncertainty, the climate research community has recently developed a set of scenarios that aim to span the range of plausible futures, quantitatively computing the evolution of socioeconomic indicators according to assumptions which are coherent to the scenario narratives. technological trends. The Shared Socioeconomic Pathways (SSPs) constitute the currently most used framework in this direction. The SSPs span a space of challenges to mitigation and adaptation, without assigning any probability to the single scenarios [79], and in particular EDGE constitutes the first attempt to assess the global implications of socioeconomic drivers uncertainty within a coherent framework [19].

The SSP framework

A brief deepening is now provided within the SSP scenarios. Due to the high level of uncertainty in future socio-economic drivers, 5 pathways have been conceptualized. Firstly, narratives were designed, in order to provide the fundamental underlying logic of each SSP. Figure 3.1 outline the main concept behind this framework. Each SSP leads to different challenges towards adaptation and mitigation to climate change issues. In SSP1, the world shifts gradually towards a more sustainable path, a more inclusive development is emphasized and environmental boudaries are respected, technological development is fast. In SSP2, the world follows a path in which social, economic and technological trends do not shift markedly from historical patterns. In SSP3, nationalism increases, investments in education and technological development decline. Finally, SSP4 represents a future in which inequality increases, while SSP5 development is pushed by fossil fuels use [80].

It is important to remark that no policy assumption was made. Therefore, based on figure 3.1, it can be deduced that lower policy efforts will be required in SSP1, compared to SSP3, because of lower levels of challenges inherent to that SSP. After the narrative development, the basic elements in terms of economic and demographic drivers were quantitatively evaluated. Therefore, they provide a common framework of data which can be taken as input in IAMs, in order to evaluate main outcomes in terms of emissions, land use and energy system development for each SSP. Indeed, figure 3.2 shows that EDGE input data on population and GDP vary across SSPs.

As can be seen from figure 3.2, EDGE model assumes different trends for HDD and CDD, according to the SSPs. In a brief summary, in the green world scenario (SSP1), the setpoint temperature for HDD and CDD calculation is respectively increased and decreased, because it is assumed that people will behave more responsibly, according to the scenario narrative. Moreover, the hypothesis behind SSP1 is that the world is lead to a lower level of climate change, compared to the other SSPs, in accordance to the challenges (figure 3.1). The effects of the global climate levels start to be important after 2050, which is why HDD do not decrease below 750 K*day. In order to determine U-values, this is an important characteristic of the model and will be recalled again in section 6.5.

Other modeling approaches

Buildings require energy along several phases of their useful life. Indeed, the first is represented by the construction, then comes the operating phase and finally the demolition. Different optimization processes can be carried out depending on the included

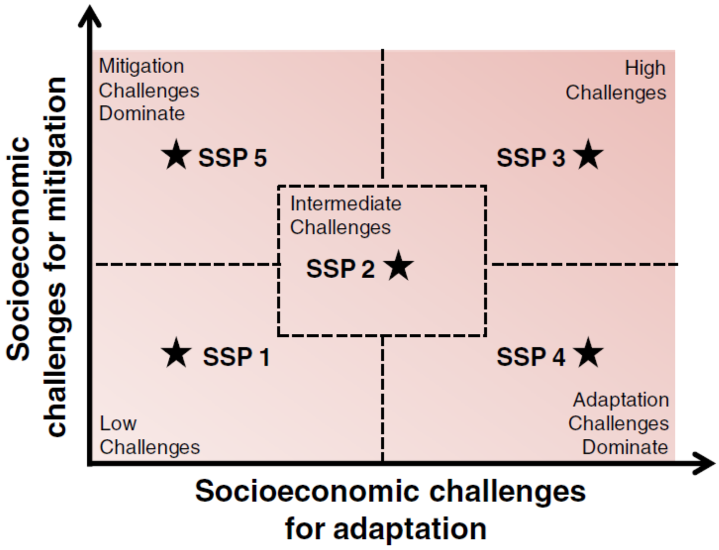


Figure 3.1: The SSPs challenges space [79]

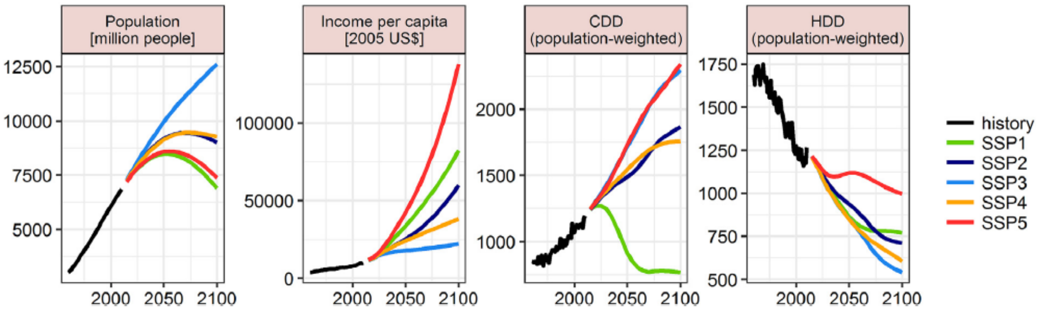


Figure 3.2: Exogenous drivers implemented in EDGE [19]

phases. Optimization of energy consumption can involve either the whole life-cycle or only the operating phase. Including all the three phases, with environmental and social impacts can lead to a more comprehensive analysis, yet at the cost of increased complexity. Moreover, occupants' behaviour can create great discrepancies between estimated and actual energy consumption, yet household lifestyles strongly depend on the local culture, thus the indications from the literature cannot be easily extended to the global level.

3.2 The EDGE model

Within the framework presented in section 3.1, global energy models were developed in order to account for the several drivers that determine buildings final energy consumption, such as population, reduction in household size and increasing wealth levels [4]. EDGE constitutes a global energy model which is developed to fit the timeframe and scope of an IAM, so that it could be coupled to a larger IAM framework. It has been used to construct baseline FED trends, to be then matched by the REMIND IAM [81, 82]. It employs statistical methods, which by means of regressions also utilizes macroeconomic indicators in order to gain the strengths of the top-down approach. Therefore, EDGE can be defined as a *bottom-up, statistically-based simulation* model, which is *multi-regional* and employs a *long-term* point of view. No price responsiveness is implemented.

Simulation Model: In this model, calculations are performed at each time step, with no optimization. According to the regression analysis calibration, the main socio-economic drivers are used to calculate the main parameters that eventually determine energy demand. No optimization is performed.

Time horizon: EDGE works on a long point of view: a 5-year timestep is implemented and computations are performed until 2100. Several parameters are used to calibrate the equations, in order for the results to match historical data for each region. It is assumed that these historical relationships will hold true for the short term, then a growing importance is given to the scenarios hypotheses across the years. This means that in the long-term, a convergence towards assumed SSP-specific parameters is assumed, which represents a shift towards lifestyles and cultural values according to the SSP narrative.

Multi-regional: EDGE is divided into 11 macro-regions, with a further detail implemented for Europe, which comprises the 28 countries analyzed in the EU commission buildings database, previously outlined in table 2.1. The following two tables present EDGE regional detail.

World level detail			
China (CHN)	Japan (JPN)	India (IND)	Other Asian countries (OAS)
Africa (AFR)	Middle East (MIE)	Russia (RUS)	United States (USA)
Europe (EUR)	Other OECD countries (OCD)	Other non-OECD countries (NCD)	

Energy carriers and end-uses detail: EDGE relies on 7 different types of energy carriers, that deliver the final energy to the consumer. These are represented by electricity, traditional biomass, modern biomass (namely improved fuelwood and pellets), coal, natural gas (which also includes biogas), liquids (which include petrol, heating fuel oil and biofuels) and heat (related to district heating). Available end-uses are shown in 3.3 and regarding this work, only space heating and cooling will be analyzed in a deeper way.

Consumer perspective: EDGE does not analyze how the estimated energy carriers will be provided by the supply sector. It only shows which carriers will be chosen by consumers, according to the scenario narrative.

Main concepts

A deep discussion on the EDGE model can be found in [19], while the main points for this work will be now summarized. EDGE relies on the concept of *useful energy*, which is built on the idea that people do not demand for the energy in itself, but they rather choose the service it provides. Useful energy is therefore the radiant energy leaving a bulb, while *final energy* is the energy made available in forms of different energy carriers, and is subject to market transactions. Studying energy demand in terms of useful energy better grasps the requirements for a certain level of service, leaving aside the conversion efficiencies, and it is crucially important when comparing regions at different stages of development. In order to be more clear, the EDGE calculation flowchart is presented in figure 3.3. Hence, the model first inputs are related to the main socio-economic and climatic drivers. These are used to project floor space demand, which is in turn an important driver of useful energy requirements. Finally, energy carriers share and efficiencies are used to shift from useful to final energy.

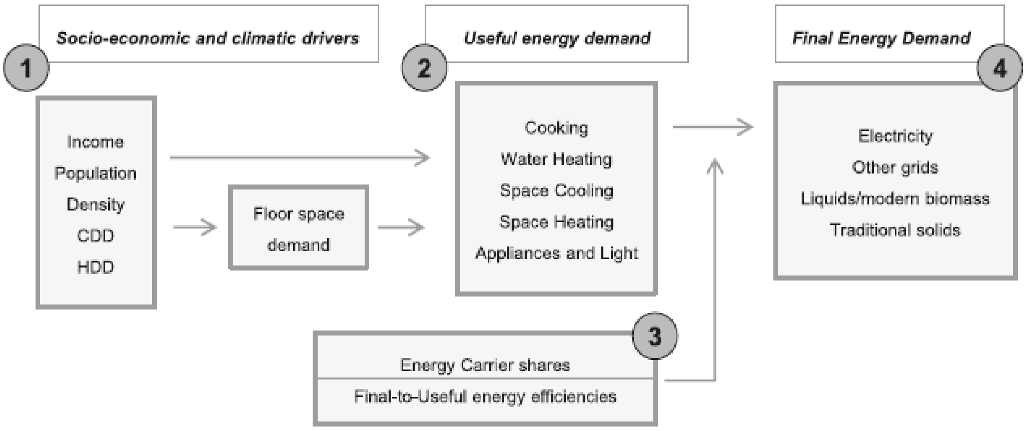


Figure 3.3: EDGE calculations steps [19]

Main equations

The main calculations of the model, which will also be relevant in this work will now be presented. First of all, it must be remarked that the calibration parameters shown in the equations of this paragraph *start in 2015 from a level that is determined in order to match historical data, then converge over a very long period (after 2100) to a certain value, which depends on the considered scenario.* These coefficients represent different behavioural and technological aspects which are not explicitly accounted for in the model, yet influence the energy demand. This is how the regional convergence over time works.

Following the calculation flow of figure 3.3, the **floor space per capita** F equation is firstly shown, since it directly influences both space cooling and space heating demand. F is assumed to be dependent on income per capita I and population density D, according to equation 3.1, being t the timestep, β and γ the elasticities respectively of income and population density. The latter two parameters are determined by an regression on historical data. Due to an expected rise in urbanization and lower floor space per capita in urban regions, income elasticity is decreased over time in most scenarios. A stepwise calculation is used, thus future floor space demand is based on the value at the previous timestep. This equation is referred to the residential floor space, while the commercial one is calibrated by regressing the ratio of commercial-to-residential area against income levels, and for developed countries it is assumed that the floorspace of both sub-sectors increases at equal pace.

$$F_t = F_{t-1}(\frac{I_t}{I_{t-1}})^{\beta_t}(\frac{D_t}{D_{t-1}})^{\gamma} \tag{3.1}$$

Space heating demand SH is then computed based on HDD, U-value U, floor space per capita and population $F \cdot POP$ and a positive parameter δ_{heat}. The final convergence value of the δ_{heat} term is obtained by regressing the left-side term of equation 3.2 against HDD, based on historical data, as will be shown in the graph on the right, in figure 3.4.

$$\frac{SH}{F \cdot POP \cdot U} = \delta_{heat} \cdot HDD \tag{3.2}$$

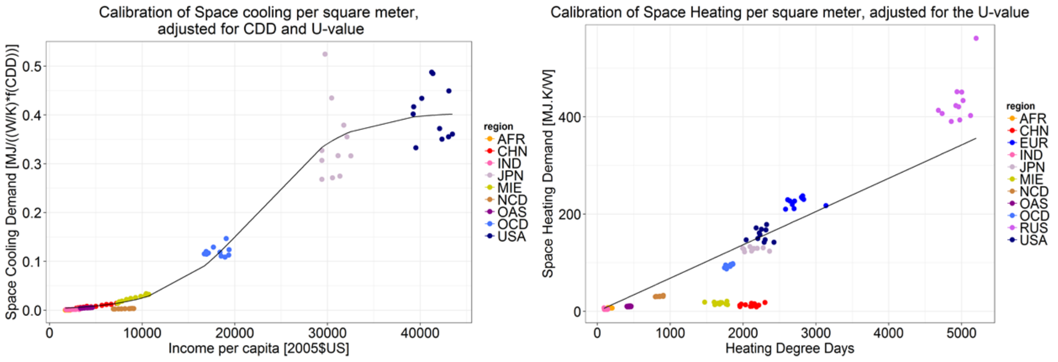


Figure 3.4: EDGE regression analyses for space cooling (left) and heating (right) demand, normalized by floor space and U-values [19]

Space cooling demand SC is then computed based on CDD, U-value U, total floor space $F \cdot POP$ and two calibration terms, which reflect the hypotheses on air conditioning diffusion. The first one is named $ClimateMax$ and depends again on CDD: it represents the climate maximum saturation effect. Indeed, it is assumed that the lower the CDD level, the lower the space cooling systems diffusion, irrespective of income. Thus, this term reflects ownership rates of air conditioners. The second calibration term, δ_{cool} is a combination of three parameters ϕ and depends on income per capita I. The three ϕ terms are obtained by regressing the left-side fraction of equation 3.3 against income levels. These terms have a physical meaning: ϕ_1 is the value of the function asymptote when income approaches infinity, ϕ_2 is the midpoint of the sigmoid curve and ϕ_3 is a horizontal scale parameter for the curve.

$$\frac{SC}{F \cdot POP \cdot U} = CDD \cdot ClimateMax(CDD) \cdot \delta_{cool} \tag{3.3}$$

With

$$\delta_{cool} = \frac{\phi_1}{1 + exp(\dfrac{\phi_2 - I}{\phi_3})}$$

Finally, the computation of **useful-to-final energy efficiencies** η for the *i-th* energy carrier is shown in equation 3.4. The conversion from useful to final energy in each region is made by computing a regional-level efficiency, computed by each energy carrier efficiency, weighted on their carrier share in the country mix. Efficiencies depend on income per capita I and again, three ϕ parameters are calibrated to match historical data. ϕ_1 and ϕ_2 respectively represent the minimum and maximum level of efficiency, while ϕ_3 describes the curvature of the function. According to thermodynamics laws, efficiencies cannot be higher than 1, apart from those of heat pumps and electric cooling systems.

$$\eta = \phi_1 + (\phi_2 - \phi_1) \cdot exp(-exp(\phi_3) \cdot I) \tag{3.4}$$

Concerning energy carrier shares, simple assumptions are made. Based on the *energy ladder* concept, traditional biomass and coal are assumed to provide energy at low levels of income. When people get richer, these carriers are firstly replaced by liquid fuels, and finally by modern fuels such as natural gas, modern biomass, district heating and electricity. Therefore, the share of traditional fuels is decreased to 1% as the GDP approaches 20000 \$/cap. However, at high income levels, there is no concept similar to the energy ladder. Energy carrier shares are partly determined by energy prices, but there is large uncertainty both on their development over time and on how the energy demand response will change over time. Thus, long-term percentages of energy carrier diffusion were defined, according to the defined scenario, and shares evolve over time towards these values.

The impact of calibration terms is not negligible at all, especially for certain regions. To further show how the calibration and convergence over time works, a brief example is provided. Looking at figure 3.4, it can be seen that regions like Middle East and China show much lower levels of heating demand, compared to the regressed straight line, which has a slope equal to $\delta_{convergence}$ while the opposite consideration holds for Russia. Therefore, the starting values of δ in 2015 will reflect this regional difference, with $\delta_{heat,RUS}$ being higher than the convergence value, and $\delta_{heat,CHN}$ and $\delta_{heat,MIE}$ being much lower. Therefore, the space heating demand of China and Middle East regions will be lower as well, while the opposite will be true for Russia. Over time, these parameters are assumed to converge to the regression value $\delta_{convergence}$. The ratio $\frac{\delta_{region}}{\delta_{convergence}}$ will therefore get closer to 1 over time, as figure 3.5 shows. Depending on the considered scenario, both faster or slower convergences can happen and the final convergence value can differ.

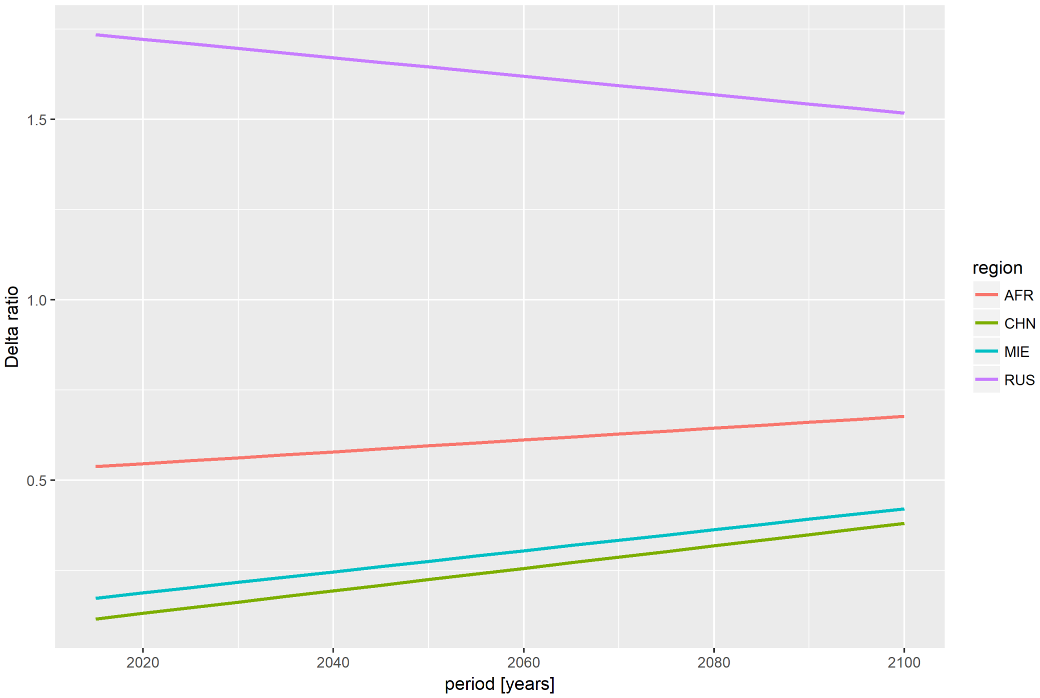


Figure 3.5: Ratio of the regional calibration parameter to the convergence value

3.2.1 U-values module in EDGE

A deeper insight into the computation of U-values is here provided. Differently to what was made in the previous section, the assumptions will also be criticized and main limits will be shown. The conclusions will then lead the discussion towards the improvement section. First of all, equation 3.5 shows the calculation of U-value levels in the current model:

$$U_{value} = \gamma(\phi_1 + exp(\alpha + \beta(CDD + HDD)) \tag{3.5}$$

The assumptions behind equation 3.5 are not analyzed:

1. Insulation increases with both HDD and CDD and these parameters are given an equal weight in determining the building envelope insulation level;
2. Insulation cannot fall below a lower asymptote of ϕ_1, which is equal to 0.45, and is then multiplied by a scenario coefficient γ, which varies from 0.35 (for SSP1, the green world pathway) to 0.85 (for SSP4, the high inequality pathway) depending on the considered scenario: therefore the lowest possible envelope U-value is 0.16 $W/m^2/K$;
3. For low income households, U-value is multiplied by a coefficient linearly decreasing from 2 to 1 when the country income increases from 0 to 15000 US \$/cap;

4. U-value of buildings is assumed to evolve only in the long term and not to follow yearly variations in HDD and CDD. Thus, U-values are linearized, to give a smooth change from the starting period to 2100, which reflects the regional climate variation;

5. Buildings insulation can only improve over time;

6. A country-specific correction is implemented for Russia. Since this region shows a very high amount of HDD (around 5000, see figure 3.4), equation 3.5 would result in a highly efficient building stock, which contradicts observations. Therefore it is assumed that Russian U-values cannot be lower than the European ones and converge to the estimations of 3.5 in the long term.

The outlined assumptions finally result in the trends outlined in figure 3.6. The impact of income correction can be highlighted by looking at developing regions (AFR, IND, NCD, OAS, MIE, CHN) U-values, especially during the starting years. The different GDP assumptions of the SSPs clearly emerge in this graph, with SSP1 showing a faster pace of income increase for all countries, and SSP4 and SSP3 showing the lowest. A second remark is related to what was outlined in figure 3.2: SSP1 gets the lowest amount of (HDD+CDD). However, SSP1 also shows the lowest U-values, which seems to contradict equation 3.5. However, this is not the case because the assumption on the γ term depends on the scenario. Therefore, this correction shows its importance in this figure.

Criticism

Based on the analyses performed in chapter 2, several remarks can be raised:

1. Insulation levels depend on a wide array of factors, with climate being certainly the most important one, together with time. However, the regression analysis in section 2.4 showed that HDD are by far a more significant parameter in determining insulation levels, compared to CDD. Thus, equal weights in the computation of U-values should not be given to them. It is yet true that at least in Europe, the amount of HDD (ranging from approximately 1000-5000 K*day [35]), is one order of magnitude higher than CDD (ranging from 0 to 500 k*day [35]), thus the former parameter will be more important in any case. This does not hold true for cooling-based climates. However, most of these countries are still in a low stage of development, thus the income correction becomes important and U-values are raised in any case. Currently, U-values in very hot countries are very high (see appendix A. It is uncertain if higher levels of CDD will push U-values down in the future, but in any case the indications from IEA are clear: insulation should not be neglected even in cooling-based climates, where reflective technologies are certainly more impacting, but they are not enough to avoid overheating [42].

2. The EU commission database shows that new buildings in the Nordic countries (Sweden, Finland), belonging to the newest vintages, already show U-values

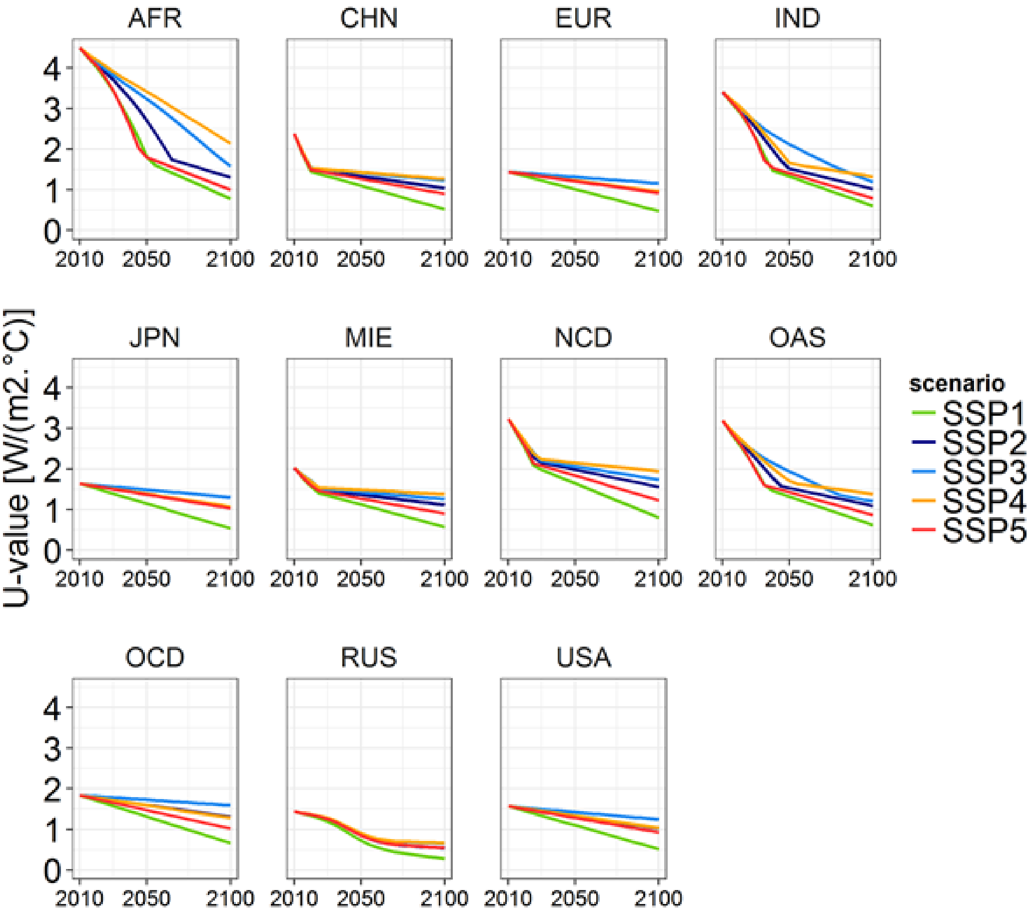


Figure 3.6: U-value projections according to SSPs [19]

which can already get down to 0.19 $W/m^2/K$ [7]. As already discussed in section 2.5.1, future cost improvements may take to the market new technologies, such as aerogel and VIPs, with much lower values of thermal conductivity. It is unlikely that country envelope U-values will actually reach levels which are lower than 0.16 $W/m^2/K$, at least at the aggregated 11 macro-regions level. However, looking into the European region, nordic countries may already be on their way to reach such low value, since they are already implementing a strong renovation of the oldest vintages (as figure 4.3 in section 4.3.3 will show) and the new construction vintages are highly efficient. Considering then the EU-EPDB directives, a further reason to believe that these countries will reach levels of U-values really closer to 0.16 $W/m^2/K$ is given. Therefore, when a higher level of detail is provided at the country level, the lower U-value limit should be decreased, down to 0.1 $W/m^2/K$.

3. According to the indications of sections 2.1 and 2.4, the effect of income results to be quite mixed in Europe. However, it certainly plays a role at low levels of richness, since investments in insulation always require a long-term point of view, but discount rate is known to decrease with income [23]. Moreover, energy

poverty represents a serious issue even in Europe, with, for instance, proportions of up to 40 % inhabitants unable to keep their house adequately warm in Bulgaria. Therefore, poor households would presumably never think about insulating their house, due to low levels of financial capability.

4. Comparing the analyses made by the EU database in 2008 and 2014, it can be seen that country-level envelope U-values generally decreased by 0.1%, yet in some countries, such as Greece, Croatia and Poland, this trend did not hold true. However, the same happened for Sweden, which contradicts what was stated at point 2. Again, some data collection issues might have arisen, as will be further discussed in section 4.7.2. Therefore it cannot be clearly stated that U-values always show a decrease over time, but two main facts should be raised. Firstly, demolition will probably occur on the oldest vintages, which constitute the worst performing buildings. Secondly, both the results of the regression analysis across vintages, performed in section 2.4, and the data from the EU database, it can be concluded that in general, country-level U-values decrease over time.

5. The reason why Russia shows higher levels of U-values, compared to the expectations based on HDDs, is linked to cheap oil and natural gas prices, which have not encouraged spending on insulation [83]. The same happens in Middle East and north Africa, for instance [16], while the same issue appears in China [84]. The importance of subsidized energy in these regions is further analyzed in appendix A and simulated in section 5.3.

Therefore, according to these points and to the analysis performed in section 2.1, energy prices may show a significant impact on U-values levels, together with income (through discount rates). Moreover, given the wide amount of data that is now available from the EU database, there is wide room for an improvement of the model: indeed, this new data source outlines that the average European-level U-value in 2014 is equal to 1.7 $W/m^2/K$, while the current EDGE model predicts it to be around 1.4 $W/m^2/K$.

Chapter 4

EDGE advancement

This Chapter introduces the extensions applied to the EDGE model. Section 4.1 presents the key dynamics of the building stock module, which constitutes the basis for the new U-value module computations, described in the remaining part of the chapter. Section 4.2 introduces the main concepts of the U-values module and the connection with the building stock module. Section 4.3 discusses the main equations, while section 4.4 introduces the input data that were chosen, based on the indications of chapter 2. Section 4.5 shows the flow of calculations which are included within the U-values module and then the ones which connect the two new modules to EDGE. Section 4.7 explains the followed approach in order to calibrate the new module results, then a comparison with the previous module outcomes is provided in section 4.8 and finally section 4.9 estimates reasonable past trends in U-values evolution and compares them with the module results. Moreover, appendix A includes all the information on the extensive literature research on U-values levels in different regions of the world.

4.1 Building Stock Module

Alongside research performed for this thesis a new module was developed in EDGE that estimates the future shares of building vintages. The development of building stock over time affecting the age shares of the current stock plays an important role in the renovation and construction potential. The building stock module together with the U-value investment module determine the average U-value of the stock.

Increased stock together with an assumed demolition rate of 0.7 % [85, 86] is assumed to be the driver of construction, following equation 4.1 (with t = time [years])

$$Construction_t = Stock_t – Stock_{t-1} + Demolition_t \tag{4.1}$$

Stock of buildings is strongly correlated with population dynamics, in terms of size and age, as well as economic growth [87]. The EU commission buildings stock data is used to perform a regression analysis, linking these drivers to the housing stock [7]. In addition we use household size data to estimate the buildings stock outside of Europe, as figure 4.1 highlights. It was found that there is a relation with a logarithmic form between occupied stock per capita and GDP per capita that saturates at approximately two people per occupied building.

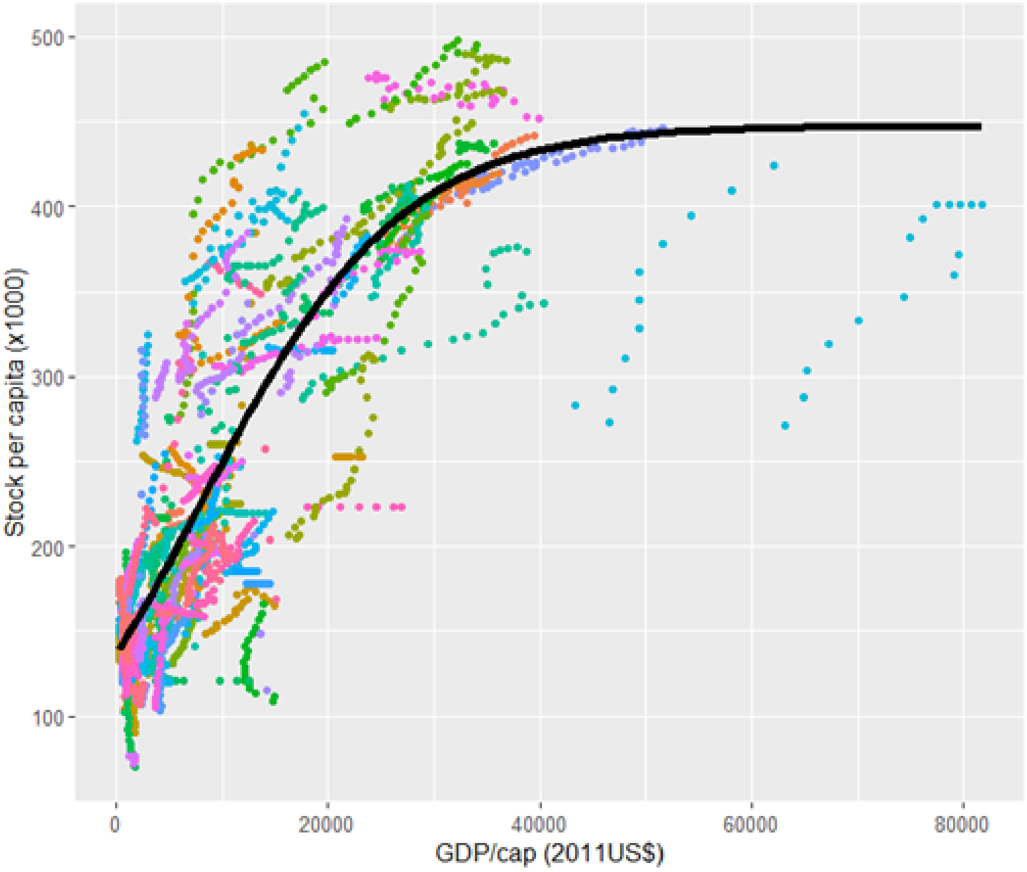


Figure 4.1: Regression analysis for the relation between stock per capita and income per capita

The logistic growth function of stock per capita, combined with the construction and demolition functions allows us the calculate historic stock following historic GDP and population development. To validate the model, these equations were run from 1945 onwards to compare the calculated stock vintages to current stock vintages for each European country, as figure 4.2 presents.

Therefore, the EDGE model will now implement a description of typical buildings related to each vintage group, according to the year of construction. In this way, characteristics typical of engineering bottom-up models will be then included. Indeed, classifying the building stock according to representative archetype values is not a new approach [17]. In energy-based models, dividing the building stock into age-groups, represented by typical buildings rated for specific annual energy consumption per m^2, allows to calculate the energy consumption per vintage, then aggregating these results will lead to the estimation of the total energy demand. However, lack of detail regarding plausible renovation intensities constituted a major weakness of these models [20]. Coupling then the building stock vintages shares with a detail on their current level of insulation can help in predicting refurbishment energy savings. Moreover, the impact of stringent building codes in the new construc-

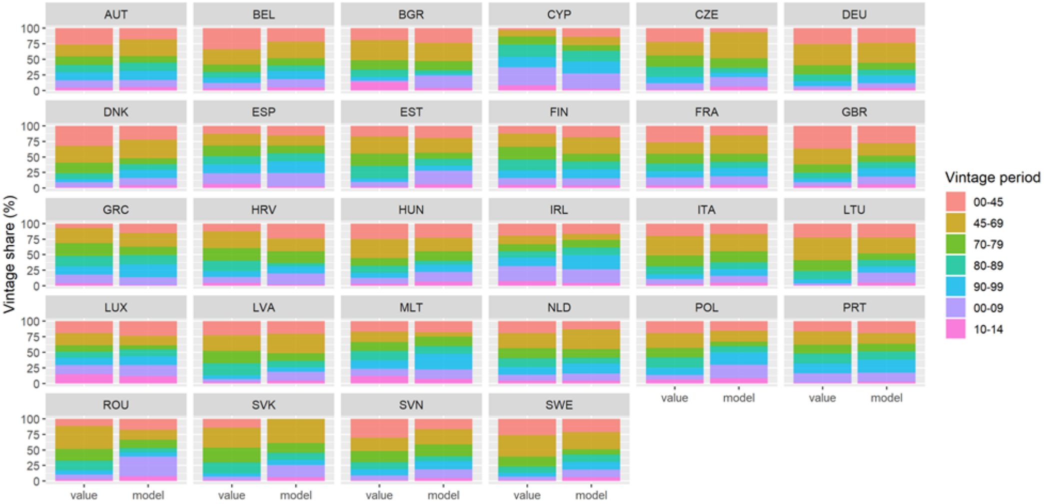


Figure 4.2: Estimated (model) Vintages in 2014 compared to current (value) vintages for different countries in Europe.

tion can also be evaluated, separately from the renovation effect, as IEA indicates 2.5.1.

4.2 U-values module: approach

The EU commission database presents data on the European building stock size, dividing the number of buildings by groups of vintages. According to the same classification, current U-values levels are related to each vintage. The building stock module outcomes constitute input data for the new implemented module on U-values. Estimations will be performed at the vintage level, for each region r, then an aggregated country-level U-value is computed by means of vintages shares, at each timestep t.

In order to choose the right approach for estimating U-values development over time, keeping into account the thesis objectives, a literature review was performed. First of all, the most important issue is related to lack of energy prices data in the model. In order to evaluate the response to increased energy prices, this limit must be overcome. Moreover, the most important energy efficiency drivers outlined in 2.1 should be included in the evaluation. However, data on future projections are not always available, especially the ones regarding house ownership.

An important indication, at the European levels comes from a report on nZEB buildings [9], which outlines that from the EPBD recast, two principles will be fundamental for future development of the building sector. While the first is related to nZEB implementation in the new construction buildings, the second concerns with *cost optimality*, for both new and renovated buildings. Accounting for all the factors determining the optimal choice for the levels of insulation of renovated and new construction buildings is therefore crucial. Firstly, increasing insulation levels would lead to both higher energy savings and investment costs. The former term depends on energy prices, while the latter is a function of technology costs. Recalling what figure 2.7 outlined, there are decreasing marginal returns of additional insulation units. Therefore there is a certain value of insulation thickness which maximizes the overall financial gains. Moreover, energy savings are recovered over the years, while technology investments are all performed at the beginning. Thus, assumptions on time discount rate should be made. The lower the discount rate, the higher the weight given to future energy savings.

However, different ways can be followed to account for *savings* and *investments*. IEA suggests that an integral approach should be undertaken, considering the whole building, in order to evaluate the most correct technologies and insulation levels within the same optimization process. This means for instance that in new construction buildings, downsizing of heating and cooling equipment due to higher insulation levels will lead to overall lower investment costs, thus the *investment* term should be decreased. Otherwise, life-cycle approaches also include environmental impacts in their calculations, outlining that the higher the insulation levels, the higher the energy that was used to construct a building (namely, *embodied energy*). Some studies show that 40-60% of the life-cycle energy in buildings is used in the production and construction phases, while others state that the operation phase accounts for the majority of the energy consumption in the building life-time [88]. Eventually, it is a matter of defining which *co-benefits* should be considered in the computations. The reasons behind the final choices will be now summarized:

- The IEA suggests to consider at least an overall building-level otpimization, considering also the heating and cooling equipment. However, technology representation is still not present in EDGE, thus this approach will be discarded;

- Including a life-cycle analysis of investments towards environmental benefits and damages would lead to further complexity and uncertainty in the evaluations, given the global and long-term point of view of the model, thus this approach will not be followed;

- Co-benefits such as employment creation, energy-security and reduced air pollution should be involved, assuming a macro-economic perspective [89]. However, accounting for them would require a too complex model. In analogy with the phylosophy of the model, the ways in which different governments evaluate such co-benefits will be represented by calibrating each country discount rate by means of historical data (further discussion is given in section 4.7).

- Detailed energy prices data are available from [10], while a thorough literature review was performed in section 2.5. Therefore, a basic evaluation of actualized energy expenditures can be undertaken and compared to investment costs, in order to estimate the optimal U-value for a defined vintage.

The new module will therefore include details on both technology and energy prices, thus making EDGE one step closer to engineering models.

4.3 Implementation

4.3.1 Net Present Cost

The IEA report on transition to sustainable buildings outlines that the primary drivers determining optimal U-values are climate, energy price, the heating system efficiency and installation costs of the insulation technology [2]. Therefore, based on the relevance and availability of drivers data, the Net Present Cost (NPC) approach has been selected, as the representative parameter of the insulation level choice at each timestep of the model. According to equation 4.2, the NPC is the sum of investment costs and energy expenditures. The NPC is expressed in $[\frac{\$}{m^2_{component}}]$, where the "component" subscript can be referred to either glazed or opaque components.

$$NPC = Investment + Expenditures \tag{4.2}$$

The formulation of the first term is shown in equation 4.3 and outlines the approach followed by several authors and reports [66, 60], moreover it follows the way technology costs have been presented in section 2.5.3. Investment costs for glazed components are only determined by a single number, representing the window cost for the considered technology. F represents fixed costs for insulation, which includes assembly costs and auxiliary equipment [58], while s [m] is the thickness of the insulation material and v the insulation variable costs, expressed in $[\$/m^2_{component}/m_{insulation,added}]$.

$$Investment_{opaque} = F + s \cdot v \tag{4.3}$$

Regarding energy expenditures, they are calculated by actualizing the yearly cash flows of money deriving by having a certain level of insulation, as equation 4.4 shows. Yearly heating and cooling Useful Energy Demand (UED), respectively are represented by SH and SC. Their computation is made by means of the EDGE model equations (3.2 and 3.3, outlined in section 3.2), with the only difference that results are now normalized by the component surface, thus they are expressed in $[\frac{kWh_{useful}}{m^2_{component} \cdot year}]$ and floor space data are not included here. Two coefficients, expressed in $[\frac{\$}{kWh_{useful}}]$, are used to translate useful energy into the market price of final energy, as equation 4.5 outlines.

$$\begin{aligned} Exp = &\sum_{t=1}^{Lifespan} (Exp_{heating} + Exp_{cooling}) \cdot (1+\rho)^{-t} = \\ = &\sum_{t=1}^{Lifespan} (C_{UE-FE,heating} \cdot SH + C_{UE-FE,cooling} \cdot SC) \cdot (1+\rho)^{-t} \end{aligned} \tag{4.4}$$

The C_{UE-FE} formulation is applied to both heating and cooling equipment. It represents the summation of each final energy carrier (FEC) coefficient, which is the ratio of its price $[\frac{\$}{kWh_{final}}]$ to its final-to-useful energy efficiency $[\frac{kWh_{useful}}{kWh_{final}}]$, weighted by the market share.

$$C_{UE-FE} = \sum_{i=1}^{n_{FEC}} C_{UE-FE,i} = \sum_{i=1}^{n_{FEC}} \frac{FEC_{price,i} \cdot FEC_{share,i}}{\eta_{UE-FE,i}} \tag{4.5}$$

Since the yearly energy expenditures do not actually vary over the years, equation 4.4 can be riformulated by means of the concept of Present Worth Factor (PWF), introduced in 4.6.

$$PWF = \sum_{t=1}^{Lifespan} (1+\rho)^{-t} = \frac{(1+\rho)^{Lifespan} - 1}{\rho \cdot (1+\rho)^{Lifespan}} \tag{4.6}$$

Therefore the concept of Energy Present Cost (EPC) can be introduced. It represents the actualized flow of energy expenditures, normalized by the component U-value.

$$Exp = (Exp_{heating} + Exp_{cooling}) \cdot PWF = U_{value} \cdot EPC \tag{4.7}$$

This evaluation allows for keeping into account both climate data, represented by HDD and CDD, and energy expenditures, summarizing information on heating and cooling plant efficiency, FEC prices and shares. Moreover, detail on technology cost is also included.

The formulation in equation 4.7 is useful in order to show an interesting property. The U-value term can be both referred to glazed and opaque surfaces. In the latter case, its formulation was outlined in equation 2.2, which has already been discussed in section 2.3. In order for the model to simulate a rational choice, the optimal U-value (i.e. the insulation level that minimizes the NPC) at each timestep, is selected. Following the approach of [66], equation 2.2 can be rewritten as a function of thickness:

$$s = \frac{U_0 - U}{U_0 \cdot U} \cdot k \tag{4.8}$$

Therefore equation 4.2 can be also rewritten as:

$$NPC = (F + \frac{U_0 - U}{U_0 \cdot U} k \cdot v) + (U \cdot EPC)$$

The optimal U-value can be then found by setting the NPC derivative equal to zero and rearranging the terms, being both U and U_0 strictly positive.

$$\frac{\partial(NPC)}{\partial U} = 0 = \frac{1}{U_0 \cdot U^2} kv + \frac{1}{U_0 \cdot U}(-1)kv + EPC$$
$$-(U - U_0)kv - Ukv + U^2 U_0 \cdot EPC = -U_0 kv + U^2 U_0 \cdot EPC = 0$$

Thus the optimal U-value and added insulation thickness can be explicitly written as:

$$U_{opt} = \sqrt{\frac{k \cdot v}{EPC}} \tag{4.9}$$

$$s_{opt} = \sqrt{\frac{EPC \cdot k}{v}} - \frac{k}{U_0} \tag{4.10}$$

Therefore, the optimal U-value depends on the product of thermal conductivity and variable costs of the insulation material. The EPC does not depend on the considered technology, thus the outlined product can be used to evaluate the competitiveness of different insulation technologies, for instance showing higher v but lower k. Section 4.4.2 will therefore utilize this approach in order to understand which technologies should be implemented.

4.3.2 Multinomial logit

The issue of computing market shares of different technologies, for both glazed and opaque components, can be overcome in several ways. In order to determine technology competitiveness, the NPC can be a reasonable indicator. The IMAGE model calculates secondary energy carriers shares by means of a so-called multinomial logit (MNL) equation, assigning each carrier a share on the basis of its relative price in a set of competing carriers. The same approach will be followed here, computing technology market shares depending on their NPC, according to equation 4.11:

$$Share_i = \frac{e^{-NPC_i \cdot \lambda}}{\sum_{i=1}^{n_{Technologies}} e^{-NPC_i \cdot \lambda}} \tag{4.11}$$

The λ term is the so-called *logit parameter* and determines the sensitivity of markets to differences in NPC. When λ=0, the market structure becomes perfectly heterogeneous, thus assigning equal shares to each technology. Conversely, the higher the λ, the more the market converges towards assigning 100% share to the most competitive technology (i.e. the one showing the lowest NPC). PBT could have also been employed as an indicator of technology competitiveness. However, when implementing it in the model, it showed several issues, compared to the use of NPC, for the computation of market shares for glazed technologies. For instance, in cold climates, the PBT of triple and double-glazed windows was basically the same, because the former technology has a lower U-value, but higher investment costs as well. However, NPC showed a clearer differentiation, across different climate levels, in the determination the optimal technology. Indeed, NPC is evaluated over a defined lifespan, thus the weight given to energy expenditures is higher and allows for a correct (in the sense that it follows actual current trends) allocation of optimal technologies across countries.

4.3.3 Endogenization of renovation rate

Once equation 4.11 is computed, an aggregated U-value and investment cost can be calculated, weighting the single technologies characteristics on their market shares.

In order to outline the profitability of a renovation measure, the aggregated U-values and cost must be evaluated against the existing level of insulation of the vintage. In order to do so, the PBT of the renovation measure is computed. Savings are computed considering the diminuition of energy demand due to gap in insulation levels (U-value). The renovation measure is then implemented only if the computed PBT, expressed in years, is lower than a defined threshold, named PBT_{max} in equation 4.12.

Once the decision to renovate or not has been evaluated, it might be an interesting question to understand to what extent a defined vintage is renovated. Therefore, an assumption on renovation rate levels was performed. Section 2.1 outlined that, according to [8], high PBT represent one of the most important barriers to renovation. Moreover, it was also highlighted that renovation works are more likely to happen in older vintages, due to general maintenance issues.. It is also known from section 2.3.1 that older vintages generally show lower levels of insulation. Hence, there is both a higher probability that in older vintages, *favourable opportunities* for energy efficiency improvement will happen, and higher profitability of the renovation measure will presumably arise. The model accounts for this effect, implementing a dependence between the renovation rate level and the PBT of the refurbishment measure, according to equation 4.12:

$$RenovationRate = Ren_{low} + (Ren_{up} - Ren_{low}) \cdot (1 - \frac{PBT}{PBT_{max}}) \tag{4.12}$$

The above equation constitutes an attempt to further show in the model, that older vintages will be renovated faster than others. No literature source was found regarding a possible functional form for this dependence, thus a linear function was implemented and a test will be performed on the impact of different functions in section 6.4. The Ren_{low} term indicates the minimum fraction of the vintage which is renovated when it is convenient to do so. Conversely, Ren_{up} represents the maximum limit. These two values had to be determined in order to follow current trends, at least in Europe. Section 4.4.4 discusses this issue.

4.4 Input data

4.4.1 Energy prices

FEC prices for electricity, fuel oil for heating, natural gas and coal across different world regions were taken from [10]. These data also indicate taxes and subsidies shares. The natural gas energy carrier in EDGE actually involves also biogas. However, [90] states that in Europe, the biogas share in natural gas use is very low, being always under 10%, with the noticeable exception of Sweden. Thus, no further research on biogas prices was performed. Modern biomass and district heating prices in Europe were taken from [60]. [91] outlines a range of prices for modern biomass pellets in China and USA, while [92] indicates district heating prices in Russia. For other nations with unknown costs, the district heating price is related to the average of coal, natural gas and oil price, with a procedure similar to [60], which related heating prices to natural gas ones (that is, slightly increasing the cost in order to account for the district heating efficiency and capital cost amortization). In this way, costs of district heating follow nation-specific prices of other carriers, even if it is recognized that some carriers could constitute a dominant share in the heating mix of the nation (e.g. in China, most of the district heating mix is provided by coal [93]). For modern biomass, based on the available data, a cost of 0.05 \$/kWh is assumed, when no information was found.

Finally, the cost of traditional biomass had to be assumed. This will have a noticeable impact in developing regions, where most of the heating is provided by this carrier. [94] states that due to low energy density, the cost of collection and transportation is a main component of the final price. However, in regions such as sub-saharian Africa, biomass is directly collected through time consuming activities by women and children, thus it does not get across any economic transaction [95]. Therefore, a representative low price of 0.01 \$/kWh is assigned to this carrier, with the idea that in any case, this carrier is not used when the country income level overcomes 20000 \$/cap, and low income households do not certainly think about better insulating their house, thus biomass prices should reflect this reality.

4.4.2 Technologies

Based on the discussion of 2.5 and aiming at a correct representation of insulation levels across countries, keeping the model simple, some technologies were discarded. This section provides a brief summary of the choices that were performed. All the costs were previously outlined in Euro/m^2. However, the model energy prices and income data will be provided into U.S.\$$_{2005}$. Thus, currency exchange rates and deflation to 2005 should be considered. However, all the uncertainty on input data will be reflected in the calculation of implicit discount rates in the calibration process (see section 4.7), therefore such a precise procedure was not applied. Moreover, two counterbalancing effects would happen: costs should be increased while translating from Euro to \$, then decreased while translating into 2005 \$.

Opaque surface insulation technologies

As outlined in section 2.5.1, the currently most important insulation technologies can be grouped into 3 main groups: traditional materials, aerogel and VIP. Other technologies are either at an RD stage and no costs data are available, or they just do not show interesting perspectives. Considering that the perspective of the research questions outlined in chapter 1 is until 2050, it is assumed that no breakthrough technology will be implemented within this period. Therefore, only these 3 groups are now considered. Keeping equation 4.9 into account, a comparison between them is performed. For the first class of materials, a representative thermal conductivity k of 0.03 W/m/K and cost v of 1.2 \$/m^2/cm were chosen. Regarding VIP, k can be assumed to be equal to 0.008 W/m/K, in order to account for ageing of the material, with v around 40 \$/m^2/cm. Aerogel k is around 0.015 W/m/K, while v roughly amounts to 27 \$/m^2/cm. With the current costs, both aerogel and VIP are not competitive with conventional materials, since the product of k and v is far higher. Considering future perspectives, aerogel cost might get down to 5 $\$/m^2/cm$, while MAI might achieve a 40% cost reduction compared to current VIP. Even if the most optimistic perspectives are assumed, still the cost of advanced technologies would be too high to be comparable with conventional materials. These advanced technologies can thus be utilized only in particular applications (i.e. when insulation thickness is strongly limited or increased living area is highly rewarded) that are behind the scope of a global model. Therefore, only this group of technologies will be implemented in the model.

Regarding insulation fixed costs, a representative value of 60 $\$/m^2$ was chosen, considering the discussion of section 2.5.1. The high costs of external wall refurbishment were not considered, since insulation costs of roof and floor are much lower. Therefore, this value should be seen as a representative average cost for insulation of opaque surfaces.

Window technologies

In order to make the model range across several performances and choose the best one, 5 groups of windows technologies were implemented, according to the indications of 2.5.2 The implemented U-values and costs are summarized in table 4.1. Single-glazed and triple-glazed U-values are referred to the upper and lower limit of windows U-values found in the EU database. The "future window" technology is referred to the indications of IEA regarding goals for high performance windows [2]. No cost indications were found for a window with such a low U-value, therefore the cost is initially assumed to be extremely high, in order for this technology to not enter the market in 2015. Then, the 2050 cost is computed assuming increasing marginal costs for an additional reduction of U-value, as happens with opaque surfaces insulation. Hypotheses on cost reductions *Red* will be applied to all the considered components.

Technology	**U-value** $[W/m^2/K]$	**Cost**$_{2015}$ $[\$/m^2]$	**Cost**$_{2050}$ $[\$/m^2]$
Single-glazed	5.8	150	$150 \cdot Red$
Double-glazed, clear glass	3.8	220	$220 \cdot Red$
Double-glazed, thermal break and low-e coating	2.3	280	$280 \cdot Red$
Triple-glazed	1.1	400	$400 \cdot Red$
Future window	0.6	1000	$500 \cdot Red$

Table 4.1: Implemented parameters related to window technologies

Reflective technologies and SHGC control

Reflective coatings and adequate SHGC windows have the potential to strongly reduce cooling loads. However, cooling is strongly linked to the interaction with sunlight. Therefore, in order to correctly model such heat flows, at least a model of the building geometry should be assumed. Moreover, solar heat gains would vary across countries, depending on their climate. Given the global point of view of the model, such a complexity has not been implemented, since reference buildings should presumably vary across regions, due to different constructions techniques. Thus, reflective technologies were not implemented in the model.

IEA also outlines that the performance of single-glazed windows can be strongly improved without any substitution of the component, only applying a low-e coating. This procedure would halve the costs for renovation measures, but it has not been implemented, since the same technologies and costs will be applied for both renovation and new construction modules. It is also recognized that both energy efficiency improvement in the occasion of a general renovation and in new construction works would show much lower costs, however within the EDGE model it cannot be really evaluated when such an occasion would happen. Moreover, as will be better seen in figures 4.4 and 4.6, the new construction module is already favoured with respect to the renovation one, since in the former one, optimal levels of technology will be implemented in any case (especially for windows, while a correction is applied to opaque surfaces), while no renovation is applied when the PBT is greater than a defined threshold.

The current limits on the differentiation between retrofit and new construction technologies and climate are suggested as future works for model improvement, in section 7.2.

Cost differentiation across regions

When the correct energy prices were implemented in the model, several issues arose with keeping the same technology costs across regions. Indeed, countries with very low energy prices could not recover the initial expenditures, resulting in the implementation of very low levels of insulation. Therefore, a rough representation of technology costs was also required. According to the approach of [60], European countries were grouped by PLI clusters, as figure 2.12 outlines. Then, the basic costs outlined in section 4.4.2 were multiplied by the corresponding PLI of the country. This means that a country with a PLI of 120 would get investment costs which are 20% higher compared to the base. The precise country PLI was not used since like all statistics, they are also affected by error margins, thus countries should preferably be clustered [77]. Considering the world level, a regression analysis showed that GDP levels of a country are highly significant predictors of its PLI. This is reasonable due to the high labour share in the building sector works. Therefore, for the other world regions, PLIs were estimated from the corresponding income level. The USA PLI has been decreased to 70, since despite showing GDP levels whcih are similar to Europe, insulation costs in this country are much lower, as section 2.5.3 highlighted.

4.4.3 Discount Rate

A thorough discussion could be provided on the importance of uncertainty on discount rates in the evaluation of building retrofit decisions. For instance, [96] states that applying a Monte Carlo simulation on Net Present Values, 60 % of their variance is explained by the discount rate, which was varied from 0 to 15%. Attempts were made in order to understand what are the levels of discount rate that consumers implicitly assume. [97] states that investments in the building envelope show high rates of 10-30%, while indicates a 18% median consumer discount rate for the same type of investments.

The PRIMES model assumed a 17.5% household discount rate which then decreases over time when policies are implemented [98]. However, the same report outlines that the use of high discount rates to map non-economic barriers and bounded rationality is not suitable: behavioural models should be implemented to perform such analyses. Moreover, [99] recalls notes from the IPCC 4^{th} assessment report, which outlines that in developed countries, rates of around 4-6% are justified, while for developing countries thsi value could get to 12%. Finally, [12] remarks that *discount rates are only relevant if an investor performs a dynamic evaluation of economic efficiency (e.g. net present value). If the existence of non-economic barriers and other decision criteria is considered to be relevant, an application of purely economic optimisation is obviously not the correct measurement to simulate investor decision making and thus, discount rates are not appropriate as a parameter for capturing barriers and other decision criteria.* Discount rates will be used as a calibration parameter: all of these considerations will be taken into account in section 4.7.

4.4.4 Renovation rates

Renovation rates are usually expressed in percentage of the total stock size. [23] outlines renovation rates of 6% for glazed surfaces and 4% for opaque components, over a period of 6 years, which therefore leads to a 1%/year. [85] shows the results of a dynamic building stock model applied to several European countries. In particular, it outlines that despite scenario analyses for energy savings commonly assume renovation rates of 2.5-3%, this does not generally happen in reality. Their model shows that refurbishment rates resulting from dwelling stocks' ownership turnover, or need for maintenance (therefore when energy efficiency measures could be readily introduced), will be far below these levels, ranging from 0.5-1.5% of the total stock. The same findings are outlined by the IEA, which indicate an yearly 1% renovation rate. Considering that, as outlined in section 1, the EU EPBD has an objective of a 3% yearly renovation rate, these considerations are particularly important. However, no information is available, from these sources, about the intensity of renovation. The most interesting data source comes from the Zebra 2020 project, which collected data on *major renovation rate equivalent* [89]: figure 4.3 outlines the results. The definition is taken from the EU EPBD recast and regards a renovation in which either the total cost exceeds 25% of the building value, or more than 25% of the building envelope surface undergoes refurbishment. It is assumed that major renovations lead to final energy reductions of about 50-80%.

In the way the model works, renovation is either implemented for all opaque surfaces and/or for windows. The EU database assumes a 25% share for the areas of each component (floor, roof, wall and window), when no information is available. As will be shown later (indicate here the section!), the model calculates very low renovation rates for windows (which is in accordance to [2], which states that windows replacement at the only scope of energy conservation is rarely profitable), while this is not the case for opaque surfaces. Since the optimal U-value for opaque components generally ranges around 0.25 $W/m^2/K$, as section 4.6 will present, it is reasonable that this kind

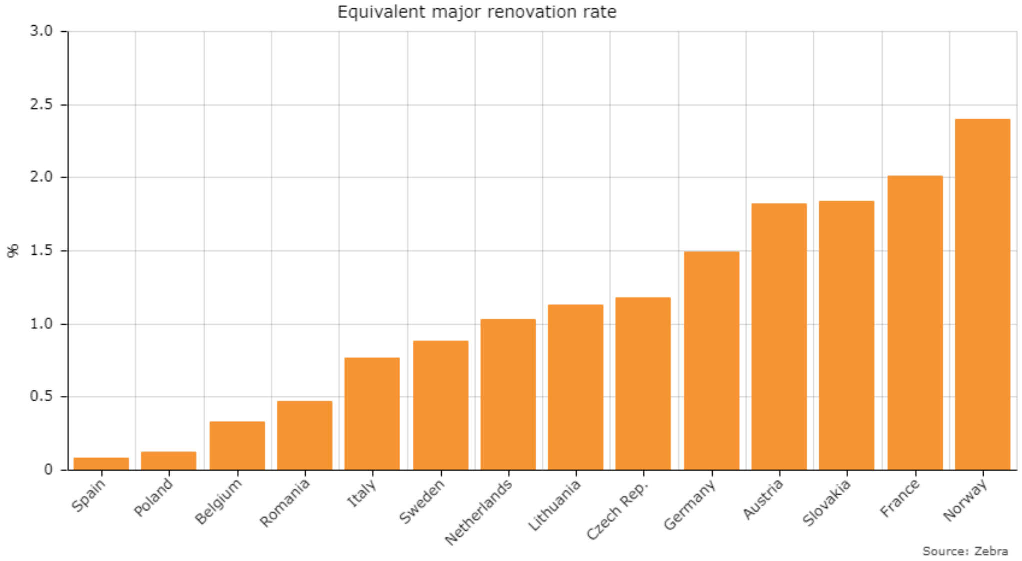


Figure 4.3: Equivalent major renovation rate [89]

of measure will lead to at least a 50% reduction of the envelope U-value. Moreover, assuming a 25% share of each component surface, the model would modify 75% of the total envelope area when opaque surfaces are renovated. Therefore, the rates indicated in figure 4.3 actually match the renovation intensity of the model and can be used to calibrate the Ren_{low} and Ren_{up} terms in equation 4.12. These were calibrated in order to match the resulting average renovation rate for the considered countries. The span Ren_{up}-Ren_{low} was then computed in order for the model results to show a variance which is lower than the actual data (since PBT is only one of a multitude of factors that influence the renovation decision).

4.4.5 Other data

Assumptions on technology cost decrease constitute a great issue, given that only qualitative indications on market entry and future improvements can be derived by the main reports, such as [2]. Moreover, given that even assuming certain levels of technology costs represented a problem (as explained in section 4.4.2), looking for historical data on the development of prices over time would not make much sense. Therefore, the available reports were reviewed, looking for assumptions on cost decrease. The most interesting indication comes from [31], which outlines ranges of cost decrease depending on the intensity of renovation. They range from a reduction of 0.5%/y for minor renovation depth (i.e. leading to a 15% energy reduction) to 2%/y for nZEB-level refurbishment (i.e. leading to a 95% energy reduction). Section 4.6 will indicate that the optimal U-value for opaque surfaces will be really low, ranging around 0.2 W/m^2/K. Assuming a starting U-value of 2 W/m^2/K, it means that renovation would decrease energy consumption by 90%, if opaque components are considered. However, section 4.6 will also outline that renovation of glazed components hardly results profitable, thus it almost never occurs. A reasonable starting U-value for an old European building can be assumed equal to 4 W/m^2/K for windows. With the hypothesis of equal surface shares of floor, roof, walls and windows, the initial envelope U-value would be 2.5 W/m^2/K, while the renovated one would be equal to 1.15 W/m^2/K. Hence, given the direct proportionality of space heating and cooling demand on U-values, it means that a typical renovation measure in Europe would lead to 45% energy savings. The considered report indicates that such an amount of energy reduction is linked to a "moderate" level of renovation, for which a cost decrease of 1%/y is assumed. Thus, technology costs in the baseline model will be reduced by the same quantity each year. In any case, a sensitivity analysis on this highl uncertain assumption will be performed in section 6.1.

Other assumptions regards the PBT_{max} term of equation 4.12, which represents the maximum amount of time that is given to the energy savings to pay back the initial investment cost. [12] assumes 30 years as the considered span of time over which the profitability of the investment is evaluated, while [100] indicates 25 years for this parameter. Based on these indications, the final choice for the model is 30 years.

Regarding the new construction lifespan, [84] outlines that the Chinese design code regulates that residential buildings should be constructed to operate for 50 years at least, while [88] indicated lifespans of 50-80 years for European and U.S. buildings. However, IEA outlines that buildings in developing countries tend to have shorter lifespans, ranging from 25-35 years [2]. [101] indicates that Japanese buildings tend to have smaller lifespans as well: 26 years against an average of 44 years for U.S. houses. Therefore, in order to balance all the indications, the final choice is 50 years. Choosing a different value would change the PWF of the investment (see equation 4.6), which is finally calibrated in order to fit the historical data, as will be explained in section 4.7.

4.5 Calculation flowcharts

Two separate modules were developed. Both compute opaque and glazed surface U-values development. Since the former group of components (floor, roof, and walls) presents similar technologies for insulation improvement, in the renovation module the starting U-values of opaque surfaces are averaged into one single value. Accordingly, also the new construction module does not distinguish between roof, floors and walls, indeed it computes U-values only for a single "opaque surface" group. Figure 4.4 highlights the renovation module computations, according to the equations that were shown in section 4.3.1. Once the renovation level is computed, figure 4.5 shows how the module computes the new insulation level of the vintage. The renovation rate which is outlined in that figure is related to a 5-year timestep (therefore it corresponds to a 2%/year)

The new construction module follows the same steps of the renovation one, without taking as input any starting U-value and without computing any renovation option. However, three additional steps are added, for opaque surfaces only. These are required in order to obtain a better calibration of the model. the reasons behind

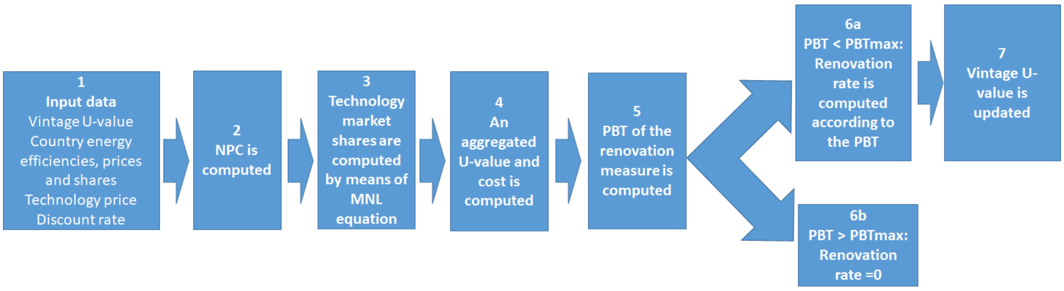


Figure 4.4: Calculation steps for the renovation module

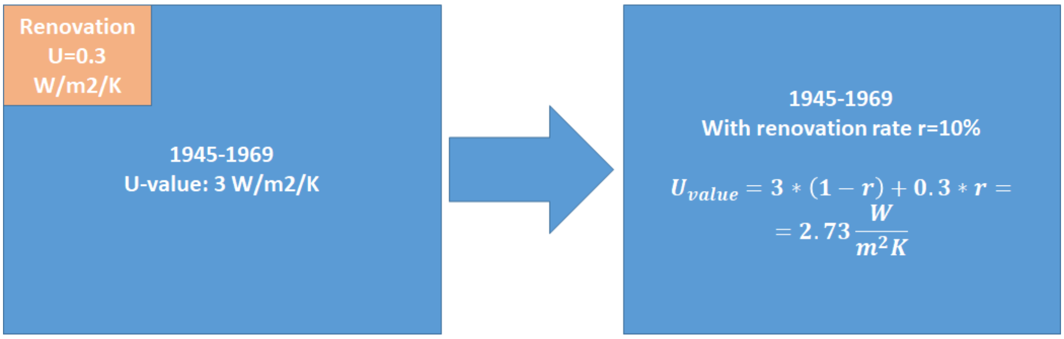


Figure 4.5: Example of U-value update for the considered vintage

this choice are explained in sections 4.6 and 4.7. It can be seen that for window technologies, the U-value resulting from the MNL aggregation is implemented in any case.

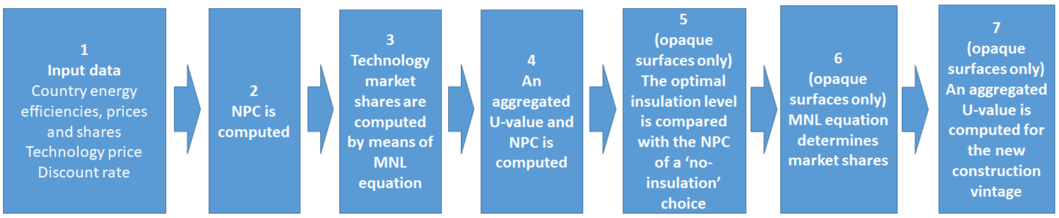


Figure 4.6: Calculation steps for the new construction module

Figure 4.7 summarizes the main connections between the new modules and EDGE, in order to finally obtain the FED estimations.

4.6 First diagnostics

In this section, a simple version of the calculations is presented in order to show how the optimization and the MNL aggregation work, together with main sensitivities to input data. Firstly, two examples related to the renovation module are presented. The first one is related to the optimization process of opaque surfaces insulation levels. Then, the optimal U-value improvement for glazed components is presented. Secondly, an example of the new construction calculation is proposed. All the input data are

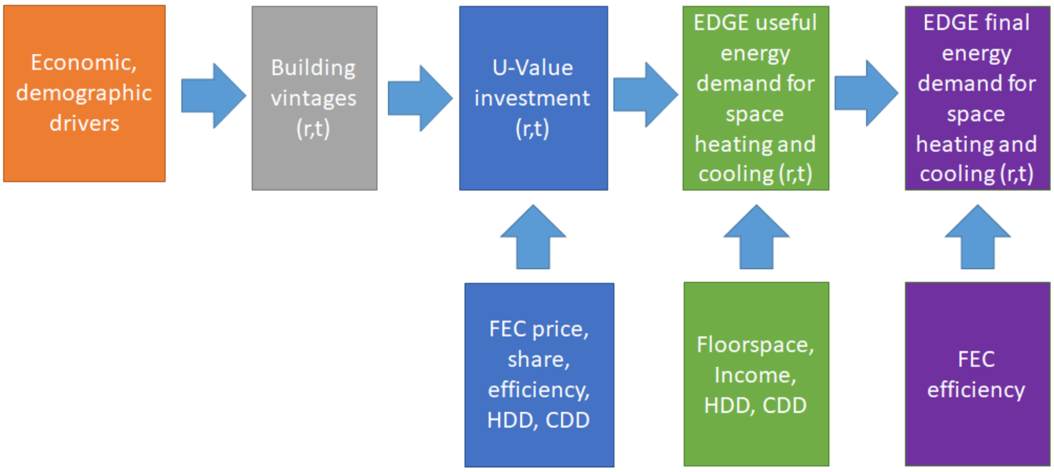


Figure 4.7: New modules addition in the EDGE calculation flowchart

related to a typical European country, with a heating-based climate and are outlined in table 4.2. The table also indicates symbols that are used in the presented graphs.

Parameter	Value	Unit	Symbol
Starting U-value (opaque)	2	$W/m^2/K$	U_0
Starting U-value (window)	4	$W/m^2/K$	U_0
Energy price, heat	0.1	\$/kWh	HEP
Energy price, cool	0.2	\$/kWh	CEP
FE-UE efficiency, heat	0.95	kWh_{final}/kWh_{useful}	H,FE-UE
FE-UE efficiency, cool	2	kWh_{final}/kWh_{useful}	C,FE-UE
Discount rate	8	%	r
Insulation thermal conductivity	0.03	W/m/K	k
Insulation variable cost	1.2	$\$/m^2/cm$	v
Insulation fixed cost /Window cost	60	$\$/m^2$	F
HDD	3000	K*day	HDD
CDD	400	K*day	CDD
Lifespan	30	years	Life

Table 4.2: Input data for the following computations

Renovation - opaque surfaces

In the renovation module, the optimal level of insulation is computed and then compared to the current U-value of the considered vintage. It is interesting to show how the NPC, the PBT and the optimal U-value are affected by changes in input data. NPC is important for the MNL aggregation, especially for windows, and the conclusions that will be drawn here will apply in the same way to glazed components. PBT is of course important for the renovation decision, while the optimal U-value is important to determine the country-level U-value development. Therefore, various cases have been computed, in which only one input parameter has been multiplied by a coefficient ranging from 40% to 160%, to simulate either an increase or a reduction of its value.

Figure 4.8 summarizes the main dependences.

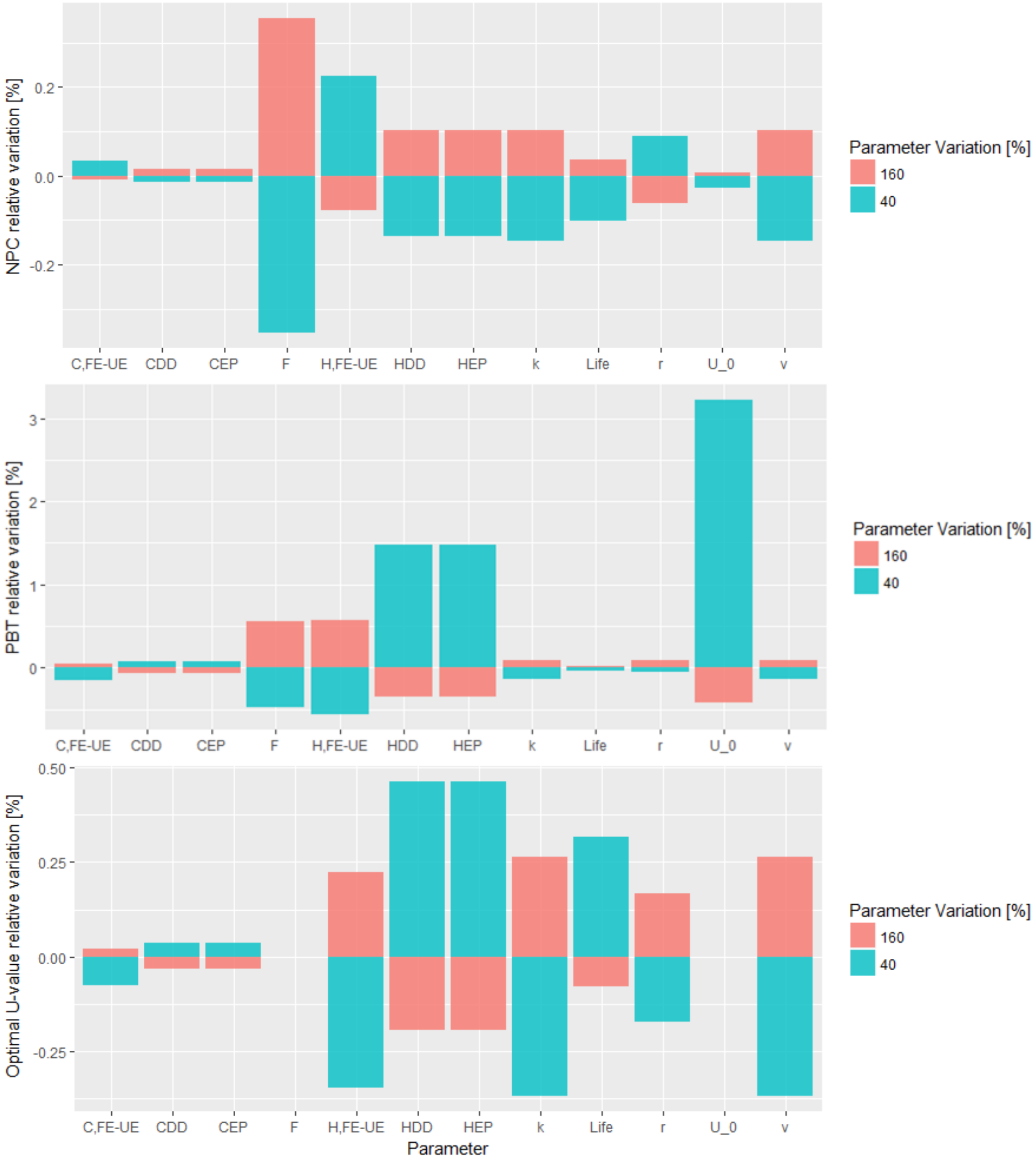


Figure 4.8: Sensitivity of NPC, PBT and optimal U-value to input data variations

As can be seen, variations in cooling-related parameters (efficiency, price and CDD) is not as important as the same variation for heating-related inputs. If a cooling-based climate were considered, the opposite results would happen (however, cooling demand in EDGE is also dependent on income, see equation 3.3, thus this would add further complications on the analysis). The basic NPC, PBT and optimal U-value are respectively around 100 $\$/m^2$, 6 years, 0.17 $W/m^2/K$. Therefore, the renovation investment is highly profitable and would lead to a very high level of insulation. The NPC is strongly affected by the insulation fixed costs, while variations in the variable costs are less impacting. This is in line with what was discussed in section 2.5.3. k and v impact the three parameters in the same way, since the optimal U-value is equally affected by both (equation 4.9). The same holds true for heating energy price and efficiency, which both impact in the same way to the EPC term in equation 4.9. Correctly, the optimal U-value is influenced by neither the starting U-value, nor the insulation fixed costs.

A first important remark regards the high sensitivity of the PBT to the starting U-value. As soon as the starting U-value decreases, the PBT strongly increases. Looking at figure 4.5, it can be seen how the starting U-value of a vintage is updated when a certain level of renovation happens. In this way, the model does not account for the fraction of renovated houses at the following timesteps, but it will work as if all the buildings in a certain vintage are slightly renovated, The high sensitivity of the PBT to the starting U-value will therefore mean that once a vintage is renovated, in the following timestep the probability of renovation will drop down, due to the decreased starting U-value. Not being able to account for the shares of buildings which are renovated is a major weakness of the model. However, the starting data from the EU buildings database are averaged as well. Therefore, a vintage showing an average U-value of 2 $W/m^2/K$ might contain better performing envelopes (i.e. having U=1 $W/m^2/K$), and worse performing as well (i.e. having U=3 $W/m^2/K$). As was shown in section 2.3.3, there is a certain distribution of buildings insulation levels in a country stock. It is reasonable to think that the same happens within a vintage, even if with lower variance for sure. In any case, since the actual distribution of U-values within a group of buildings is unknown, vintages will accordingly be seen as "black boxes" with a defined U-value level, keeping the procedure outlined in 4.5. This causes of course some issues, as will be seen in section 6.6, yet it seemed the most reasonable choice. In any case, further work on this aspect is suggested in section 7.2.

Then, it can be deduced that the optimal U-value is not highly responsive, in absolute terms, to HDD variations. Indeed, a 25% addition to a U-value of 0.17 $W/m^2/K$ would mean getting to 0.21 $W/m^2/K$. This constitutes a problem, since in section 4.7, a calibration will be performed and the new construction module results will be compared with the historic data. Given that, as is explained in appendix A, the newest vintages of developing countries show U-values of 3 $W/m^2/K$, the response to climate of the computed U-value had to be increased. This is why, as can be seen from figure 4.6, in the new construction module some additional steps were implemented. This procedure is further explained later in this section.

Renovation - glazed surfaces

In this paragraph, the calculation to obtain the U-value for renovation, from the 5 windows technologies is presented, in order to clarify how the MNL aggregation works. The considered cost for the *Future window* technology in this case is 500\$/m^2. This U-value will be then compared to the starting U-value of the vintage and according to the resulting PBT, it will be decided whether to renovate or not. Figure 4.9 outlines the outcomes of this calculation.

As already stated in section 4.3.2, when the logit parameter (named λ in equation 4.11) is equal to 0, the computed mix is totally homogeneous (this means that the calculated U-value of the renovation option is an average of the U-values presented in table 4.1).

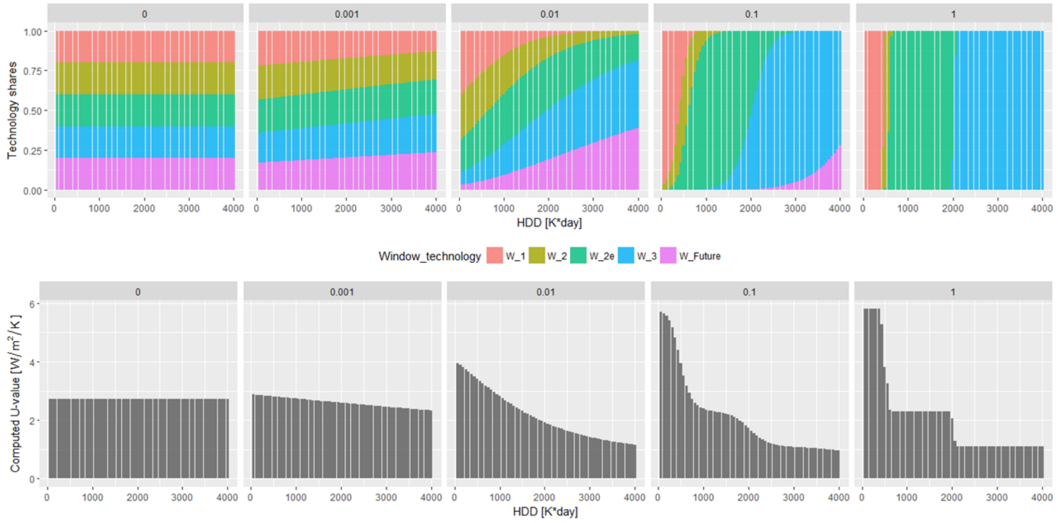


Figure 4.9: Computed window technology shares and U-values according to HDD and logit parameter

Therefore, the computed U-value is not responsive to climate levels. Conversely, for λ equal to 1, the model almost converges to the optimal choice, with sudden shifts across HDDs. This eventually results in sudden shifts of U-values: the model becomes very responsive to input data variations. While for λ=0.001 the mix is still almost perfectly heterogeneous, λ=0.01 appears to be a case which is in between the totally-heterogenous and the almost-optimal mix. This is important in order to decide which value should be assigned to λ in the model calibration. The 0.01 value seems to be the most correct one, considering the more gradual shift of technologies. However, to represent low-HDD climates, a higher λ would be preferred, because warm countries mostly employ single-glazed windows.

Moreover, it can be seen by figures 4.8 and 4.9 that with lower HDDs, the optimal U-value will be higher. Recalling figure 3.2, this means that in scenarios with higher amounts of HDD and CDD, insulation levels will increase to a higher extent. Therefore, the final heating demand would be increased by higher HDDs, but decreased by a lower U-value. The corresponding results, for a λ=0.01, are outlined in figure 4.10. The final heating demand eventually increases with HDDs, yet not in a directly proportional way.

The same counterbalancing effects would arise from final-to-useful energy efficiency variations. In fact, a higher efficiency of the heating equipment would lead to a lower computed U-value, since lower expenditures on energy would arise. Therefore, the final heating demand would be increased by a higher U-value, but decreased due to a higher final-to-useful efficiency. As happens with the HDDs, the U-value increase would not offset the efficiency growth, thus leading to an overall lower heating demand. All these remarks will be particularly important in the discussion of section 6.5, since different SSPs lead to variations in efficiency as well as to different levels of HDDs and CDDs.

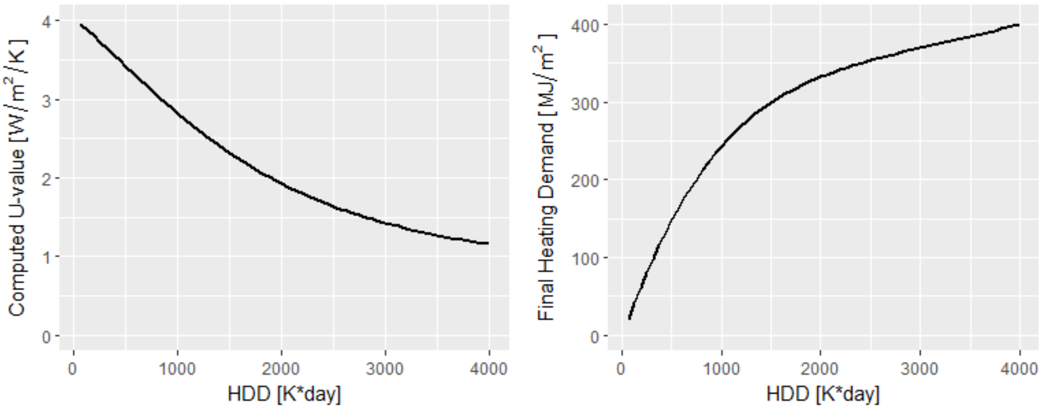


Figure 4.10: Computed U-value and corresponding heating energy demand variation according to HDD

A final remark comes from the analysis of PBT dependency. Indeed, implementing a λ=0.01, in the basic case, the PBT already exceeds 50 years. If the optimal λ is implemented, PBT dereases to 40 years, which is still very high. This is again in line with what IEA outlines: the substitution of windows at the only purpose of energy efficiency improvement is rarely profitable [2]. Therefore, the model will always predict lower levels of window renovations, compared to opaque surfaces.

New Construction - opaque surfaces

In this paragraph, the procedure implemented in steps 5, 6 and 7 of figure 4.6 is explained. In step 5 of figure 4.6, the computed U-value and NPC are compared with a 'no-insulation' choice. This option is computed assuming the U-value of an opaque surface which is not insulated (U=2.7 W/m^2/K, estimated from the EU database) and thus having no investment cost. The energy expenditures related to this option are strongly dependent on climate and by choosing a correct logit parameter λ, a higher sensitivity to climate can be reached, in order to better fit results at the world level. As can be seen from figure 4.11, for λ=0.1 the dependence on climate is basically lost, while in the λ=0.001 case, the mix is almost heterogeneous. Instead, when λ is equal to 0.01, a small dependence on climate persists. As will be shown in the following section, the new construction U-values in heating-based countries will generally be low. Choosing a different U-value for the no-insulation option would not lead to an improvement of the model. It is recognized that uninsulated walls have much higher U-values, yet implementing a greater U-value would only lead the model towards choosing the insulation option, therefore there would be no point in implementing this correction

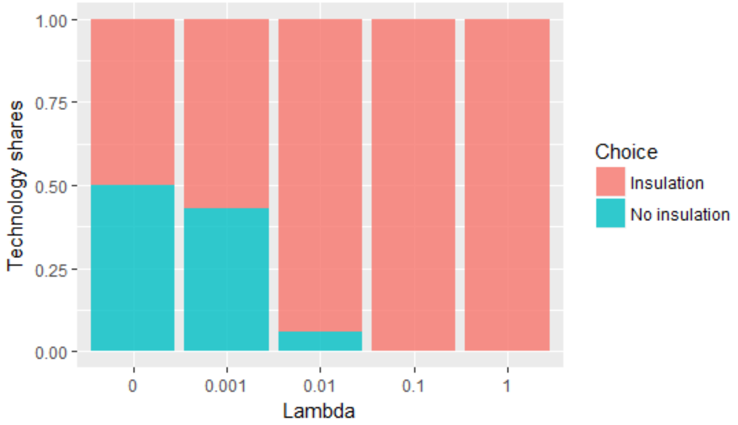


Figure 4.11: Computed shares in new construction according to different logit parameters

4.7 Calibration

Calibration of the model outputs represents a complex issue, considering that few historical data are available. The main idea behind the calibration is to regulate model outputs so that they match real trends. For instance, renovation rates outlined from figure 4.3 could be used, yet data would not be available for all countries. U-values from EU buildings database are affected by renovation mechanisms, especially for the oldest vintages. However, this is not the case for the newest vintages, in which presumably no renovation had already occurred. Data collection was performed in two different years. Therefore in the first analysis (2008), the 2000-2009 vintage can be considered as "new construction", whereas this holds true for the 2009-2014 vintage in the second analysis (2014). Then, a way to calibrate the model was represented by the comparison of its new construction module outputs with the actual data. The 2008 data will be compared with what the model calculates in 2010, while the 2014 data will be compared with the 2015 computations of the model.

4.7.1 Windows area

It has been outlined that the model works on two different groups of surfaces (opaque and glazed), being the U-value for opaque surfaces calculated as the average of floor, roof and wall U-value. The results from each computation are eventually aggregated in order to calculate the envelope U-value, following equation 4.13. Looking at historical data, it was noted that in some cases, in the EU database, the envelope U-value was not calculated as the average of the components values. Indeed, the resulting share of windows in the total envelope area, calculated from equation 4.13, was not always equal to 25%, especially for the newest vintages. This is presumably due to better estimations of the components area shares, which were then used to calculate the envelope U-values. Hence, in order to account for this, the A_{win} term was estimated from the considered historical data and was fixed for the estimations of future new construction U-values. In this way, the computations of the new construction module could be aggregated in the best way, in order to fit the data.

$$U_{envelope} = U_{opaque} \cdot (1 - A_{window}) + U_{window} \cdot A_{window} \tag{4.13}$$

4.7.2 Implicit discount rates

The first model outcomes were compared to the actual data, resulting in great differences between computed and historical data. General trends were correctly followed, with high-HDD countries showing low U-values and developing countries with warm climates showing high U-values (remember from section 3.2 that cooling demand depends on income). However, looking at the detailed results, weird outcomes were shown by some regions, which are deeply discussed later in this section. Therefore, a need of better matching historical data arose. A discussion with EDGE developers finally lead to the definition of *implicit discount rates*, in order to better follow the general philosophy of the model. The choice of considering discount rates, was lead by the great uncertainty which is inherently related to the level of this parameter, as discussed in section 4.4.3. Historical data were found to be available, while this parameter can basically only be assumed. Through this calibration process, historical (2010 and 2015) data on U-values will be matched, while uncertainty on the evolution of discount rates over time will be tested in section 6.3. Thus, levels of each country implicit discount rate were computed, in order to match historical data. In order to obtain reasonable values, upper and lower limits were respectively fixed to 3% and 15%. The outputs are shown in the red bars of figure 4.12.

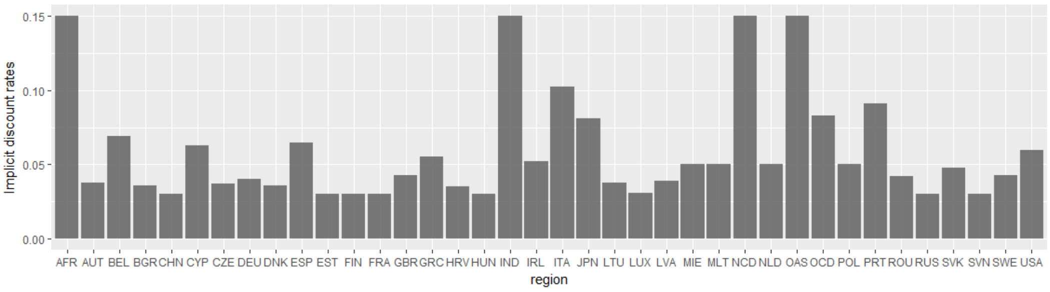


Figure 4.12: Computed implicit discount rates and from the calibration process

A correction on the logit parameter λ was also required in some cases, thus the blue bar presents its values as well. Indeed, the implemented λ is equal to 0.01, yet with this assumption the model outcome could not be pushed towards choosing very low levels of insulation, as already outlined in section 4.6, by means of figure 4.9. In developing countries, λ was increased in order to better match the results. An exception is represented by Malta, since it is the only European country which still installs very low levels of insulation in its new construction stock. Given the high sensitivity of the model outcomes to the logit parameter, the possibility of increasing λ over a value of 0.05 was not considered. Figure 4.13 outlines the computed values.

From this figure it can be seen that the computed implicit discount rates seems to be

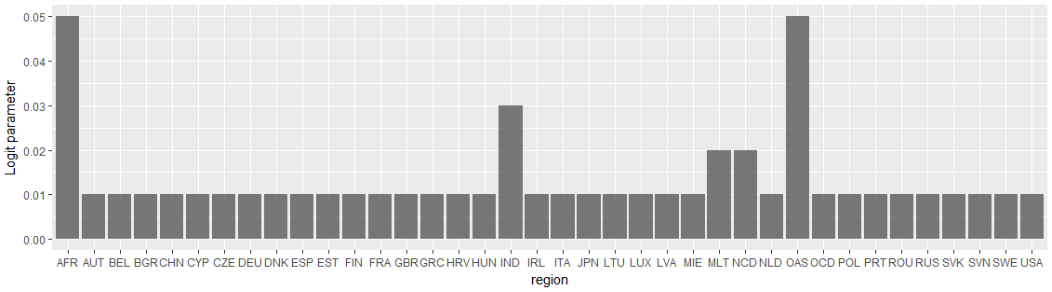


Figure 4.13: Computed logit parameters from the calibration process

reasonable, especially looking at European nations, which on average show levels of 5%. A noticeable exception is represented by Italy, which shows an implicit discount rate of 10%. Explanations for such a high value are given later in this section. Regarding developing countries, a discount rate of 15% is actually found, meaning that even if it would be convenient to insulate, in these regions U-values are definitely high. These results are in accordance to the indications of IPCC [98].
Recalling the outlines of section 4.4.5 regarding the assumed lifespan of the building in the new construction module, an interesting remark can be made here. Choosing a higher lifespan would lead to increased PWF, thus to higher implicit discount rates would be calculated in order to counterbalance this effect. In any case, unless the discount rate is very small (i.e. 3-4%), the PWF function derivative over the lifespan becomes very small when the lifetime is high (i.e. over 30 years), thus important changes would not happen by choosing a different value.

Then, the comparison of the model outcomes, before and after calibration, together with actual U-values, is presented in figure 4.14. This chart is related to the 2010 period. A general improvement of results is reached. The only exception is represented by China, which in both periods shows higher U-values compared to the actual data. This is due to the strong reduction in heating demand which is imposed by the model, as was remarked in figure 3.5. Moreover, in 2010 and 2015 China can still be considered a low-income country, with values of GDP not exceeding 10000 $\$_{2005}$/cap. Therefore, its cooling demand is also curtailed by equation 3.3 of the model. Moreover, the model calculates heating demand according to the country energy mix. However, China presents a huge efficiency gap across rural and urban buildings [102]. Considering that most of the Chinese new construction will be placed in cities, as discussed in appendix A, a different energy mix and income level should be considered. This is not possible with the current detail of the model, thus a correction which is specific for China will be added, in order to reduce the new construction U-value.
Finally, the new module allows for the possibility of increasing U-values over time. In the renovation module, U-values remain constant, in the worst case, because no renovation happens. Instead, since the calculations for new construction are not limited by any boundary, in a pessimistic case it can happen that the computed U-values actually become high, possibly leading to a decrease in country insulation levels if this effect offsets the improvement due to renovation.

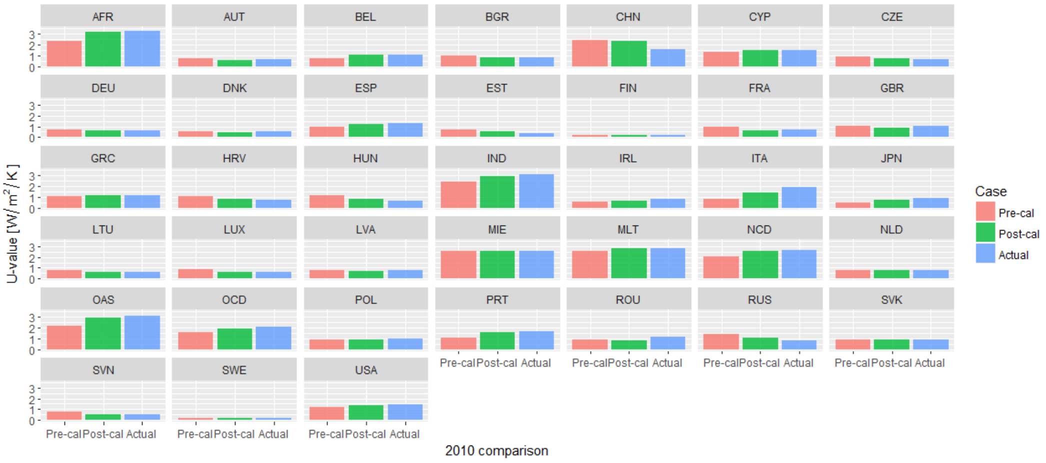


Figure 4.14: Comparison between actual and computed U-values, before and after the calibration

Discount rate and logit parameter evolution over time

As already stated, the development of country implicit discount rates over time is highly uncertain. Given that these parameter show reasonable values for developed countries, no change on them will be done across the years. Regarding developing countries, keeping discount rates as high as 15% would not be coherent with the scenario narrative, which predicts their GDP to grow over the years. Therefore, since it has already been stated in section 2.1 that discount rates were shown to decrease with increased wealth, this assumption was done in the model. Therefore, discount rates were assumed to linearly decrease, down to 5% when their GDP is equal to the European countries average in 2015, weighted on their population (i.e. 27500 $\$_{2005}$/cap).

In the same way, the logit parameter of developing countries (and Malta as well) was progressively decreased to 0.01 when the income levels of these regions reach 27500 $\$_{2005}$/cap. It is thus assumed that once that threshold is reached, technology markets in these countries start working as they now do in Europe.

Computed discount rates: discussion

Strange values of discount rates were determined when performing the calibration. This is due to regional-specific factors that could not be accounted for in the model. For instance, Italian new construction U-values are approximately equal to twice the level of the French ones, despite these countries have similar levels of income and HDDs. Moreover, Italy has higher energy prices than France. Therefore, thew model calculated really low U-values for the Italian country, while this was not reflecting reality at all. Therefore, the corresponding implicit discount rate of Italy was found to be really high, as if there would be a great potential for increasing insulation levels, which is not exploited in reality. The opposite happened for France. Since neither income nor climate help understanding the reasons behind such a difference, a possible explanation could be found in the GINI index value. In fact, in 2015 this indicator was equal to 36% in Italy, while it was 3% lower in France [38]. Therefore, a high income inequality within a country may play a role in determining insulation levels. An attempt to include the GINI index as a predictor of U-values levels was made, using the projections developed by [103]. However, results did not show an overall improvement, since eastern Europe and Baltic countries were instead penalized.

Within these nations is interesting to notice that Bulgaria and Estonia show very low implicit discount rates. These countries show relatively low prices of energy, however insulation levels are not so low. This is quite surprising: considering the high shares of population with inadequate heating in Bulgaria (40% [7]), it would not be expected that consumers decide to increase their insulation levels. Explanations for Estonia might be related to the fact that many buildings in this country were built when it was under Russia. Another possible explanation for this might derive from noticing that these two countries show the highest shares of public-owned non-residential buildings (around 85-90%) in Europe [104]. Therefore, the state might show a great importance in reducing U-values at the country level.

After this discussion, a last remark regards data quality issues, which were already outlined in section 2.3.1. Table 4.3 indicates the new construction U-value data for Italy. Despite the single components U-values show a strong decrease between the two years, this is not the case for the envelope U-values, which only show a very slight reduction. The only explanation for this might be linked to an increased share of glazed surfaces in the envelope, but it seems unreasonable.

Year	Envelope	Walls	Roof	Floor	Windows
2008	1.91	0.85	1.2	1.6	4
2014	1.78	0.41	0.34	0.41	2.6

Table 4.3: Italian new construction U-values

4.8 Comparison with the previous model

The main results of the model computations can now be compared to the previous EDGE model, in order to look at significant differences that may arise. First, European trends are compared, since the new module includes data from the EU database as the starting U-values for each country (while in the old model, insulation levels were only estimated, according to the procedure described in section 3.2.1). Secondly, a comparison between the world regions U-values is performed, choosing the SSP2 scenario computations.

Before showing the results, the procedure followed to aggregate vintages U-values to the country level is shown. Given the equations 3.2 and 3.3 used to compute FED, the sum of heating and cooling demand of each vintage i must be equal to the total country consumption:

$$(SH + SC)_{total} = \textstyle\sum_{i=1}^{vintages} (SH + SC)_i$$
$$\mathrm{U}_{country} \cdot F_{country} \cdot (HDD \cdot \delta_{heat} + CDD \cdot \delta_{cool}) =$$
$$\textstyle\sum_{i=1}^{vintages} U_i \cdot F_i \cdot (HDD \cdot \delta_{heat} + CDD \cdot \delta_{cool})$$

Therefore the country-level U-value should be calculated weighting the vintage-level U-values on the floor space share of each vintage.

$$U_{country} \cdot F_{country} = \sum_{i=1}^{vintages} U_i \cdot F_i$$
$$\mathrm{U}_{country} = \sum_{i=1}^{vintages} U_i \cdot \frac{F_i}{F_{country}}$$

However, no data are available in order to compute the ratio on the right-hand side of the above equation. Therefore, it has been assumed that the floor space per building ($F_{b,i}$ in equation 4.14) remains equal for each vintage i in a country, therefore $F_{b,i} = F_b$, $\forall i$. In this way, vintages U-values can be weighted on the share of buildings of that vintage, which is an output of the building stock module, in order to obtain country-level U-values according to equation 4.14.

$$U_{country} = \sum_{i=1}^{vintages} U_i \cdot \frac{F_{b,i} \cdot Buildings_i}{\sum_{i=1}^{vintages}(F_{b,i} \cdot Buildings_i)} = \sum_{i=1}^{vintages} U_i \cdot \frac{Buildings_i}{Buildings_{country}} \tag{4.14}$$

Looking at the results, figure 4.15 outlines that both models show decreasing U-values levels over time. However, while the previous model calculates linear trends, the new one computes convex curves.

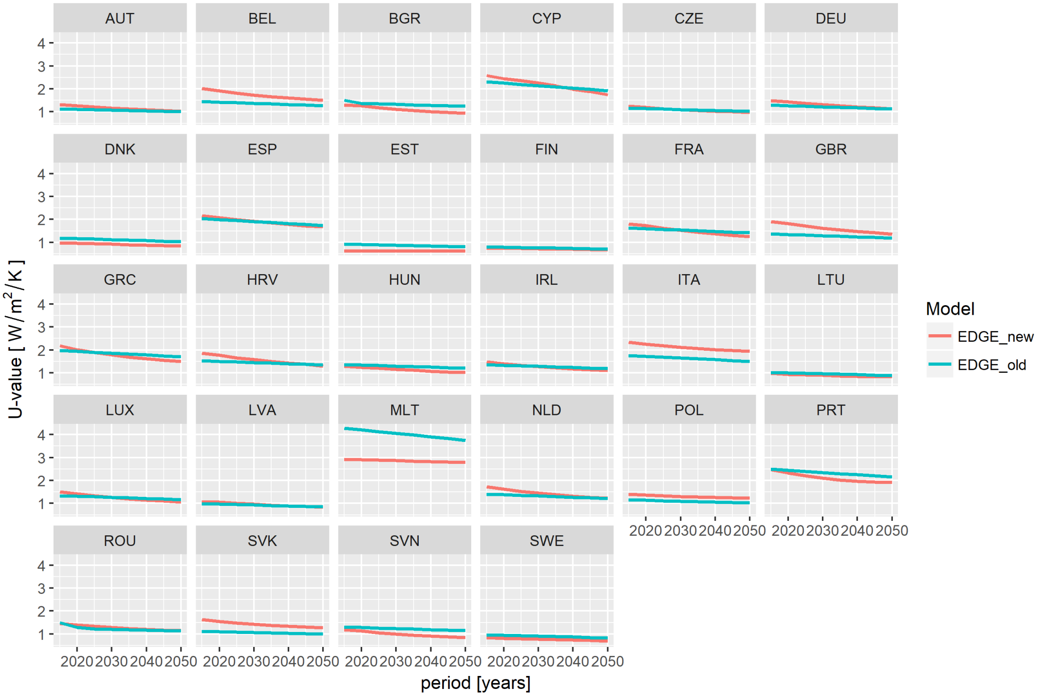


Figure 4.15: Comparison between U-values computed by the previous and by the updated model, at the European level

Thus, higher reductions in U-values are generally reached during the first timesteps. This happens because of the renovation mechanism, which works on the oldest buildings. Recalling figure 2.7, it can be remembered how easy it is to strongly decrease U-values for non-insulated buildings. However, after the initial drop, further decreasing

U-values becomes more and more difficult. Figure 4.16 outlines the computed renovation rates for the currently existing building stock, divided by vintage.

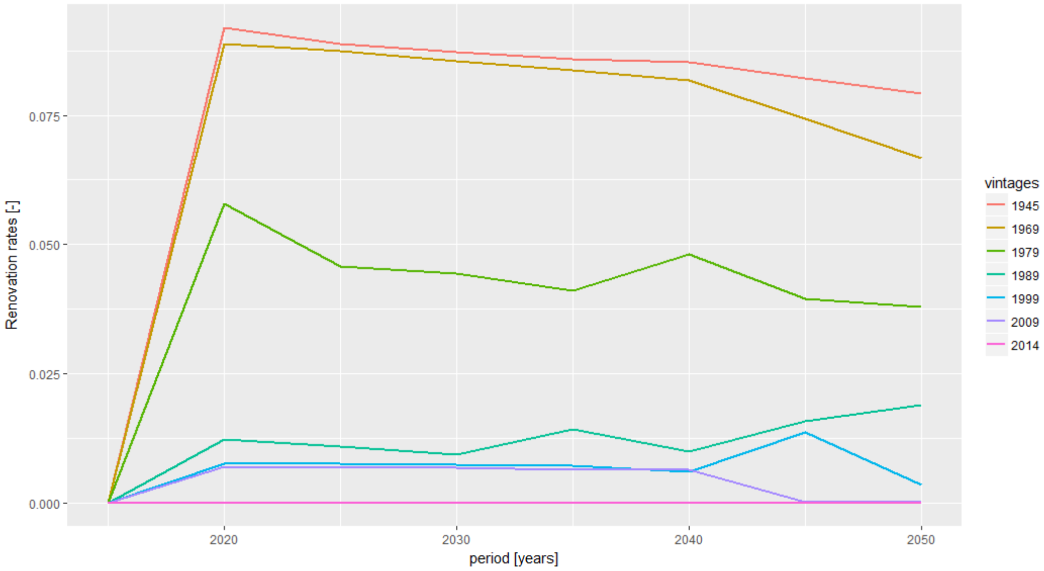


Figure 4.16: Computed renovation rates at the European level, by vintage

In the model computations, renovation rates are normalized by the building stock size. Therefore, increasing shares of new construction (which is so efficient, in the baseline, that it never gets renovated) also make renovation rate decrease, due to the reduced shares of currently existing buildings in the stock. Another mechanism that works in the direction of reducing U-values is demolition. As explained in section 4.1, a demolition rate of 0.7% is applied at every timestep. Since the stock of oldest buildings is greater and the same rate is applied to all vintages, demolition rates in absolute terms (i.e. in terms of number of buildings) are higher for oldest buildings, causing the country-level U-values to decrease. The second remark is related to starting U-values differences for some countries. Italy actually shows higher U-values in the new module: as already discussed, in this country the insulation levels are quite high compared to what would be estimated from the climate levels. This is also the case for Belgium and Great Britain. However, given the high discount rate of the Italian country, U-values decrease over time is slow, while the latter nations manage to catch up with the estimations of the model in 2050, since insulation levels in both of them are pushed down by high HDDs. Malta U-values are actually greatly higher than the actual ones: this happens because the calculated HDDs and CDDs related to this country are really low. At the world level, differences between the modules are higher, reflecting different hypotheses on developing countries dynamics over time, as figure 4.17 outlines.

U-values estimations for Japan, USA and OCD regions are pretty similar and this would be the case for Russia as well, however in the available version of the model the correction on U-values (described in section 3.2.1) was not applied. If figure 3.6 is recalled, it can be seen that starting U-values for Russia are actually around 1.5 W/m^2/K, as the new module estimates. Regarding China, starting U-values are ac-

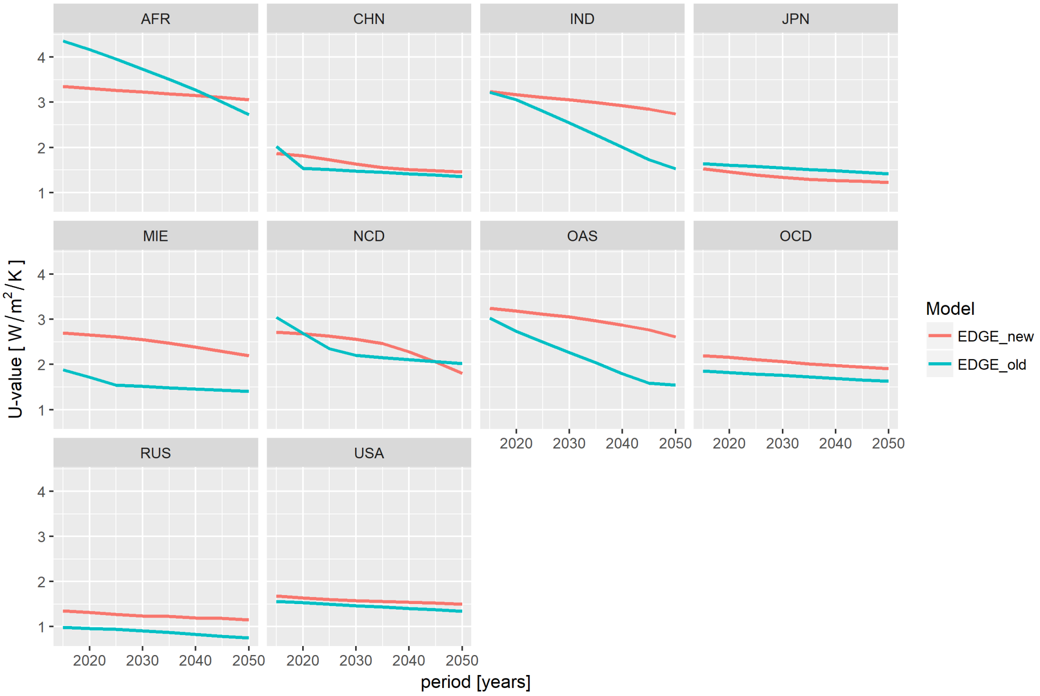


Figure 4.17: Comparison between U-values computed by the previous and by the updated model, at the world level

tually between 1.7 and 2 $W/m^2/K$, as outlined by the literature [105] and described in appendix A. Regarding developing countries, the old model assumed a strong decrease in U-values as soon as their income levels approach 15000 \$/cap; then reduction trends are calculated with the same procedure of developed countries. The new model estimates much slower dynamics over time and it can be seen that, differently from figure 4.15, concave curves arise in low and middle income countries. This is mostly related to the dynamics implied by the building stock module and the assumption on increasing cooling demand increase with income (see the description of equation 3.3 in section 3.2). Since both income and population increase, the new construction stock will quickly gain high shares in the country building stock. Figure 4.18 displays the population increase, relative to 2015 value, income trend and vintages shares dynamics for the selected countries.

Africa shows a higher population increase, but lower income rise compared to the other regions: eventually, these effects are reflected in similar shares of new construction. It should be remembered that cooling demand remains very low until 10000-15000 $\$_{2005}$/cap, as figure 3.4 outlined. Once income exceeds that threshold, cooling demand explodes, following the sigmoid curve implemented in the model and then it becomes convenient to build a new construction stock which is more efficient. Therefore, the increased share of a highly efficient new construction stock eventually pushes U-values down. These dynamics do not certainly happen within the first timesteps, since developing countries income is assumed to reach high levels only after several years. This is the main difference with the renovation dynamics, which make the U-value curve

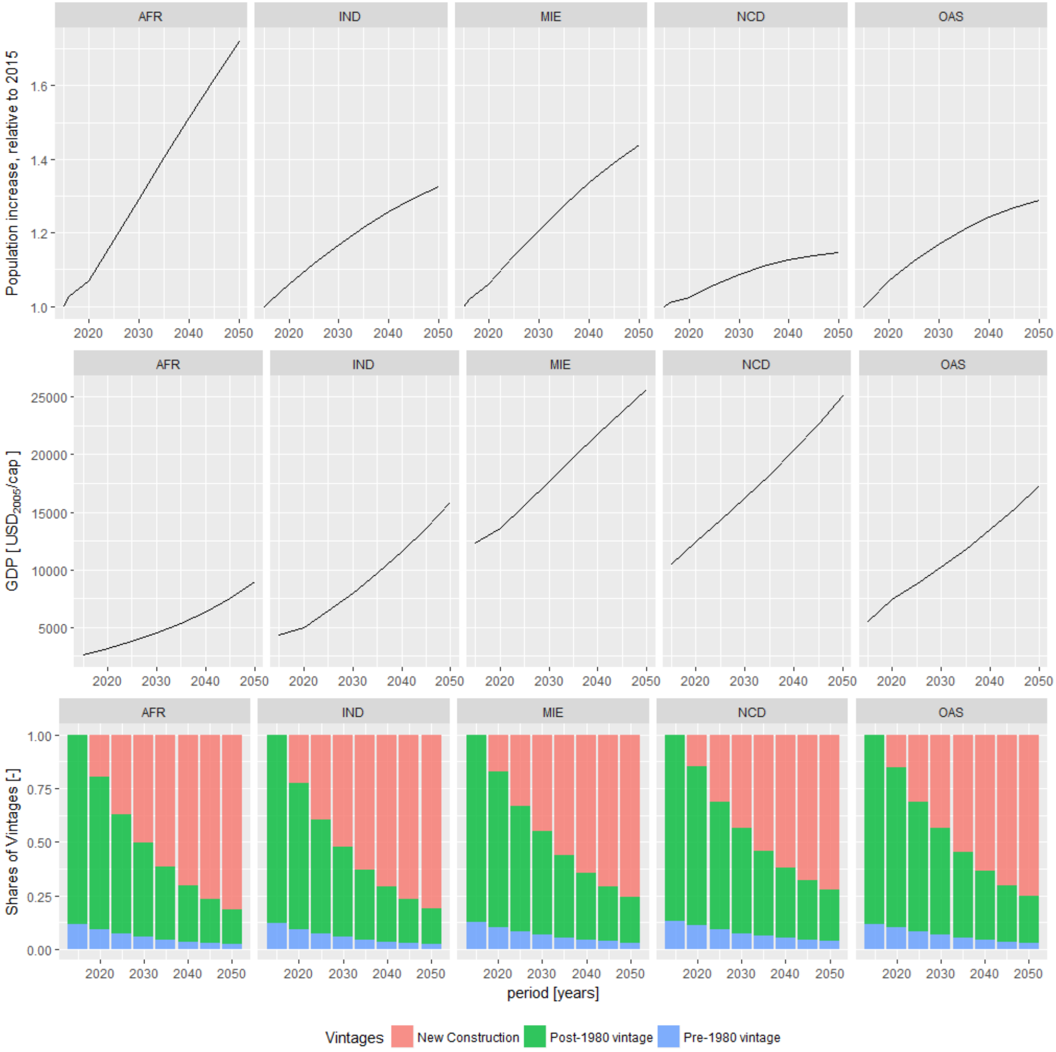


Figure 4.18: Dynamics of GDP and population resulting in the share of vintages across different regions

convex. China would follow this dynamic as well, however due to the correction on the new construction U-value, explained in section 4.7, a more linear trend results.

Another remark regards Middle East. Even if the correction on income is applied, still HDD and CDD are the main determinants of insulation levels in the previous model. The literature research explained in appendix A outlined that Middle East countries generally show low levels of insulation: this trend was not reflected in the previous model.

4.9 Comparison with trends of the past

A feasible way to assess the validity of the model estimations is represented by looking at historical trends. According to the SSP2 narrative, *technological trends do not shift markedly from historical patterns* [80]. Therefore, the trends that the model computes for this scenario are compared with historical development. However, the calculation of U-values past trends does not constitute an easy task, given that the EU database performed only two analyses, in 2008 and 2014. A way to estimate historical trends is then represented by exploiting the building stock module. It can compute the development of building stock size from 1945, classified by vintages. Assigning to each vintage its current U-value, it is possible to estimate the past trends of insulation levels for each country. In this way, it is assumed that the current U-values actually reflect the envelope thermal performance of the building when it was constructed. In this way, the renovation impact on the oldest stock has been neglected. In any case, estimating the extent to which refurbishment affected current U-values levels is another difficult task, given the lack of data, thus it will not be made here. Moreover, the uncertainty on past trends estimations decreases the closer the year is to 2015. The resulting trends, divided by European countries, are shown in figure 4.19.

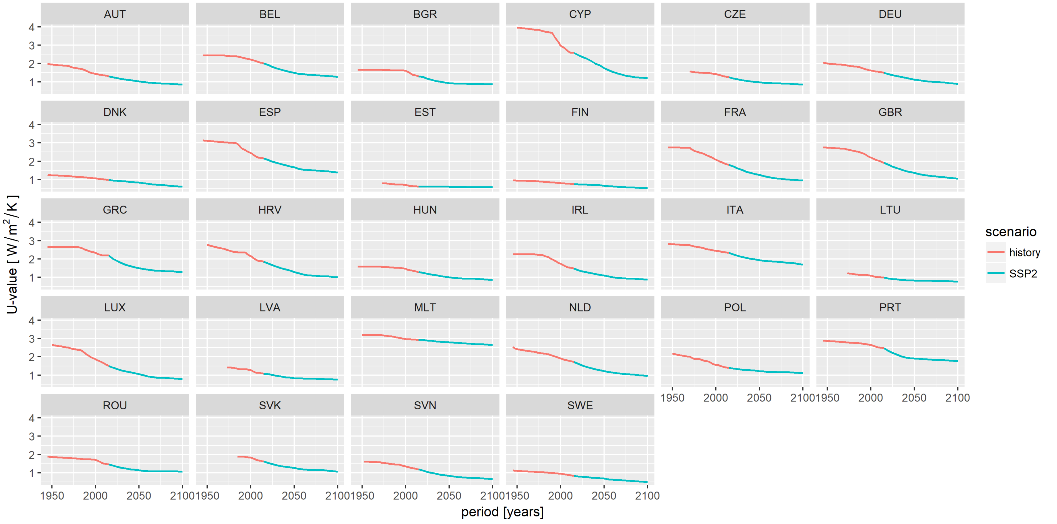


Figure 4.19: Comparison between estimated past [7] and future trends of U-values at the country level in Europe

As can be expected, country-level U-values show strong decreases after 1980: this is in line with the indications made in section 2.3.1. Some countries, such as Lithuania, Estonia and Slovakia do not show any value at the beginning since they did not constitute a separate nation in those years. In order to look at European trends, country U-values were aggregated, weighting them on the size of the national building stock. The resulting curve, for both the estimated past and future dynamics, is shown in figure 4.20. Some discontinuities in the past trends appeared, due to the different availability of data across regions. Moreover, the model computes a slightly higher 2015 U-value at the European level (the right value is 1.69 W/m^2/K), due to differences introduced by the calculations of the building stock module. In any case, it is important to notice that no important shift from estimated past trends happens in 2015. Therefore, the SSP2 narrative is respected.

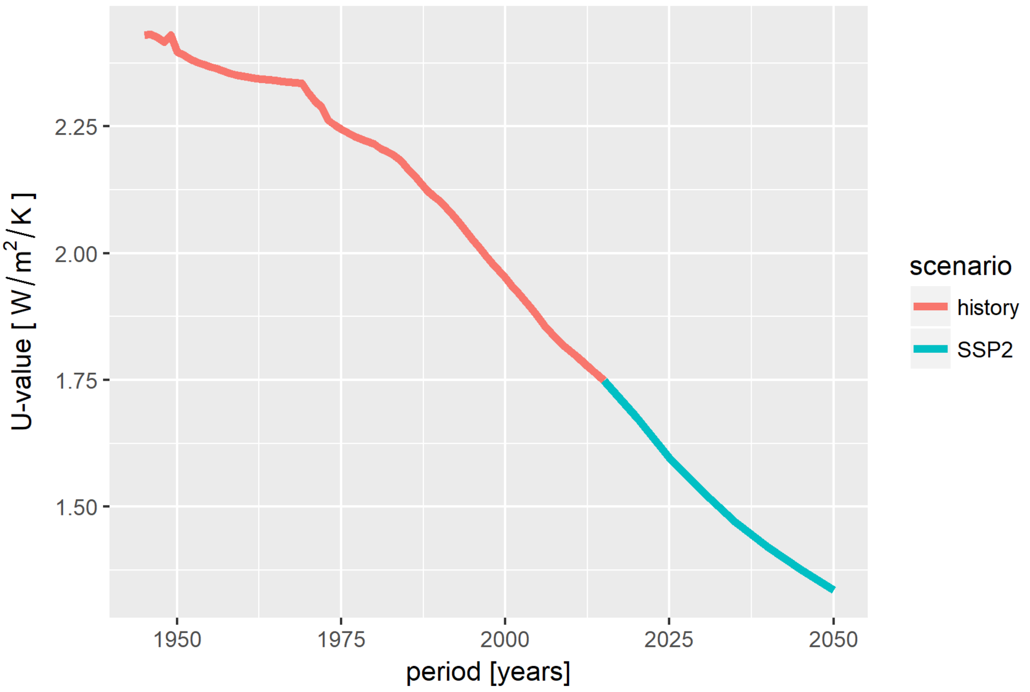


Figure 4.20: Comparison between estimated past [7] and future trends of U-values at the European level

Chapter 5

Scenarios

In this chapter, the research questions outlined in chapter 1 will be answered. Section 5.1 outlines main results regarding energy demandestimations, both useful and final. While Useful Energy Demand (UED) captures the quality of the service that is provided to the population, FED is important since it is more directly linked to the usage of energy consumption and thus, to the emissions. Given the context of this thesis, after this section, only FED trends will be shown. Given that U-values are related to space cooling and heating only, all energy demand estimations will only be referred to these end-uses. Then, section 5.2 analyzes the implications of the European energy policy. Finally, section 5.3 investigates the implications that energy price increases may have in the long-term FED. All the results in this section will be derived in the SSP2 context.

5.1 Energy Demand

The objective of this section is to outline how the main dynamics implied within the building stock and the U-values module were coupled with the remaining EDGE modules, in order to determine the estimations of the space heating and cooling FED. Given the wide amount of trends and calibrations that are inherent to the two new modules and also to the EDGE calculations, several graphs will be shown, in order to help identifying the main effects derived by the assumptions in the model.

In order to estimate the impact of each vintage U-value and share in the building stock, the regional FED for space heating and cooling $SH + SC$ must be allocated to each vintage i:

$$(SH+SC)_{share,i} = \frac{(SH+SC)_i}{(SH+SC)_{total}} = \frac{F_i \cdot U_i \cdot (HDD \cdot \delta_{heat} + CDD \cdot \delta_{cool})}{F_{tot} \cdot U_{tot} \cdot (HDD \cdot \delta_{heat} + CDD \cdot \delta_{cool})}$$

As was made in equation 4.14, equal floor space per building is assumed, thus the ratio F_i/F_{tot} can be substituted by the $i-th$ vintage share in the country building stock, thus leading to equation 5.1:

$$(SH+SC)_{share,i} = \frac{Buildings_i}{Buildings_{tot}} \cdot \frac{U_i}{U_{tot}} = \frac{Buildings_i \cdot U_i}{\sum_{i=1}^{vintages}(Buildings_i \cdot U_i)} \tag{5.1}$$

First of all, figure 5.1 outlines the main results of the new modules and the corresponding space heating and cooling FED, for 5 regions, selected according to their importance at the global level and their different stages of development. Europe was chosen since it is the region with the highest data quality, and together with USA represents the developed regions typical trends. China is certainly the region that is projected to have the steepest improvements in income levels and given its population size, it must be analyzed. This region in particular helps outlining all the most important hypotheses on cooling demand development which are included in EDGE, since it is expected to shift from a low to a high level of development, eventually catching up with Europe and USA, within 2050. Africa and India are included as representative of the main trends that are involved across developing countries. The already existing building stock is split into two parts, choosing 1980 as a separator, given the marked shift in U-values that happened after the oil crisis of that year, as analyzed in section 2.3.1.
The charts are now analyzed, in the same order of the model flowchart: the building stock module constitutes an input for the U-values one, and then insulation levels are used to compute the FED:

1. Looking at the vintages shares, it can be deduced that in developed countries (especially in Europe), the weight of the already built stock will remain to be important in the upcoming years, as IEA also outlined [2]. Conversely, developing countries such as Africa and India will show great increases in their new construction stock, as was already discussed in section 4.8. Moreover, while for Europe the new construction share in the building stock increases almost linearly, by around 4% every 5 years, in developing countries the newest vintages already reach a 50% share of the total stock within 15-20 years. Then, from 2030 to 2050, new construction still gains a 25% share, reaching 75-80% of the total stock in Africa and India. Therefore, while the change from old to new stock will be gradual over time and not particularly strong in Europe, the change of building stock composition in developing countries will be tremendous and concentrated within a few decades.

2. Considering the U-values charts, it can be seen that the older the vintage, the higher the U-value, and the energy efficiency improvement from pre-1980 to post-1980 buildings is really evident in Europe and USA, due to the implemented policies after the oil crisis. The same holds true for China, given that most of the post-1980 vintage is constituted by buildings constructed after 2000 and building codes were implemented for the newest vintages. Moreover, developed regions experience certain levels of renovation of their oldest building stock. Once income levels of China are sufficiently raised (further discussion will be provided by figure 5.3), it starts implementing some refurbishment of the pre-1980 vintage as well, which is mostly linked to rural inefficient dwellings, as stated in appendix A. On the contrary, no improvement happens for the oldest stock of Africa and India, even if any amelioration of these vintages would have really low effects in the energy demand, given their low share in the regional building stock.

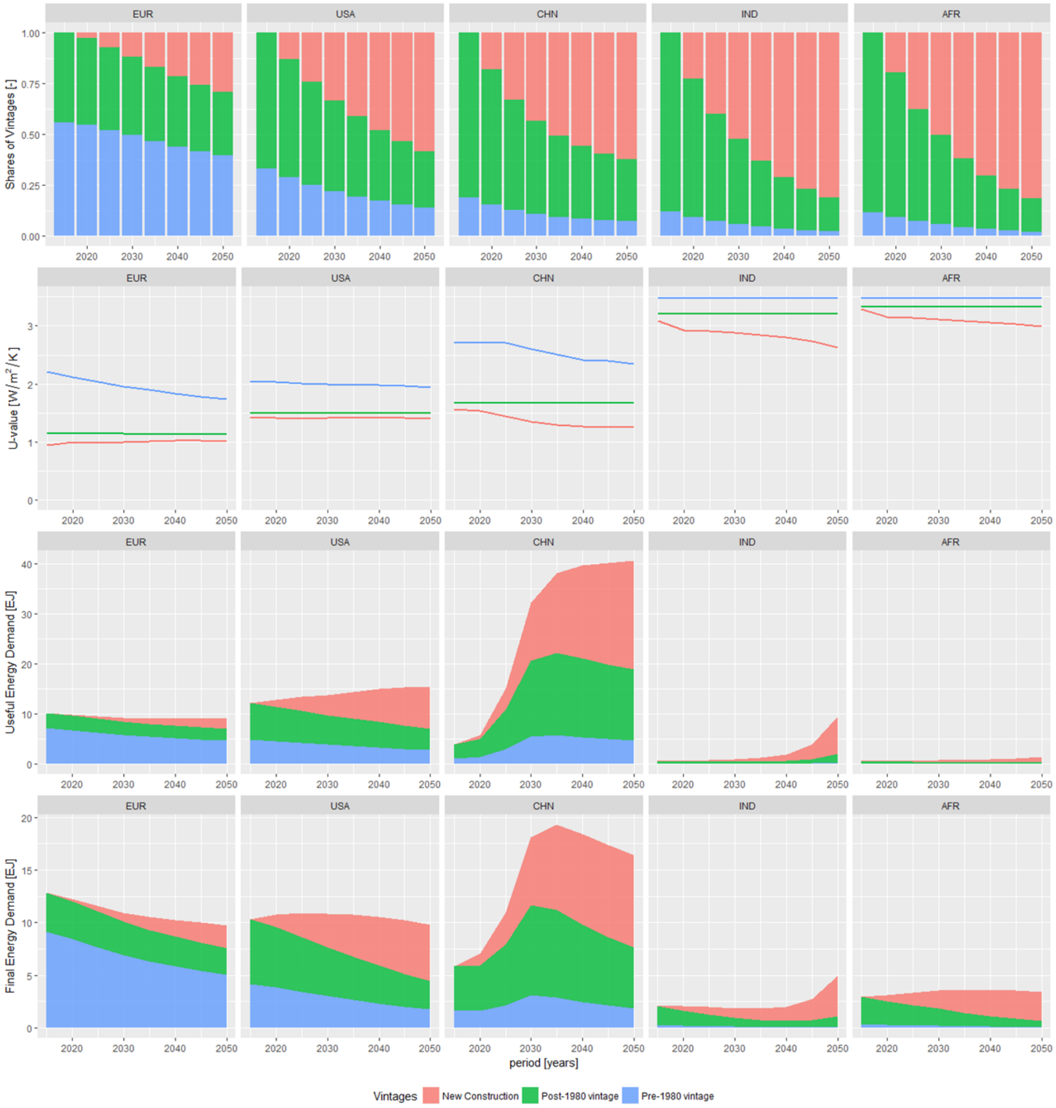


Figure 5.1: Building stock shares, U-values, Useful and Final Energy Demand dynamics

Regarding the post-1980 group, only a small renovation of it happens in some regions of Europe, while nothing happens in the other highlighted regions. This further remarks the increased level of efficiency of this group of buildings, since it was highlighted in section 4.6 that the PBT for renovation greatly increases as soon as the starting U-value of the building decreases, thus very low levels of renovation happen.

Finally, the efficiency of the new construction stock appears to improve over time in developing regions. This is mostly due to the increased cooling demand, due to rising income levels, and to growing heating demand as well, due to the hypothesis of convergence towards consumption levels of developed countries (see the explanation of figure 3.5 in section 3.2). Conversely, this does not happen in developed regions. In USA, this is mostly due to the assumption of increasing efficiencies (which depend on income, according to equation 3.4) of the heating and cooling systems, which eventually reduces energy expenditures, thus making less convenient to insulate new buildings to even higher levels. This holds true for Europe as well, but it should be remembered that for this region, the U-values of figure 5.1 are aggregated across different countries. U-values of the new built stock in this region actually show an increase: this happens because most of the new buildings in Europe will be constructed in countries such as Romania, which are currently at a middle-income level of development. High income regions in Europe are estimated to build very efficient dwellings, yet with a very low rate of construction.

3. Then, the UED for these regions is presented. It can be seen that in 2015 Europe and USA shows the highest UED across these regions, followed by China. However, the situation in 2050 is estimated to strongly change, with China being the highest energy-consuming region and USA UED overcoming the European levels. African UED is practically negligible across the analyzed period and the same consideration holds true for India, at least until 2040. After this year, Indian UED reaches 10 EJ only within 10 years: an enormous increase.
   With a deeper analysis, it can be seen that in Europe, most of the UED comes from the oldest vintages in 2015 and even in 2050, more than half of the energy consumption can be attributed to that group, despite the impact of demolition and renovation, which respectively decrease the share of that vintage group in the building stock and the related U-value.
   Looking at USA, UED steadily increases, due to two slight effects: the increase in floor space demand, rise in cooling demand due to increase in CDD (since the planet gets warmer). These dynamics offset the small decrease in country-level U-value. Some issues in the allocation of energy demand across vintages arise, because of differences across floor space and building stock calculations. Both of them grow with population and income, yet with different elasticities. Indeed, the building stock module estimates high amounts of new construction. Contrarily, floor space only slightly grows, as will be seen in figure 5.4. This eventually results in a decrease of UED of the already existing building stock across the years, which is only partly due to renovation and demolition.
   Conversely, for China building stock and floor space growth seem to be coherent (see figure 5.4, thus this issue does not emerge. This region shows a 8-fold increase in energy use only within 2015 and 2035, after which the UED gets basically saturated. This is due to the explosion of cooling energy demand, which follows a sigmoid curve as soon as the GDP of the nation overcomes a threshold, as explained by figure 3.4. Once cooling demand approaches saturation, it becomes highly convenient to insulate, thus renovation of the oldest buildings starts in 2030. However, given the low share of oldest vintages in the Chinese building stock, this effect does not manage to decrease energy demand.
   Looking at developing countries, India experiences a great UED rise in the last 10 years, due to increasing space cooling consumption, as soon as the Indian GDP approaches 15000 \$/cap. African income levels are not projected to reach this

threshold within 2050, in this scenario, thus cooling demand remains really low and heating demand is not important in this region. These effects will be further explained in figure 5.4.

4. Finally, the FED for these regions is presented. It can be seen that in these graphs, the orders of magnitude of FED across different regions are now comparable. Shifting from UED to FED, Africa and India show a much higher energy demand, Europe presents only a slight increase, while USA and especially China display much lower energy demands.
   Comparing different regions, the European group shows the highest FED in 2015, followed by USA and China. However, as in the UED charts, the situation in 2050 is estimated to strongly change, with China being the highest energy-consuming region and USA energy consumption being equal to the European one. Indian FED shows again an increase in the last 10 years.
   A deeper analysis reveals that Europe FED results to be 20% higher than its UED. This happens because the energy demand in European countries is generally based on heating, with modern energy carriers (e.g. natural gas) delivering the final service and heating equipment efficiencies being around 90%.
   Looking at USA, FED reaches a peak and then, differently from UED trends, decreases. This is mainly due to the increase in final-to-useful energy efficiencies of the system, which happens for heating equipment as well, but is projected to be stronger for cooling appliances. In fact, while small penetration of heat pumps occurs, heating systems generally continue to be based on boilers, which cannot exceed efficiencies of 100%. This is not the case for cooling systems, which are based on electricity and can exceed the 100% value in final-to-useful energy efficiency. This will be further remarked in figure 5.6.
   The increase in cooling efficiencies is even more apparent when looking at China: its FED trend shows a peak as well, in 2035, then a progressive decrease. It reveals once again that the big increase in Chinese UED is mostly due to a raise in cooling demand.
   Looking at developing countries, the FED amounts to about 5 EJ, which is ten times higher than their UED. Cooling demand starts to increase only in the last 10 years, in India, while it is negligible in the other periods. Therefore, most of the FED at the beginning comes from heating. The reason why FED is much higher than UED is linked to the assumption of the model that at low income levels, space heating is satisfied by means of traditional biomass (see section 3.2), which has a very low efficiency: around 10 to 15%. Accordingly, FED is 10 times higher than UED.
   FED across the years follows a flat curve in these regions. This is the result of two counterbalancing effects. Space heating demand increases due to growing floorspace, which is especially due to rising population levels, as will be seen in figure 5.3, and to an increase of the δ_{heat} correction, as figure 3.5 outlined. Conversely, rising incomes make the heating mix shift away from traditional biomass towards modern fuels, which show more than doubled energy efficiencies, thus

decreasing FED.

Once the dynamics implied within the building stock and U-value modules have been explained, the UED trends at the global level are shown, divided by end-use and groups of countries, in figure 5.2. High income countries include USA, Japan and OECD regions, while the middle income group involves Russia, non-OECD countries and Middle East. Europe and China are separately presented, respectively due to the high quality input data and to the importance at the global level.

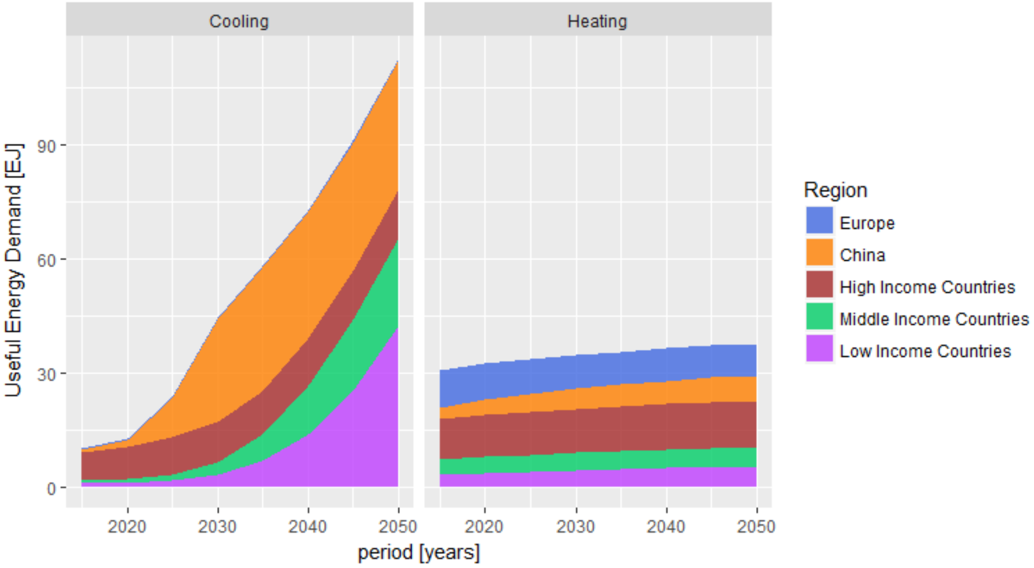


Figure 5.2: Heating and Cooling Useful Energy Demand estimations, divided by groups of regions

Both heating and cooling UED are projected to increase over the years, yet growth rates are strongly different, with the former showing an 11-fold increase (from 10 to 112 EJ) and the latter only rising by 23% (from 31 to 38 EJ). Looking at the distribution across groups of countries, it can be seen that two thirds of the heating demand are associated to high income countries and Europe and shares do not substantially vary over the years.

This is definitely not the case for cooling. While in 2015 most (75%) of the air conditioning demand comes from high income countries (mostly USA and other OECD regions), in 2030 the situation is already twisted, with China holding around 60% of the cooling demand on its own, and the remaining part being split among low, middle and high income regions. Then in 2050 the situation is again different. During these 2 last decades, China only slightly increases its cooling demand by 7 EJ, whereas low and middle income countries experience a growth in cooling demand, similar to what was shown by China in the 2015-2030 period. Therefore, in 2050 China holds around 30% of the total cooling consumption, while Low and middle income countries respectively account for 38% and 21%. High income countries share in cooling demand eventually decreases to 10%, thus outlining the dramatic changes that are estimated to happen.

The assumption on the evolution on cooling demand, across a sigmoid curve which depends on income and with a upper asymptote that is a function of CDD (see the explanations of equation 3.3 and figure 3.4 in section 3.2) has a huge impact on the cooling UED, which results in important dynamics. Moreover, floor space trends also affect the results. Therefore, a deeper analysis is now required, to show how the outcomes of the model are influenced by assumptions which are outside the building stock and U-value modules. Of course, climate also plays a great role, as outlined in section 4.6. However, HDD and CDD do not strongly change across the considered period, in the SSP2 scenario, thus they are not related to thee great shifts.

Firstly, figure 5.3 presents the main drivers of floor space and cooling demand development. Population size only affects the first parameter, while both of them increase with income. Some significant regions were selected in order to show how different countries in the world can either show great or negligible shifts in their trends. The blue and red dashed lines on the right side graph represent the levels of income at which cooling demand respectively starts steeply increasing and gets saturated.

Figure 5.3: Population and income per capita trends for selected regions

It can be seen that population is projected to rise for most of the selected countries, but not for China, which in 2050 shows a decrease of 10% compared to the 2015 level. Conversely, Africa is projected to increase its population by 70% and the other countries show growth rates that vary from 30 to 10 % within the considered period. Income per capita levels are estimated to increase for every country, with China showing the highest gradient, followed by USA. It can be noticed that Chinese income moves from 15000 to 30000 $\$_{2005}$/cap across 2020 and 2035, which constitute the period in which cooling demand explodes and then gets saturated.

The trends of total floor space are shown in figure 5.4, together with the correction on cooling demand. The latter is expressed as the ratio of the two calibration terms ($ClimateMax$ and δ_{cool}, see equation 3.3) to what would be obtained if these factors were not applied.

Floor space is projected to steadily increase for all regions, while it basically saturates for China (due to population decrease). This is why the Chinese UED trend in figure 5.2 eventually flattens. Concerning cooling demand, the sigmoid increase is well highlighted by the Chinese curve, which shows how the increase in income levels from 2020

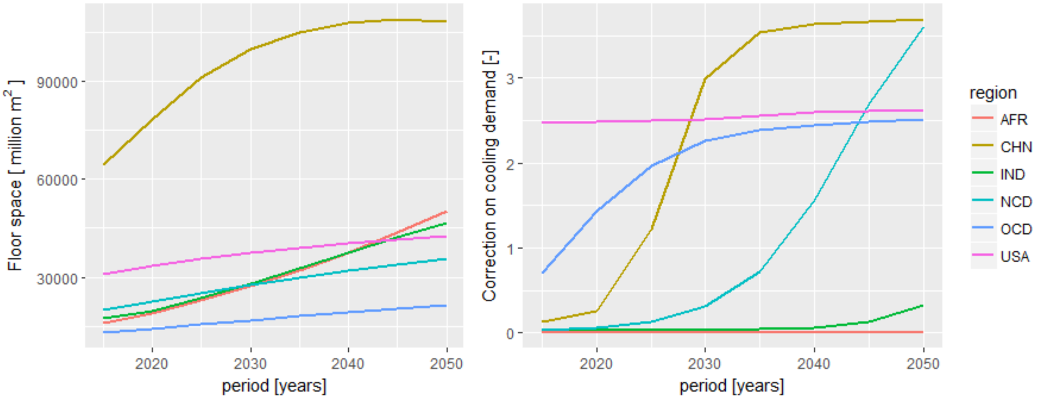


Figure 5.4: Correction on cooling demand and Floor space development over time, for selected regions

to 2035 translates into cooling UED rise.

Looking at other regions, USA shows an almost constant curve, since its GDP in 2015 is already over the red dashed line of figure 5.3, which means its cooling demand had already been reached the saturation in the past. The slight increase is due to a moderate rise in CDD levels over the years, which happens in an SSP2 scenario due to global warming.

The OCD region reaches saturation in 2035, as China does: indeed their income levels cross each other in 2040. NCD region approaches saturation in 2050. Again, the different levels of saturation are due to the dependency of the upper asymptote on the CDD levels of the region. Moreover, India income overcomes the blue dashed threshold across 2040 and 2045 and this is reflected in the beginning of the increase in cooling UED, which was also outlined in figure 5.1. Finally, African income never manages to reach the blue dashed line, thus its cooling demand remains negligible.
Moreover, the effect of the $ClimateMax$ asymptote can be seen as different countries converge to different levels of saturation, depending on their CDDs.

After this discussion, the FED trends at the global level are presented in figure 5.5. The first great difference with figure 5.2 is that cooling FED is now lower than the heating one. This again remarks the much higher final-to-useful energy efficiencies of the cooling equipment. The effect of efficiencies is highlighted by the fact that heating FED reaches a peak and then decreases, while the same holds true for the Chinese and high income countries cooling FED. In fact, as soon as the cooling UED is saturated, then efficiency increase makes the FED decrease, keeping the UED steady. Due to this, global cooling FED shows a slightly lower explosion compared to UED: an 8-fold increase (from 5 to 40 EJ) happens from 2015 to 2050, while heating FED decreases by 10% (from 45.5 to 41 EJ). In this graph, low-income countries show levels of FED which are comparable to the other regions due to their low efficiencies, as already outlined. Discussions on different shares of countries in heating and cooling FED are similar to what was outlined for the UED figure, with low-income countries showing much more impact in the cooling demand.

Global FED for space heating in 2015 amounts to 45.5 EJ, while space cooling con-

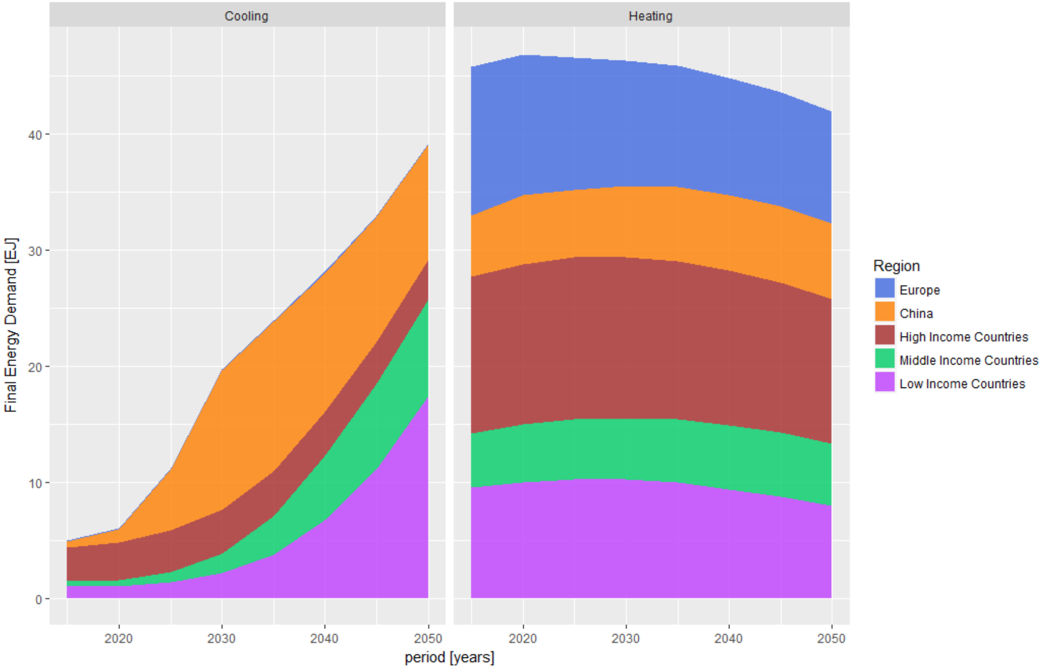


Figure 5.5: Heating and Cooling Final Energy Demand estimations, divided by groups of regions

sumption is equal to 5 EJ. These estimates look higher than the estimations provided by the reviewed sources. IPCC reports space heating and cooling consumption to be respectively around 38 and 4 EJ in 2014 [3], while IEA indications are equal to 34.5 and 4.7 EJ in 2013 [2]. Concerning the EU-28 nations, FED is almost at all constituted by heating (space cooling impact is negligible) and amounts to 12.75 EJ in 2015. This is quite in accordance to the literature, which estimates 3347 and 134 TWh respectively for space heating and cooling FED in all sectors, which totally correspond to 12.5 EJ [106]. Therefore, the greatest issues seem to be related to space heating demand at the world level.

The data which are used by the model to calibrate FED are taken from the Primary, Final, Useful energy database of IIASA [107]. Heating and cooling FED in this database respectively amount to 4.8 EJ and 42.7 EJ in 2015. Thus, the model results are 3 EJ higher. The calibration process within the connection with EDGE should be refined, in order to account for the new U-values module [1], as will be suggested in section 7.2.

In any case, the aim of this thesis is to show how trends in energy efficiency are affected by a more precise estimation of insulation levels and building stock dynamics. This is what will be mainly discussed. Values of FED were especially checked for Europe, given the availability of data on U-values.

Finally, the final-to-useful energy efficiency trends are presented in figure 5.6, in order to further clarify what was discussed until now.

First of all, the different scales of heating and cooling efficiencies are clearly apparent,

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[1] Remember that in order to calculate space heating and cooling demand, the left-side terms of equations 3.2 and 3.3, which include the U-value, are respectively regressed with HDD and income

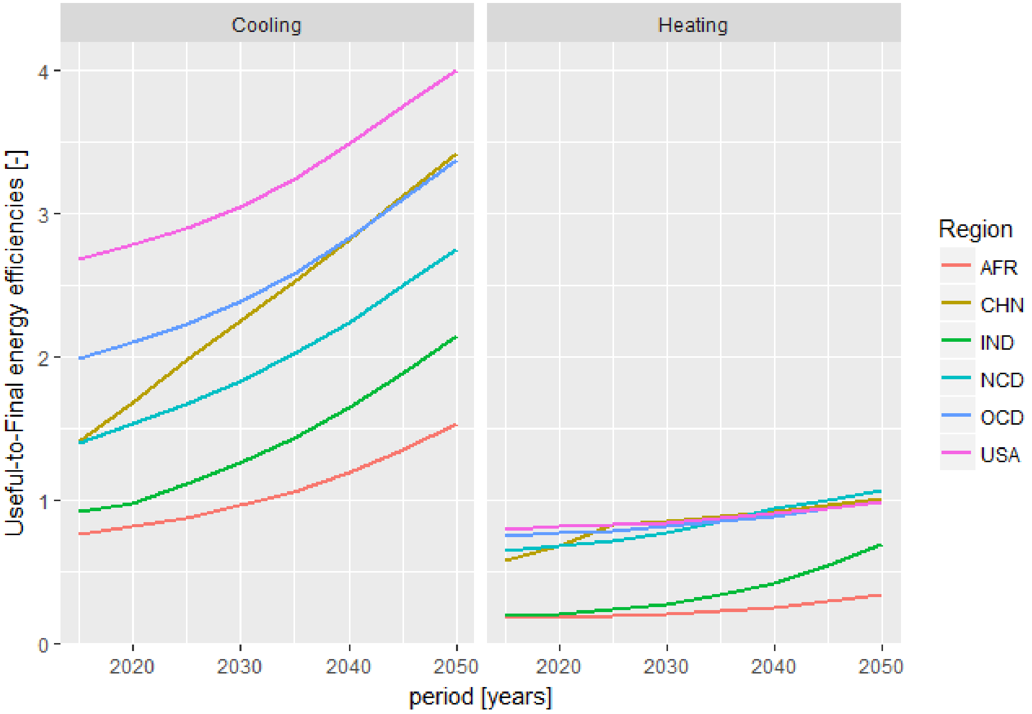

Figure 5.6: Final-to-useful energy efficiencies, divided by end-use

with heating systems exceeding 100% value only in developed countries, after 2050, due to the penetration of electric heat pumps. Considering the cooling end-use, the relation of efficiencies with income can be clearly outlined, with China showing the highest gradient in GDP in figure 5.3 and accordingly, the same happens for its efficiencies, which catch up with OCD region in 2040. USA show the highest levels, as it is the richest nation between the selected ones.

Regarding heating efficiencies, it can be seen that Chinese values reach the other countries, in 2025. This happens because of the shift to modern fuels (remember from section 3.2 that traditional biomass utilization for space heating is abandoned as soon as the country GDP approaches 20000 $\$_{2005}$/cap). Indian GDP grows more than the African one and accordingly, its efficiencies show a steeper increase due to a faster shift to modern FEC. Other drivers determining the efficiency level for developed countries regard the specific regional energy mix and are marginal compared to the effect of income, thus they will not be discussed.

5.2 European Energy Policy for Buildings Directive

Firstly, the impact of the implementation of the EPBD in European countries is analyzed. Then, the same policy is applied to the whole world, with a discussion on global and regional consequences.

The EU EPBD is divided in two objectives, with the first one regarding new construction and the second one related to renovation of the already existing building stock. It is interesting to firstly understand to which level the FED decreases if this policy is successfully implemented and the amount of energy savings that would be achieved, compared to current trends. Then, it is also important to outline which of the two policy objectives would lead to the highest amounts of energy saved.

As concrete numeric thresholds or ranges are not defined in the EPBD, EU member states are allowed to define their nZEB in a very flexible way taking into account their country specific conditions [31]. Therefore, an assumption on which levels of insulation might be representative for a nZEB must be made. Looking at the EU database, the lowest level of U-value in the 2014 vintage is 0.3 $W/m^2/K$, with Sweden and Finland going even beyond and reaching 0.2 $W/m^2/K$. The Zebra 2020 project outlines that insulation levels in nZEBs generally do not differ much across climates: they are really high in any case, with opaque surfaces U-values being around 0.1-0.2 $W/m^2/K$ and triple-glazed windows with low-e coating ($U=1.1\ W/m^2/k$) installed [31]. Due to these considerations, a representative U-value for an nZEB was chosen to be 0.3 $W/m^2/K$.

In any case, even if warmer countries will probably install slightly higher U-values, it is also likely that nordic countries will manage to reach even lower U-values, especially if window technologies will develop further. In order to simulate the implementation of the policy, new construction U-values were thus fixed to 0.3 W/m2/K, while the already existing stock U-values are assumed to linearly decrease to that level. In this way, a 100% renovation of the current stock is reached in 2050, with an average rate of 3%/year, as required by the EPBD. In order to keep the model simple, renovation is assumed to occur at the same rate for each vintage. In reality, renovation of the oldest vintages would probably happen first, thus leading to even higher energy savings in the short-term.

5.2.1 Implementation in Europe

The results at the European level, in terms of U-values and FED decrease, are shown in figure 5.7, with a detail on the impacts of renovation and new construction policies alone.

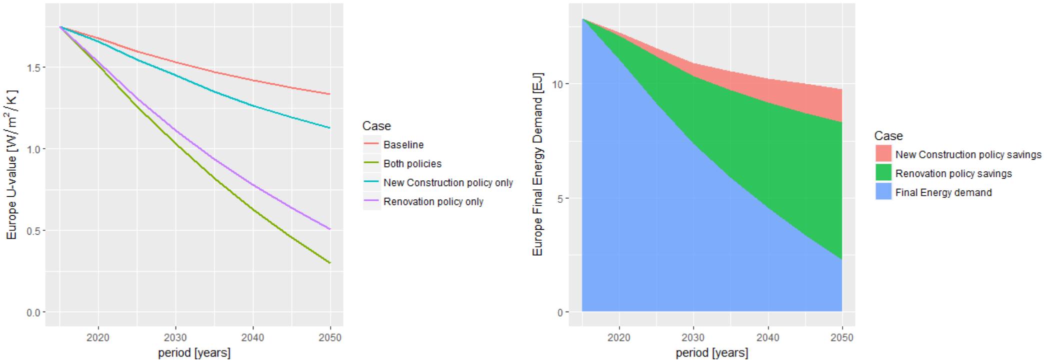

Figure 5.7: Europe U-value reduction and final energy savings according to the considered policy

As can be seen from the left-side graph, European U-values progressively decrease, reaching 0.3 W/m^2/K in 2050, starting from 1.75 W/m^2/K. Therefore, if the EPBD is implemented, U-values would become around one sixth of the initial value. Accordingly, the FED would decrease from 12.75 to less than 2.5 EJ/year. Compared to a baseline FED decrease of 20% in the considered period, the EPBD implementation would lead to an additional 60% reduction, finally leading to an overall 80% decrease.

The two figures also outline that most of the final energy savings would be derived by the implementation of the renovation policy. In fact, as outlined in figure 5.1, the new construction share in the building stock would only reach 25% in 2050. Moreover, new construction U-values have reached quite low U-values already in 2014, as can be seen from figure 4.14. Therefore, the additional effort required in the new construction stock is not high. This is not the case for renovation, which currently shows quite low rates, compared to the 3% objective, as several authors pointed out [89, 85]. Moreover, old vintages still show very high U-values. In 2050, the FED savings derived by reaching the renovation objective amount to 6 EJ, while the new construction policy would only lead to additional 1.45 EJ saved. Thus, 80% of the policy savings would come from renovation of the oldest building stock.

These results are affected by the model hypotheses. Given that once the starting U-value decreases, the renovation PBT strongly increases, renovation is certainly penalized in the baseline computations: in fact, the model implements very small refurbishment rates for the post-1980 vintages. Moreover, given the input costs of glazed components, very low levels of renovation for windows of all vintages are computed. Lower costs could have been implemented, thus increasing the profitability of renovation. However, they would increase the profitability of insulating in new construction as well. Therefore, a lower FED would be reached in the baseline case, yet the share in energy savings coming from the implementation of the two policies would be the same. Moreover, implementing lower costs would lead to higher implicit discount rates in the calibration process (see section 4.7.2. It has been shown that with the current prices, European discount rates average 5%, which make sense according to the indications from IPCC and BPIE [12, 99].

Due to the model limitations, discussed in section 4.3.3, the actual gap with the renovation objective of the EPBD might be lower. However, it must be reminded that refurbishing an already efficient building is described to be not profitable (the "lock in" effect quoted in section 2.1), therefore renovating the current building stock to nZEB levels presumably requires the strongest policy effort and is much less likely to happen.

It is now interesting to understand which EU countries would save the highest amounts of final energy from the implementation of this policy. This is shown in the first row of charts of figure 5.8.

The major European nations were explicitly separated, while the remaining ones are aggregated depending on their HDDs: countries with HDD¿3000 K*day are considered to be "cold" and the opposite happens for the "warm" group. This figure outlines that the highest additional energy savings would generally derive from cold countries and from Italy. Moreover, it can be also seen that in general across all European countries, renovation of the oldest group of buildings would hold the highest energy

Figure 5.8: Europe final energy savings, in absolute and relative terms, divided by policy

savings. The situation slightly changes for Spain and Poland, in which savings from the renovation of post-1980 vintage group are equal, or even higher, than the ones deriving from the renovation of the oldest vintages. This is due to the high share of post-1980 buildings in the country stock.

The indications from the first row of charts in figure 5.8 are expressed in absolute terms and depend on several factors, such as the size of the country building stock and HDD and CDD levels. Clearly, the bigger the country, the greater the amount of energy that can be saved. Moreover, the colder the country, the higher the expenditures on space heating, thus the higher the amounts of energy saved for a unit of U-value reduction. Therefore, the second row outlines how these energy savings relate to the baseline FED of the group. It results that cold countries would reduce their energy demand by 70%, while this percentage generally increases to 80-85% for warmer nations. This outlines that cold countries are already closer to nZEB levels compared to the warm ones.

The third row outlines the amount of energy saved per building. In this way, the amounts of energy saved are related to the size of the group building stock, in order to have a fair comparison. In fact, most of the buildings in Europe are located on cold climates and this might be why higher energy savings would be obtained from cold countries. It actually results that cold and warm countries show similar quantities. In fact, warm countries show lower levels of insulation, but also lower expenditures on energy per unit of U-value, due to both low HDDs and not significantly high CDDs. This row also shows that the highest amounts of energy per buildings would be saved in Italy, Poland and Great Britain. This means that these countries show levels of insulation that are relatively low, considering that due to type of climate in which they are located, they consume a significant amount of energy.

5.2.2 Implementation all over the world

It is interesting to extend the EPBD analysis to the world level, in order to look at the energy savings that would also be obtained from reducing cooling demand in warm regions. In fact, even if in Europe, warm countries generally show low levels of insulation, a strong increase in insulation levels for those nations would not even lead to high amounts of final energy savings, since their levels of FED is not high. This is not the case at the world level, since some warm regions experience high levels of cooling FED, yet they show low insulation levels. Figure 5.9 outlines what would happen if all the regions in the world implemented this policy.

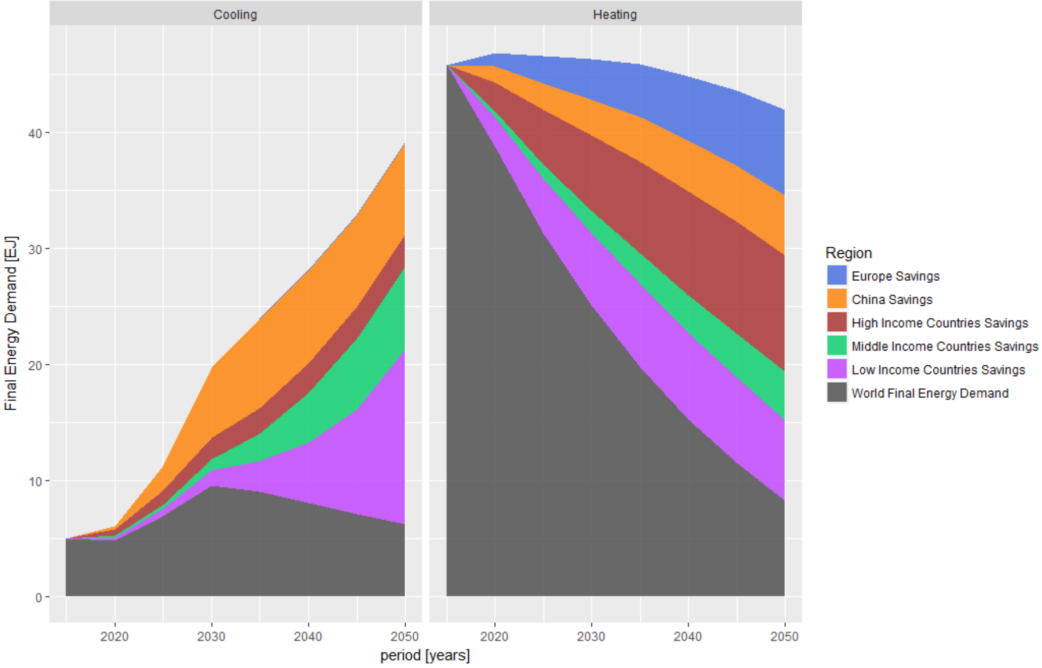

Figure 5.9: World final energy savings, divided by country group and end-use

While the 2050 final heating demand would be strongly reduced, compared to the 2015 levels, as it happens in Europe, this would not happen for cooling demand. In fact, the 2050 cooling demand would be more of less equal to the 2015 level. Therefore, even in this extremely optimistic case, global cooling FED would not diminish. Actually, it would even show a peak in 2030, which, as can be expected from the discussion of section 5.1, is due to China. Thus, if the assumptions on cooling demand growth with income are believed, the conclusion is that the world cannot avoid to deal with an increase in cooling FED, even in the most optimistic case.

Figure 5.9 also outlines where the savings would come from if such a policy is implemented in all the world. They mostly reflect the shares of heating and cooling demand that were outlined in figure 5.5. From the right-side graph, it can be seen that a successful application of the EPBD policy in the only European region would make the global heating FED decrease by 7.5 EJ. Thus, the global heating FED would be reduced by 20% in 2050. Finally, the overall FED for space cooling and heating would be decreased from 81 to 72.5 EJ: a decrease of 10%. This is the weight that such a policy would have at the global level. In terms of cooling demand, the effect is totally negligible.

Figure 5.10 outlines which regions would save most of the energy, again according to 3 components of the EPBD, being two of them related to renovation and the third one to new construction.

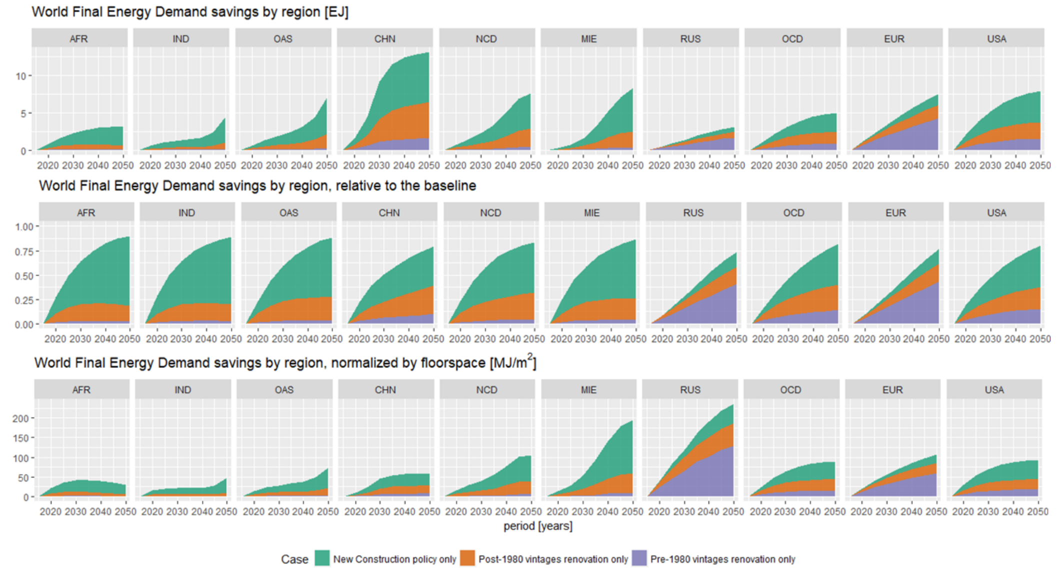

Figure 5.10: World final energy savings, in absolute and relative terms, divided by policy

Differently from figure 5.8, renovation of oldest buildings would not hold the highest energy savings at the world level. While renovation would hold 70-80% of the total energy savings in Europe and Russia, this percentage decreases to 40-50% in China, USA and OCD regions, while further reducing to 20-30% in developing countries. Therefore, especially in the latter regions, it would be much more important to implement stringent energy codes. Of course, this is an extremely optimistic case, since it is not realistic to believe that nZEBs will be constructed in Africa and India, yet these graphs outline the importance that building an efficient new construction stock would have in the future energy demand of these regions.

The key message related to this figure is that once the cooling demand sharply rises, having a highly efficient building stock would lead to a great amount of energy savings. This happens for instance between 2025 and 2030 in China, after 2040 in NCD, MIE and OAS regions, and finally across 2045 and 2050 in India. Differently from the European and Russian region, the increase in energy savings in not at all linear and is linked to both the sharp increase in new construction and in cooling demand. Looking at the absolute values of energy savings, China would save around 13 EJ on its own, while several regions would reduce their energy consumption by 6-7 EJ, as Europe does.

Moreover, higher demolition rates were applied in developing regions, so that approaching 2050 the savings related to renovation flatten. This is even clearer by looking at the second row of charts, in which energy savings were normalized by the baseline FED. The great impact of new construction and cooling demand in countries which shift towards a higher level of income makes the FED savings curve concave, which means that higher savings are reached within the first timesteps, then the slope of the curve diminishes, as happens for China.

Finally, normalizing the energy savings by the floor space of the country, it can be seen which regions are inefficient, relatively to their amount of energy demand. Russia results to be the worst one, meaning that given its high amount of heating energy demand, it is relatively bad-performing and much higher savings per m^2 of floor space would be reached by the implementation of a strong renovation of its building stock. In this region, sreat refurbishment rates do not happen in the baseline computations, since due to subsidies on energy prices it is not convenient to insulate. The same holds true for Middle East. This will be further outlined in section 5.3. Despite having very low levels of insulation, Africa and other developing countries do not show very high savings per m^2 of floor space, since their energy demand is quite low. Conversely, China, Europe and USA show much higher FED, however their stock will be developed in a relatively efficient way.

5.3 Energy price analysis

In this section, two main analyses were performed. The first one analyzes the impact that rising energy prices would have on the FED gap between the EPBD objectives and the estimated future trends, based on current levels of policies. The second one outlines the impact that subsidies on energy prices have in different regions of the world.

Prediction of future energy prices is highly uncertain and depends on a multitude of factors which have not been analyzed here. However, it has already been outlined in section 2.1 that increased energy costs would lead to mitigation of rebound effects, due to the response of consumers. Therefore, technical reports typically either decide to keep prices fixed, or assume an increase over the years [12, 60, 89], to analyze how the models respond in terms of energy efficiency improvement.

The Ecofys report named ”Renovation tracks for Europe”[60] makes the hypothesis of increasing electricity and other FEC prices respectively of 2%/year and 2.8%/year, until 2032, based on expected trends outlined by [11]. After 2032, no hypothesis was made on energy prices development and in order to employ a conservative point of view, prices were kept constant. One of the latest studies on European energy trends estimates an increase of oil prices by 2.3%/y from 2016 to 2030, which then flattens to +0.7%/y until 2050 [108], therefore it makes sense to include a slower increase after 15-20 years. Moreover, BPIE [12] implemented both a ”low” and ”high” energy price scenario, in which prices increased respectively by 1.3%/y and 4.3%/y, with a ”medium” reference of +2.8%/y which seems in accordance to Ecofys. In addition, input data from [10], also outline the levels of subsidies on energy prices. Therefore, 4 different scenarios were tested and compared both to the baseline development of U-values, which assumes fixed energy prices over the 2015-2050 period, and to the

EPBD targets. The hypotheses and the main results are summarized in figure 5.11.

Scenario	**Hypothesis**
Subsidies	Subsidies on energy are linearly decreased to 0 in 2050
BPIE$_{low}$	Energy price increase of 1.3%/y
Ecofys	Electricity price increase of 2%/y, Other FEC increase by 2.8%/y, until 2030. Then, constant prices are assumed
BPIE$_{high}$	Energy price increase of 4.3%/y

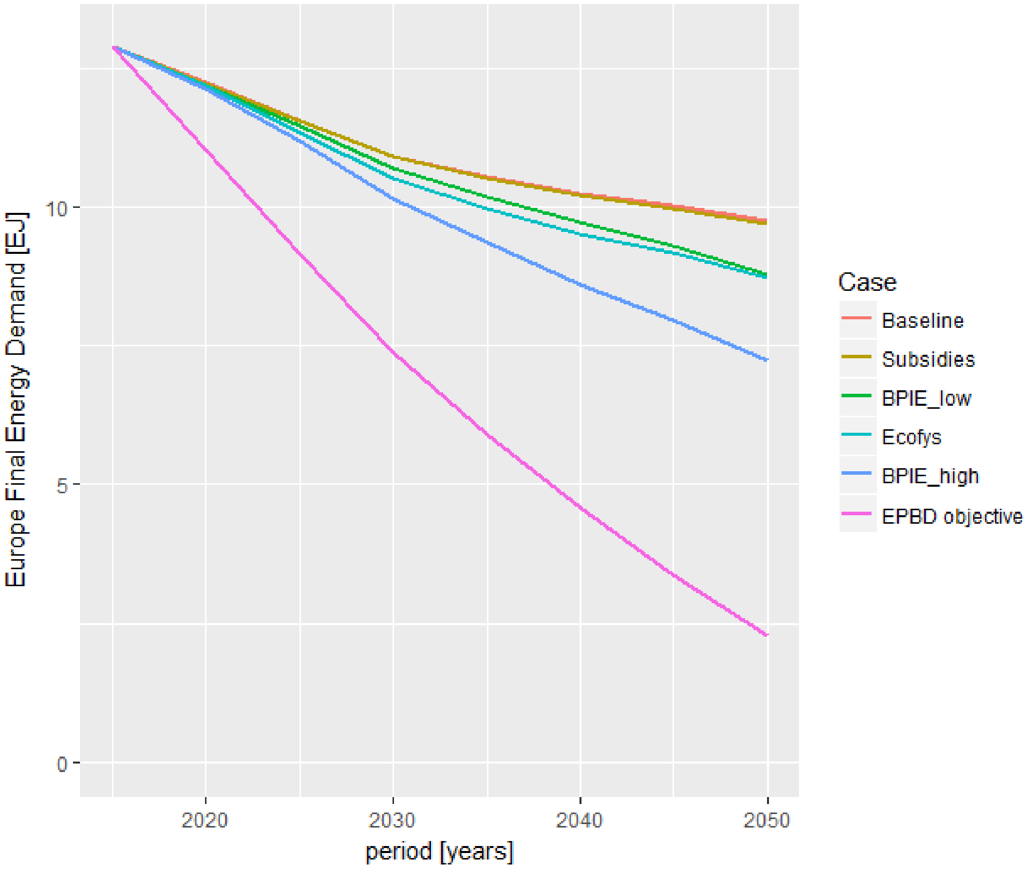

Figure 5.11: Europe final energy gap reduction, compared to the EPBD target, in 4 different scenarios

In the most optimistic scenario, a further FED reduction of 2.5 EJ is achieved in 2050 compared to the baseline, thus the remaining gap with the EPBD objective amounts to 5 EJ. Subsidies reduction leads to a FED decrease of only 0.05 EJ, which means around 0.5% of the baseline European FED in 2050. Their impact is therefore negligible in Europe.

The gap between the BPIE$_{low}$ and Ecofys scenario firstly widens, then it becomes progressively thinner, with the former case catching up with the latter when approaching 2050. This happens because in the Ecofys scenario, costs do not increase anymore after 2030. In the BPIE$_{low}$ case, costs manage to increase much more within 2050: if an average price growth in the Ecofys scenario is assumed to be 2.4 %/y, in 15 years costs will increase by 42%, while a 1.3% increase over 35 years finally leads to a 60% rise in 2050. However, since in the former case high cost levels are already reached in 2030, a greatly efficient new construction stock and higher renovation rates will be implemented earlier. Through higher refurbishment rates, the BPIE_{low} scenario will easily catch up with the Ecofys case. However, this is not the case for new construction: every new building will remain in the stock for several years before being demolished. This eventually results in *inertia* for policies stimulating buildings efficiency and at the same time, creates a strong path dependency of choices made now for the future efficiency potential. As already outlined in section 5.2.2, the sooner the most efficient buildings will be constructed, the higher will be the benefits, especially for developing countries, which will experience high construction rates. This is even more important when considered in a climate change perspective: reducing FED now has a higher impact, compared to achieving the same, or even higher, decrease later. This is due to the fact that the current energy mix is still highly pollutant, in terms of CO_2 emissions, while presumably in the future the diffusion of renewable technologies will make the provision of the same levels of FED with lower emissions possible. In conclusion, the sooner energy prices are increased, the higher the impact on the emissions from the building sector will be, for both the inertia and dirty energy mix effect.

The second analysis is related to the implementation of the *Subsidies* scenario all over the world. However, several reports outline the importance that such a measure would have in regions such as Russia [83], Middle East [16] and China [84]. Therefore, the derived FED savings by region are outlined in figure 5.12. It is immediately apparent that most (77%) of the savings at the global level would actually come from the three regions that were previously outlined, with Middle East providing 55% of the savings on its own, particularly due to its big increase in cooling demand, which makes even more important to increase efficiency. The 2050 FED savings amount to 2.7 EJ, which constitute approximately the 3% of the world total FED in the same year. Thus, the effect of subsidies removal will certainly not be negligible at all at the world level.

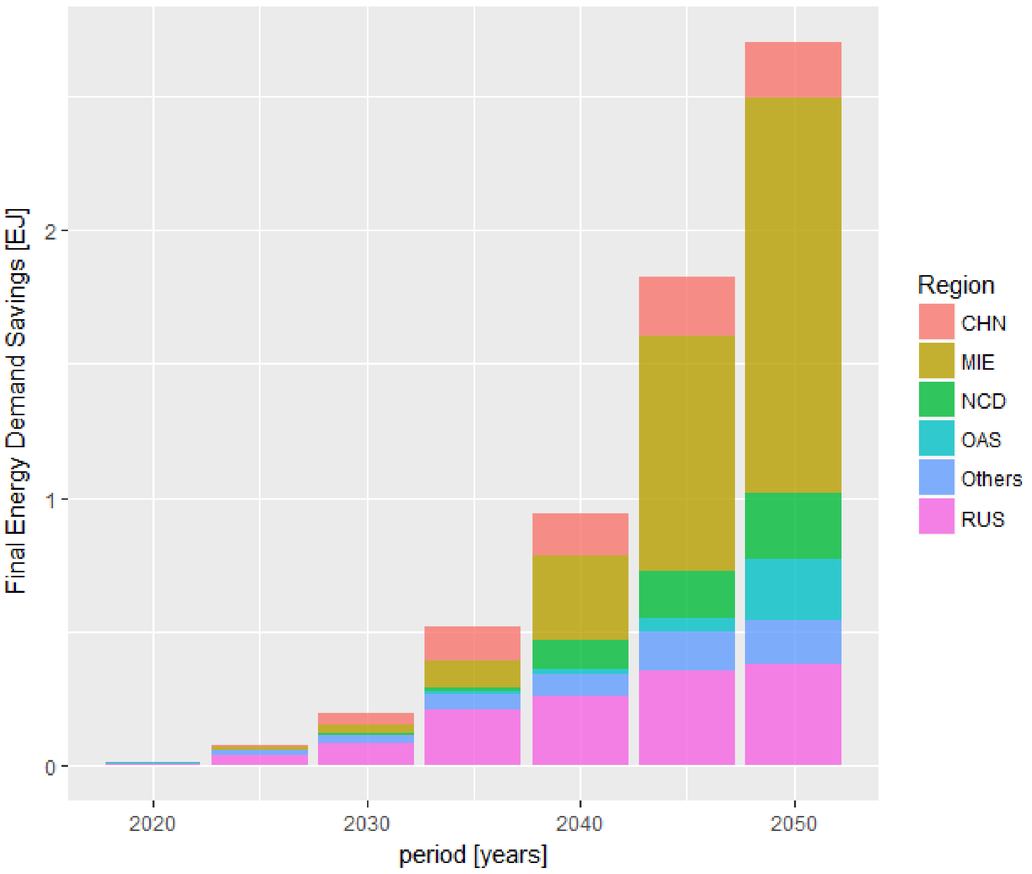

Figure 5.12: Final energy savings compared to the baseline, at the world level in case of subsidies reduction

Chapter 6

Robustness Analysis

As already discussed in section 3.1, several uncertainties on input data can affect the results, thus the robustness of the model outcomes must be checked by means of sensitivity analyses on the most unpredictable drivers. All the results are shown with the EPBD target trends, in order to give a indication on what is the lowest limit which is reachable for FED and U-values.

Therefore, section 6.1 analyzes the impact of different assumptions on cost decrease. Then, since another highly uncertain trend is constituted by the evolution of the logit parameter of equation 4.11 and this is tested in section 6.2. As already outlined in section 4.4.3, discount rate variations may also strongly affect the results, thus different evolutions are tested in section 6.3. Moreover, renovation rates are tested in 6.4. Since the evolution of the main socioeconomic drivers and how these will affect global warming constitutes another great source of uncertainty, section 6.5 exploits the SSP concept, outlined in section 3.1, and investigates the different outcomes that are derived. Finally, the actual possibility of reaching the EPBD targets is tested in section 6.6.

6.1 Technology cost decrease

In this section, the impact of different assumptions on technology cost decrease is tested. Results are gradually presented, starting from the regional impact on U-values, then looking at how these changes translate into FED variations within each region, and finally looking at the world level heating and cooling FED differences across the tested cases.

Indications on technology cost decrease were taken from [31]. This report outlines ranges of cost reduction from 0.5 to 2%/y. In the context of this sensitivity analysis, 3 cases, additional to the baseline, were tested. Briefly, one scenario assumes no cost decrease. The second outlines the possibility of doubled cost decrease (as made in [31]) compared to the baseline. Moreover, another case has been added, which is even more optimistic and implements a 3%/y cost decrease. Figure 6.1 outlines the impact of cost decreases on regional U-values, indicating also the EPBD objectives.

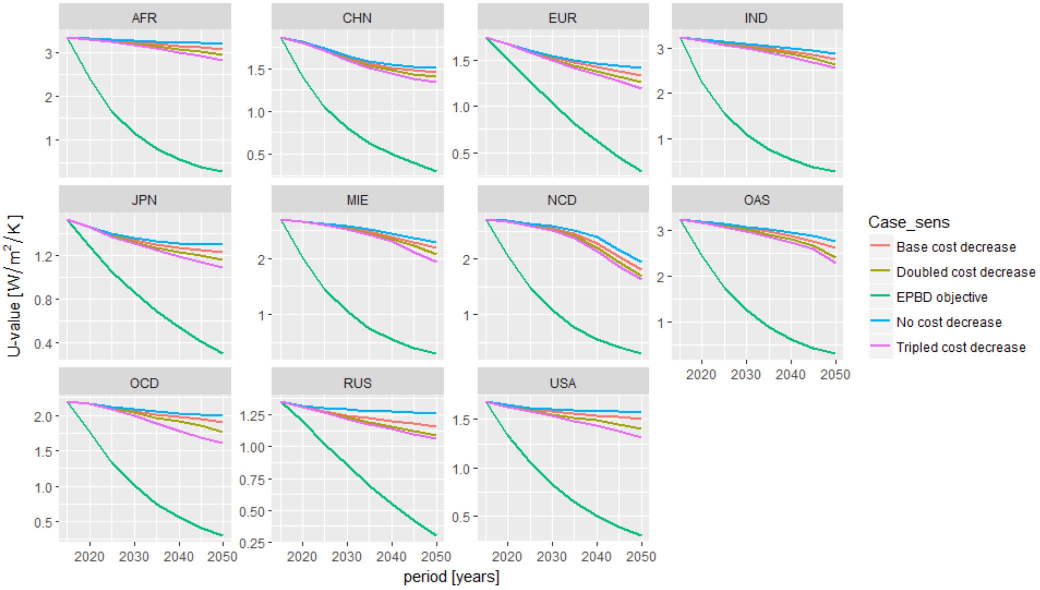

Figure 6.1: Regional U-value dependence on cost decrease

Ffrom the worst to the best case, in general developed regions show a decrease in U-value of 0.25 W/m^2/K, while the reduction amounts to 0.5 W/m^2/K for developing regions. Therefore, cost decreases are more impacting, in absolute terms, in the latter group. This is due to the higher discount rates that are implemented in these regions, which decrease the importance of the *expenditures* term in the NPC calculation (see equation 4.2), thus attributing much more importance to the *investment* term, which is affected by technology cost decrease. However, considering that developing regions also show much higher starting U-values in 2015, it can be stated that the relative impact is generally similar across regions.

Then, figure 6.2 outlines how U-values reductions translate into FED shifts across different regions. Even if countries such as Africa show U-values decrease of almost 0.5 W/m^2/K from the worst to the best case, the corresponding reduction in FED is much smaller than what happens in other regions. As can be presumed, regions holding the greatest impacts are China (with a decrease of 2.5 EJ between the upper and lower limit cases), Europe, USA, Middle East and non-OECD countries, since they hold the highest levels of FED in 2050.

Finally, figure 6.3 indicates the corresponding shifts in FED, divided by end-use. Regarding space heating, it can be stated that an additional cost reduction of 1%/y decreases FED by 0.6 EJ in 2030, while in 2050 the gap between each different case increases to around 2 EJ. Concerning cooling FED, the impacts of technology cost decrease start to be significantly high as soon as cooling FED explodes in different world regions (i.e. after 2030). Thus, even in the most optimistic case, the gap with the EPBD objectives remains quite high, amounting to 29 EJ for both end-uses.

Within this analysis, costs were equally decreased for all the technologies. Separately applying cost decreases to opaque and glazed surfaces holds to the conclusion

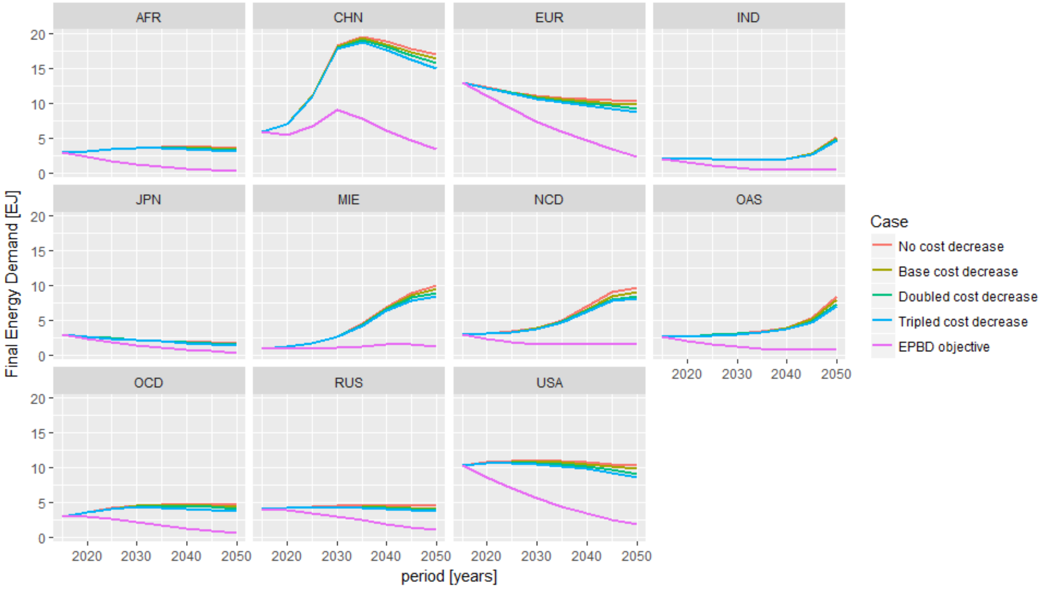

Figure 6.2: Regional Final Energy demand variation due to cost decrease

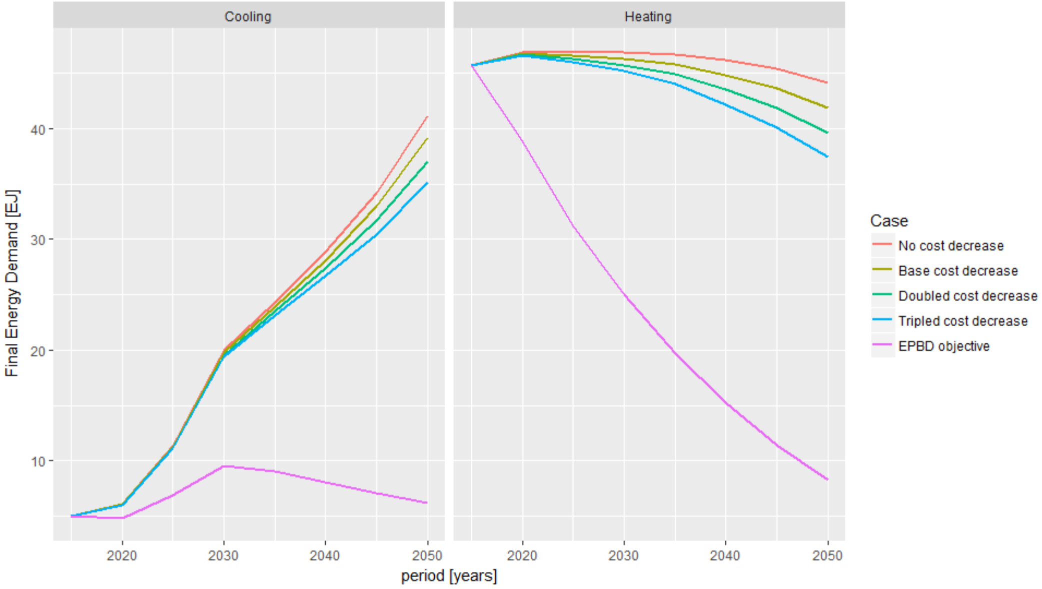

Figure 6.3: World Final Energy demand variation due to cost decrease

that prices reduction are more important for the former components, as figure 6.4 outlines.
This is the result of different effects:

- The share of opaque components in the building envelope is higher.
- Window cost decrease is applied to all the 5 groups of technologies, indicated in table 4.1, thus favouring even the single-glazed ones, for instance. Of course, cost reduction in absolute terms is higher for the best performing technologies, since they start from higher costs, thus leading to an overall improvement. How-

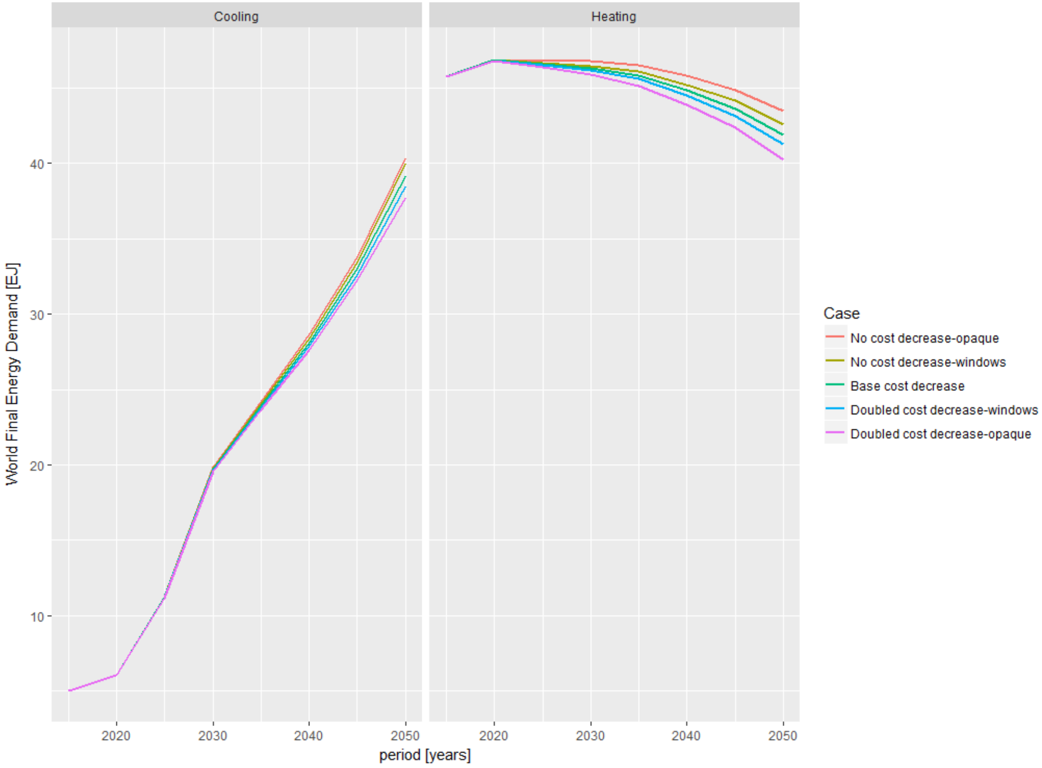

Figure 6.4: World Final Energy demand variation due to cost decrease of either opaque or glazed components

ever, this effect is slightly mitigated by the fact that the worst technologies are improved as well. This does not happen for opaque components, in which cost decrease is applied to both fixed and variable costs. The latter ones in particular are related to the optimal U-value, as equation 4.9 indicates. Therefore, both renovation and new construction mechanisms will reach lower U-values.

- Significant amounts of renovation happen for opaque components, even if costs are kept steady. This is not the case for windows: even in a 2% decrease scenario, no refurbishment happens until 2030, while reaching 1-2% in 2050 in the European and non-OECD regions. Therefore, the renovation mechanism is not affected by cost decrease in window components, while refurbishment rates for opaque surfaces show a significant increase if further cost reductions are obtained (figure 6.29 outlines renovation rates in a 2%/y technology cost reduction). This is also why cost reduction for insulation of opaque components has a greater impact across the regions.

- Applying a 1%/y decrease to opaque technologies fixed costs would mean that fixed costs for insulation would decrease from 60 to 57.06 $\$/m^2$, for instance, from 2015 to 2020. The same reduction rate would instead decrease the 3-glazed window cost from 400 to 380 $\$/m^2$, thus causing a much greater reduction in absolute terms. This is the only effect that favours glazed components.

Cost decreases for windows could have also been applied only to the best performing technologies, leaving the prices of single-glazed and double-glazed, clear glass windows constant. This was not made, since it is assumed that reductions in material costs would impact all the 5 groups in the same way, in relative terms. Only for the fifth group, named *Future window* in table 4.1, it was assumed that cost decrease are not only due to materials improvement, but also to technology development, determining the entrance of this technology into the market. Different assumptions on quicker entrance into the market of the most advanced window do not lead to significant changes in results.

6.2 Logit parameter

The logit parameter λ determines the heterogeneity of markets in the allocation of different technologies. It was shown in figure 4.9 that the higher the λ, the more the model converges towards choosing the optimal insulation level, which means implementing high U-values when it is not convenient to insulate and conversely, very low U-values in the opposite case. With respect to the base case, two additional scenarios were tested. In the first one, it is assumed that all the world countries start with the λ assigned by the calibration process, but linearly converge over time to an optimal allocation of technology shares: therefore, the λ value in 2050 is fixed to 0.1. The second case analyzes the opposite situation: all countries converging towards heterogeneous choices, with λ=0.001 in 2050. Figure 6.5 outlines the impact of these scenarios on regional level U-values.

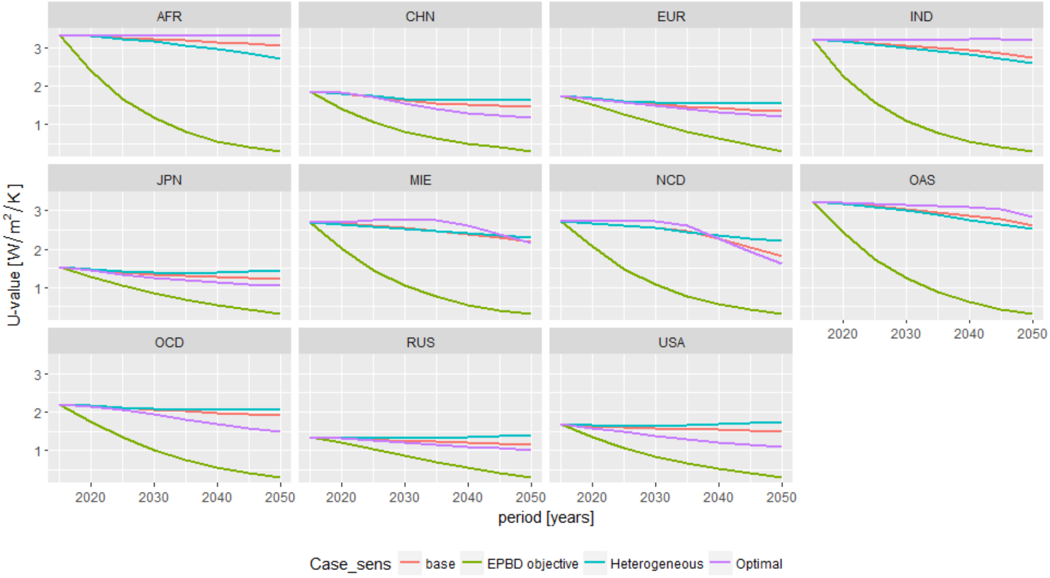

Figure 6.5: Regional U-value dependence on logit parameter

It immediately results that for developed regions, convergence towards an optimal technology choice increases insulation levels, while the opposite happens for developing regions. Mixed effects are shown by China, Middle East and non-OECD countries, which in this period are projected to shift from a low to a high level of income (recall figure 5.3 in section 5.1). In fact, they show trends typical of low-income regions at the beginning (with higher λ resulting in higher U-values), while they move to typical trends of developed countries in 2050 (with higher λ resulting in lower U-values). Moreover, the beginning of such a shift can be seen for the OAS region as well, which starts inverting its trends only in 2050, with the curve related to the "optimal" scenario showing a shift downwards.

This trend happens because developing countries are related to cooling-based FED, which in turns depends on income, as outlined by figure 3.4. Thus at low levels of income, cooling FED is really low. Moreover, during the first timesteps, heating FED in developing countries is also curtailed by the model, due to the δ_{heat} term of equation 3.2, which gradually increases over time (see figure 3.5). These two effects make higher insulation levels not convenient, thus the optimal scenario converges towards higher U-values. Once income grows and convergence with developed countries happens, the optimal choice is shifted towards implementing higher levels of insulation.

This is even clearer by looking at figure 6.6, which shows how these trends relate to FED evolution over time.

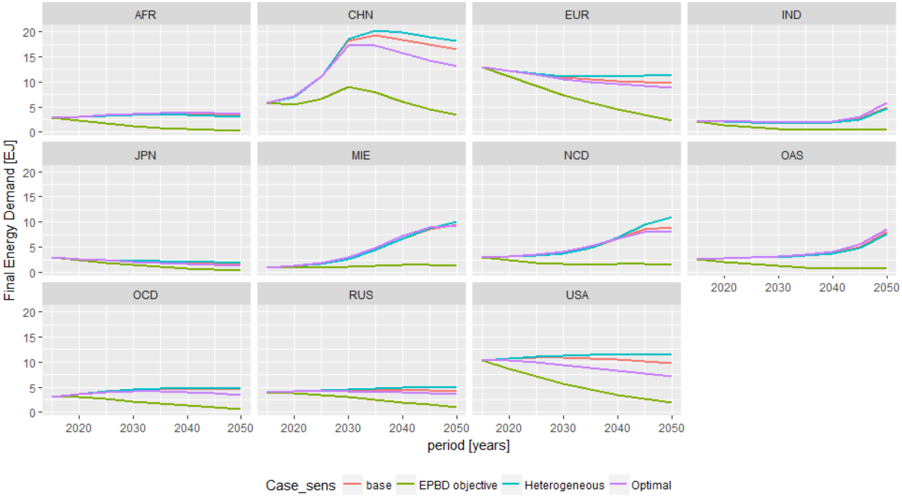

Figure 6.6: Regional Final Energy demand dependence on logit parameter

Connecting figures 6.5 and 6.6, it can be noticed that for the NCD and China regions, once the cooling demand greatly increases, the optimal choice is shifted towards lower U-values. The same conclusion hold true for Middle East but it is less clear, since the shift happens close to 2050. India and OAS regions are only at the beginning of their cooling FED increase, thus the optimal choice still leads to lower insulation levels in this countries even in 2050. As already remarked, developed regions show that the optimal scenario always leads to a reduction of their FED.

Finally, figure 6.7 shows how the different trends over regions combine and affect the world-level FED.

It results that heating FED is much more affected by the scenario choice, compared to the cooling one. This happens because most of the heating FED is determined by

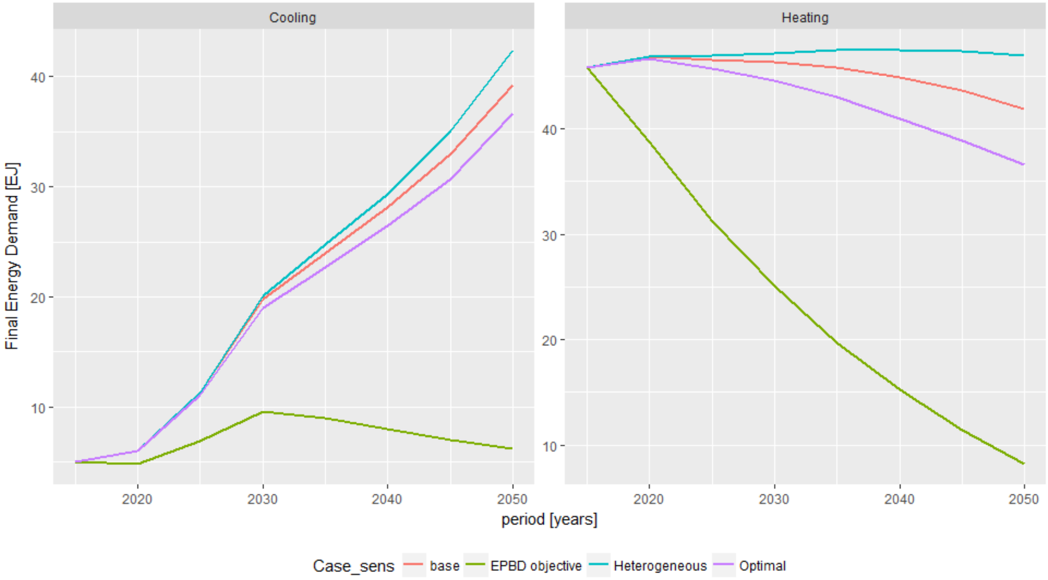

Figure 6.7: World Final Energy demand dependence on logit parameter

high-income regions and China (see figure 5.5), which all shift towards higher levels of insulation in the optimal scenario. Instead, cooling FED is mostly attributed to lower-income countries, in which counterbalancing trends across regions arise: the optimal scenario leads to lower cooling demand in China, while this does not hold true for the OAS region, for instance. However in general, regions showing high cooling FED increase eventually shift to lower U-values if λ is increased, thus the overall effect is a reduction of FED in the optimal scenario.

In conclusion, the gap with the EPBD objective in the optimal scenario may be reduced respectively for heating and cooling FED by 5.4 and 2.5 EJ in the optimal scenario, thus leading to a remaining difference of 28.3 and 30.5 EJ in 2050.

6.3 Discount rate

Discount rate development over time is highly uncertain and has a significant impact on the profitability calculations for insulation measures. This section is divided into 2 parts: in the first one, different developing countries discount rate decrease over time are tested. In the second one, an analysis on possible changes for other regions are discussed.

Developing countries

The assumption that rising incomes will lead discount rates of developing countries down to 5% with a linear decrease will be tested in this section. Several critiques about this hypothesis may be raised. Developing countries face a number of additional risks, which range from political to economy and regulatory risks and often lead to significantly higher discount rates [109]. The assumptions that increasing incomes will push these countries to reach the same habits of developed nations is certainly criticizable, For instance, [95] outlines that rising incomes in sub-saharian Africa did not actually lead to a fall in the use of traditional biomass. Stagnation in sub-saharian Africa has a wide number of causes, ranging from low social development to colonial legacy [110].

Thus, different discount rate decays were tested for the 4 world regions whose implicit discount rates were found to be equal to 15% (see figure 4.12). Figure 6.8 outlines the scenario hypotheses and the resulting impact on regional U-values.

Scenario	**Hypothesis**
No decrease	Discount rates are kept fixed to the 15% level
Partial decrease	Discount rates linearly decrease with income, not over 10%
Quicker decrease	Exponential decay with income

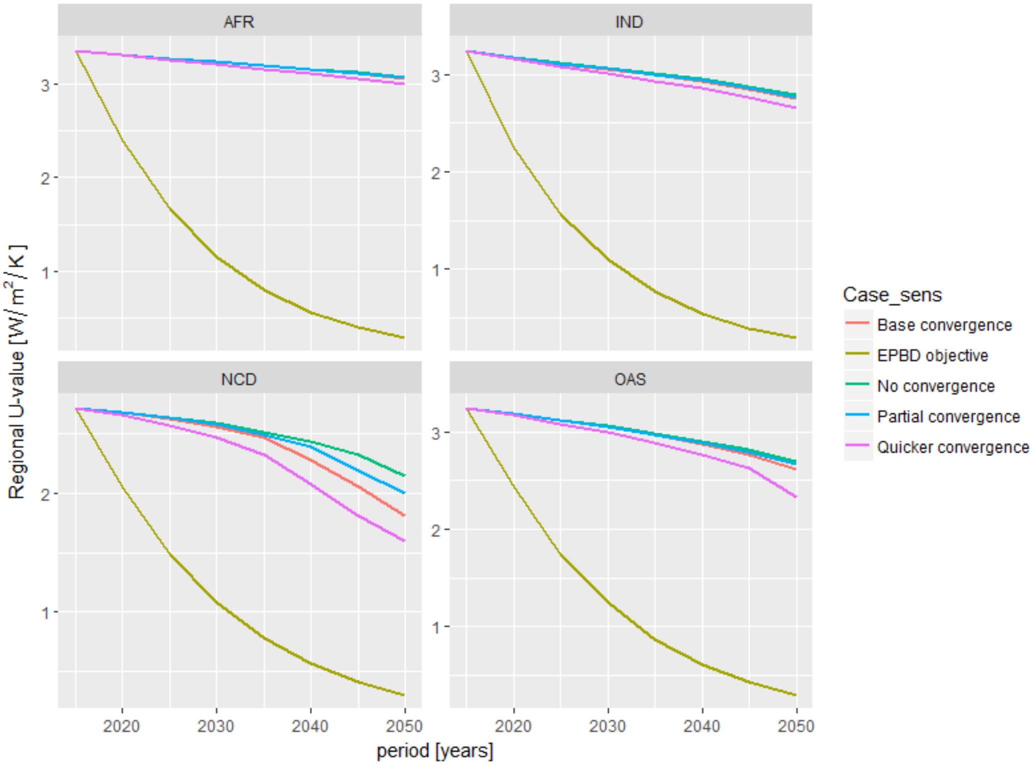

Figure 6.8: Developing countries U-value dependence on discount rate variation

This figure outlines that Africa does not substantially change its outcomes, depending on the different assumptions. This happens because across this period, in the base case its income does not grow up to a level at which discount rate reaches low levels and cooling demand increases (see figure 5.3). Conversely, the NCD region reaches high levels of income within 2050, thus it increases its energy demand and becomes more sensitive to further discount rate variations (since the *expenditures* term in equation 4.2 depends on this parameter). Therefore, regions with low energy demand do not seem to change substantially their U-values, while the opposite holds true for the others. Figure 6.9 further outlines this: only NCD, and partially OAS, are responsive to discount rate variations, due to the increase in their cooling FED, caused by income rise.

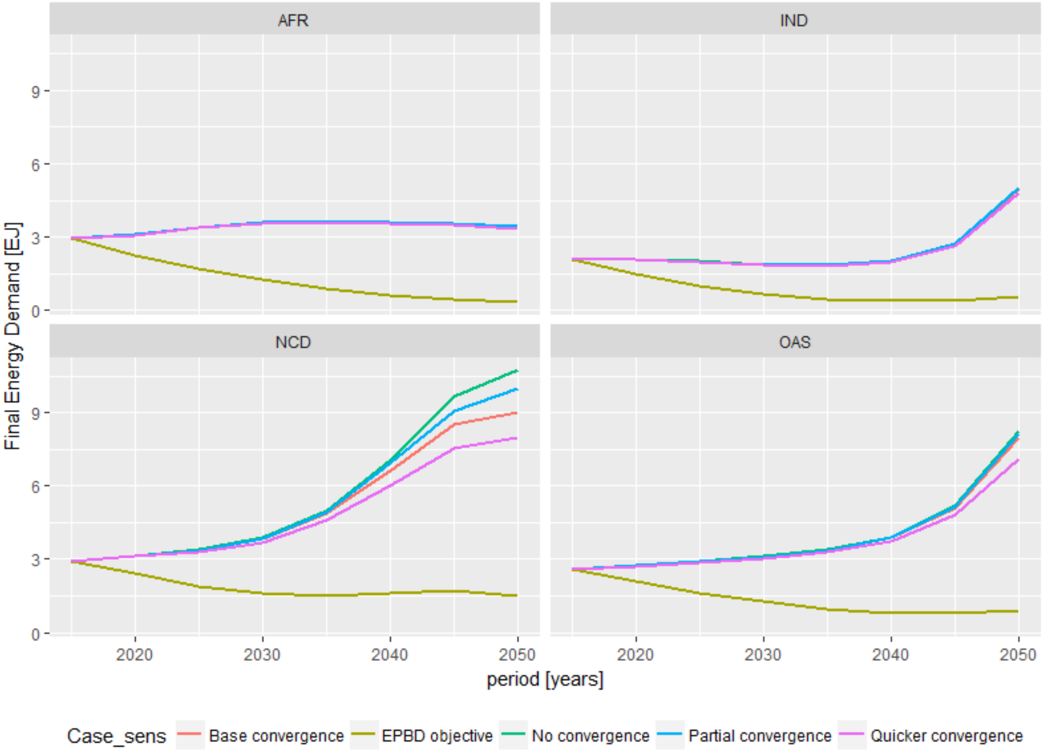

Figure 6.9: Developing countries Final Energy Demand dependence on discount rate variation

Finally, figure 6.10 outlines the FED variations according to these scenarios, which are mostly caused by the NCD region.
Given that all the 4 regions are related to cooling-based climates, shifts in the left-side graph are higher. Cooling and heating FED respectively increase by 1.6 and 0.5 EJ in the ”no decrease” scenario, while decreases by 1.6 and 0.4 EJ in the most optimistic one. Compared to the other sensitivities, this hypothesis seems to not show a huge importance, given that the 4 considered regions generally show low levels of FED (apart from NCD region). In the same way, changing the GDP threshold from 27500 $\$_{2005}$/cap to another reasonable value does not hold significant differences in the main trends.

Other countries

In the basic case, countries in which discount rates were lower than 15% were assumed to not change this parameter over time. In this section, reasonable decreases and increases are tested. Given that IPCC justifies discount rates being equal to 4-6% in developed countries [99], two cases were implemented. In the first one, discount rates linearly decrease over time, to a level of 3%. In the second one, a linear convergence over time, until a 7% level in 2050 is assumed. Developing countries discount rate decay with income was not corrected and it was left equal to the base case. Figure 6.11 outlines the results for the selected regions.
Depending on the implicit discount rate, different trends arise. For China and Russia,

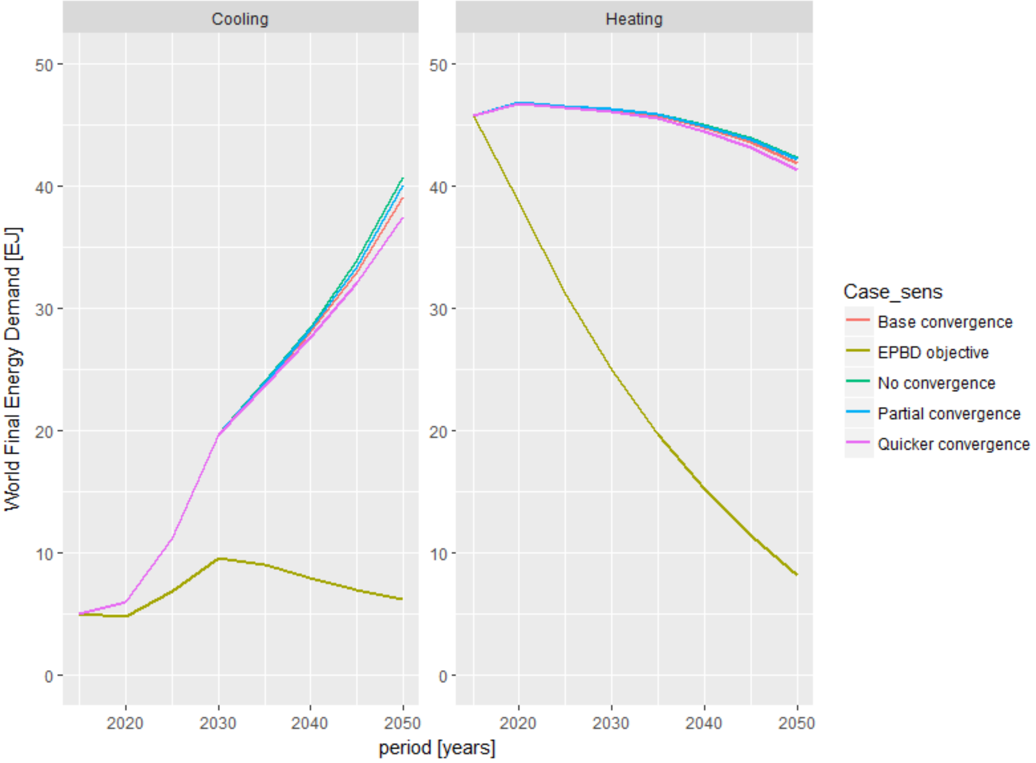

Figure 6.10: World Final Energy Demand dependence on developing countries discount rate

a 3% discount rate was computed in the calibration, thus the "base" and "3%" case overlap. Japan actually shows improvements, compared to the baseline, even in the 7% case, since its implicit discount rate is equal to 8.1%. For the remaining countries, the "base" case is in the middle of the others. In order to be more synthetic, since it is already known how these regions contribute to the world FED, figure 6.12 directly shows the final results.

Since most of the considered regions are related to a heating-based climate, the impact on the right-side graph is higher. Cooling and heating FED respectively increase by 1 and 1.9 EJ in the "7%" scenario, while decrease by 0.8 and 2.4 EJ in the "3%" scenario. Therefore, if discount rates are kept within these ranges, the results do not substantially vary and the gap with the EPBD objectives remains high. Assigning discount rates lower than 3% would not represent a realistic case, while overcoming 7% would not be coherent with the SSP2 narrative of low shifts from historical trends.

6.4 Renovation

In this section, the assumptions regarding renovation rate levels and functions are analyzed. Firstly, different dependences of renovation rate on the PBT (see equation 4.12) are tested. Then, the impact of different renovation rate levels are discussed.

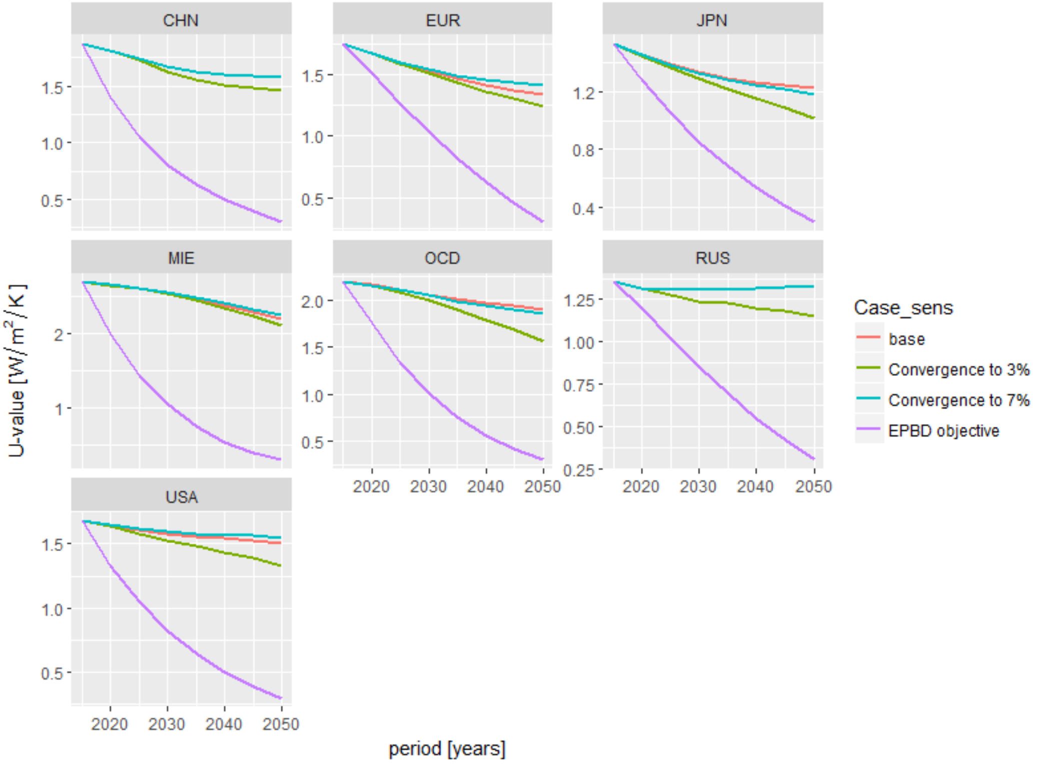

Figure 6.11: Other countries Final Energy Demand dependence on discount rate variation

Renovation function

Different functions were tested for the dependence of renovation rate on PBT. These are shown in the left-side graph of figure 6.13, together with the corresponding results for the European region U-value.

Recall from section 4.3.3 that the upper and lower limits of renovation rate are computed in order for the model to calculate a 1%/y refurbishment rate for the European stock in 2020, which is equivalent to a 5% every five years. This figure shows that only slight changes are associated to the implementation of different renovation functions, with a U-value reduction of 0.03 $W/m^2/K$ from the worst to the best case. This is due to the small span of variation (3%: from 7.5% to 10.5%) of renovation rate due to the PBT, considering that the average of the lower and upper value of the interval is 9%. Since as will be seen in figure 6.16, Europe is the region showing the highest renovation rates, it can be deduced that changing this function has no significant impact at the world level.

Renovation rate levels

In order to follow the SSP2 narrative, the Ren_{low} and Ren_{up} terms of equation 4.12 were calibrated so that an average renovation rate of 1%/y in Europe is computed by the model in 2020. However, other assumptions could have been made. Therefore, 3 additional cases were tested: the first concerns with no renovation at all, in order to outline the impacts of the efficient new construction buildings and building stock

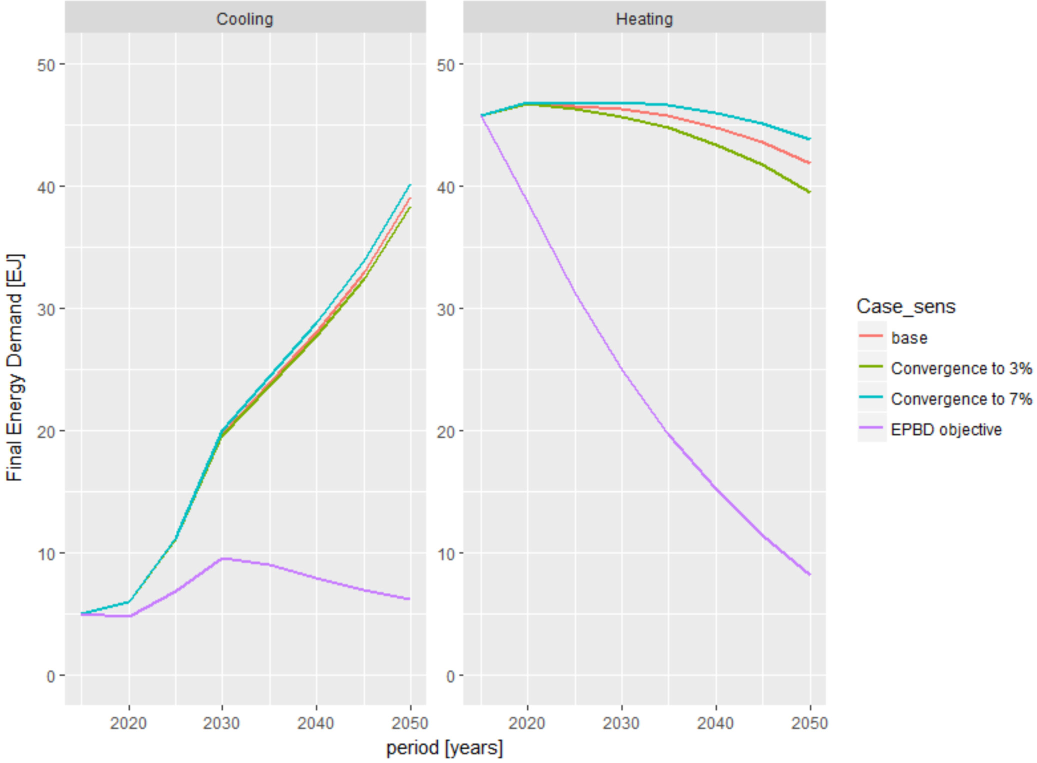

Figure 6.12: World Final Energy Demand dependence on other countries discount rate

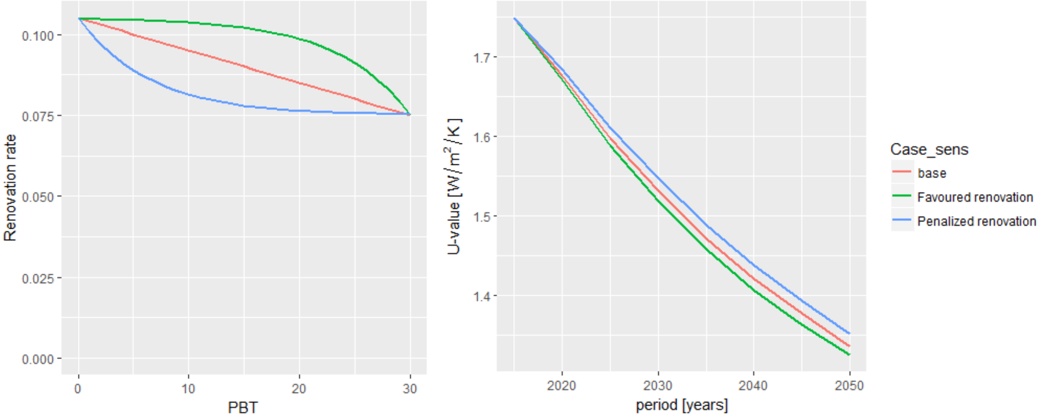

Figure 6.13: Implemented renovation functions (left) and European U-value dependence on different renovation functions (right)

demolition. The second and the third are respectively implemented so that a 2% and 3% renovation rate is computed for the 2020 period. Figure 6.14 outlines the U-value results for the most sensitive region: Europe.

Looking at the no-renovation case, it can be seen that roughly half of the European U-value decrease until 2050 in the base case is attributable to the renovation mechanism, with the other part being related to new construction and demolition. The tripled renovation case instead leads to a greater reduction of U-values in the short-term, after which the curve flattens, because the model does not find any profitable refurbishment

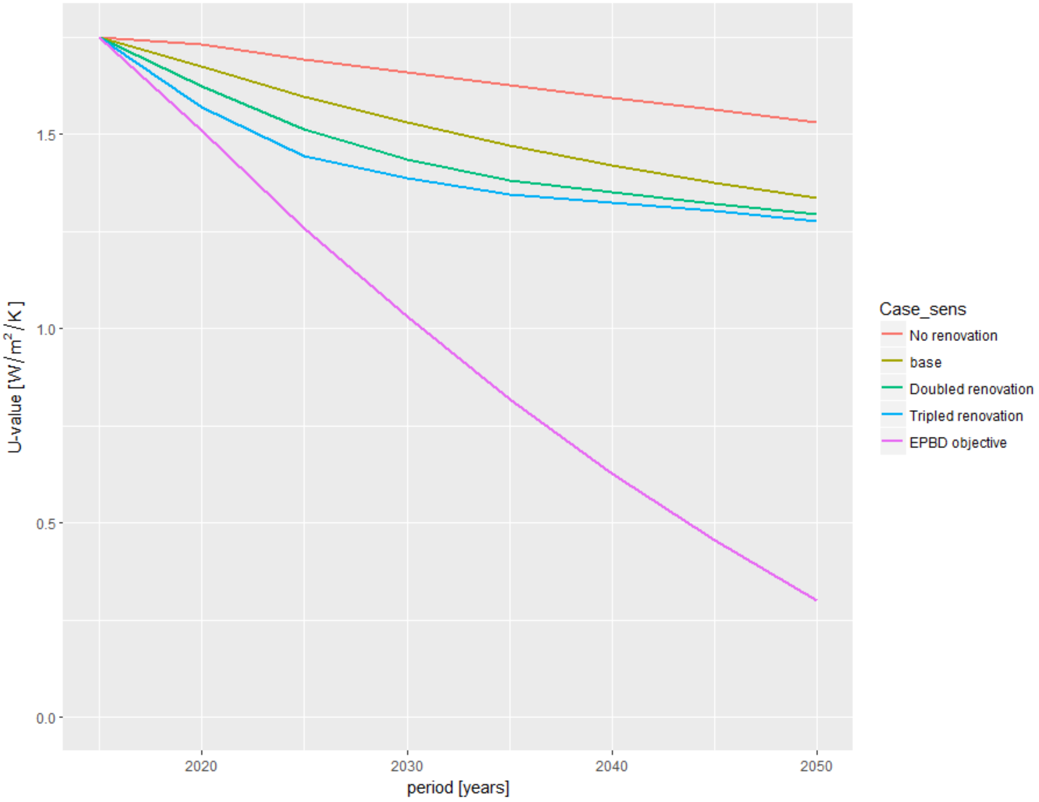

Figure 6.14: Regional U-value dependence on renovation rates

anymore, as figure 6.15 shows.

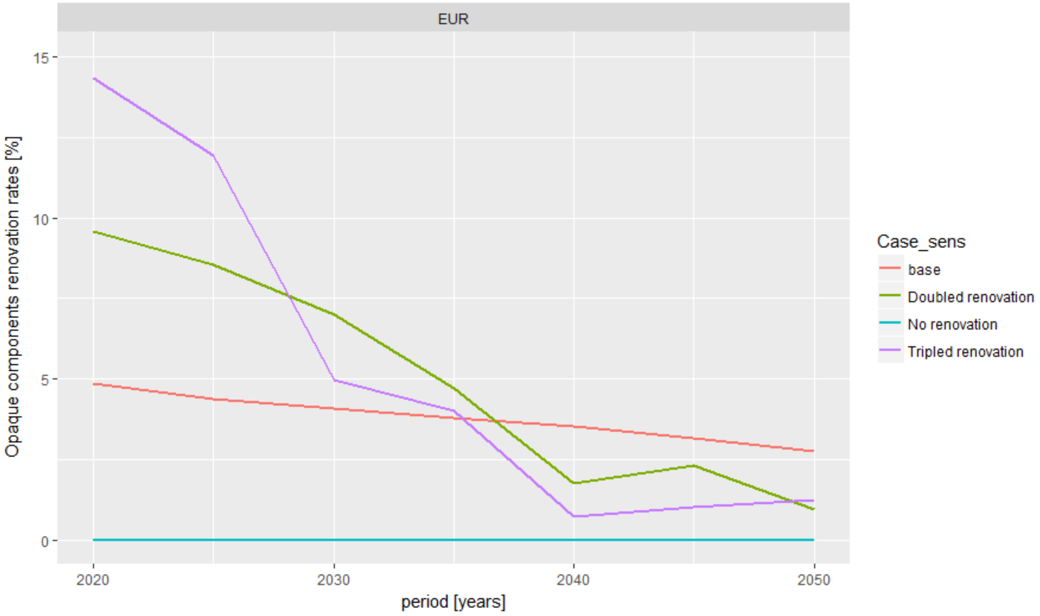

Figure 6.15: Computed renovation rates for opaque surfaces, in the European region

This is due to the high dependence of PBT on the starting U-value of the vintage,

as outlined in section 4.6. Thus, in the this case, the renovation rate (for a 5-year timestep) immediately decreases to 5% in 2030. Conversely, the "base" case computes more stable renovation rates, which start from around 5% in 2020 and slowly decrease to 2.75% in 2050. This is due to both less renovation happening and to the progressively reducing share of the currently existing building stock (which is the only part that gets renovated) over the total.
Continuing the analysis, figure 6.16 presents FED variations.

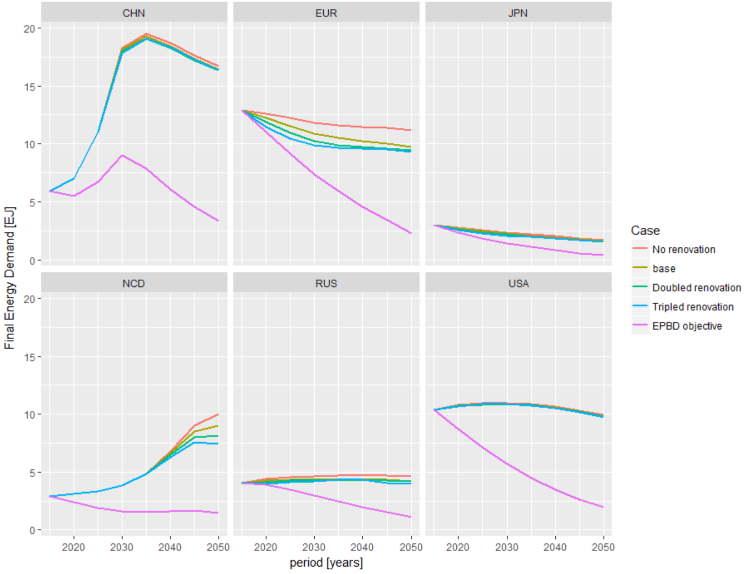

Figure 6.16: Regional Final Energy Demand dependence on renovation rates

Compared to Europe, other regions show much smaller differences, across the analyzed cases. Regions such as OCD, AFR, IND, MIE and OAS do not even show any variation. This is due to the much lower share that the currently existing building stock will continue to have over the years, due to generally higher new construction rates compared to the European ones. Countries such as China start implementing very efficient new buildings from 2020, that as a consequence, will never be renovated. Figure 5.1 outlined that in this country, new construction dwellings will already hold a 45% share of the total building stock in 2030 and no renovation happens before the same year. Therefore, partial renovations of the currently existing building stock will show a low impact on the country FED, due to the low share that pre-2014 vintages have in the total stock from 2030 on. Conversely, non-OECD countries show a quite important sensitivity on this assumption. This happens because once cooling FED strongly increases in this region (i.e. after 2040), it becomes convenient to renovate the oldest buildings and even the post-1980 vintage is refurbished.

Finally, the impacts on the world FED are presented in figure 6.17.
As can be expected, since renovation is more important in developed regions, heating FED is more affected than the cooling one. It is interesting to remark that without the renovation mechanism, heating and cooling FED would respectively increase by 2.4 and 1.1 EJ, thus adding a 4.5% to the total global FED. Conversely, in the best

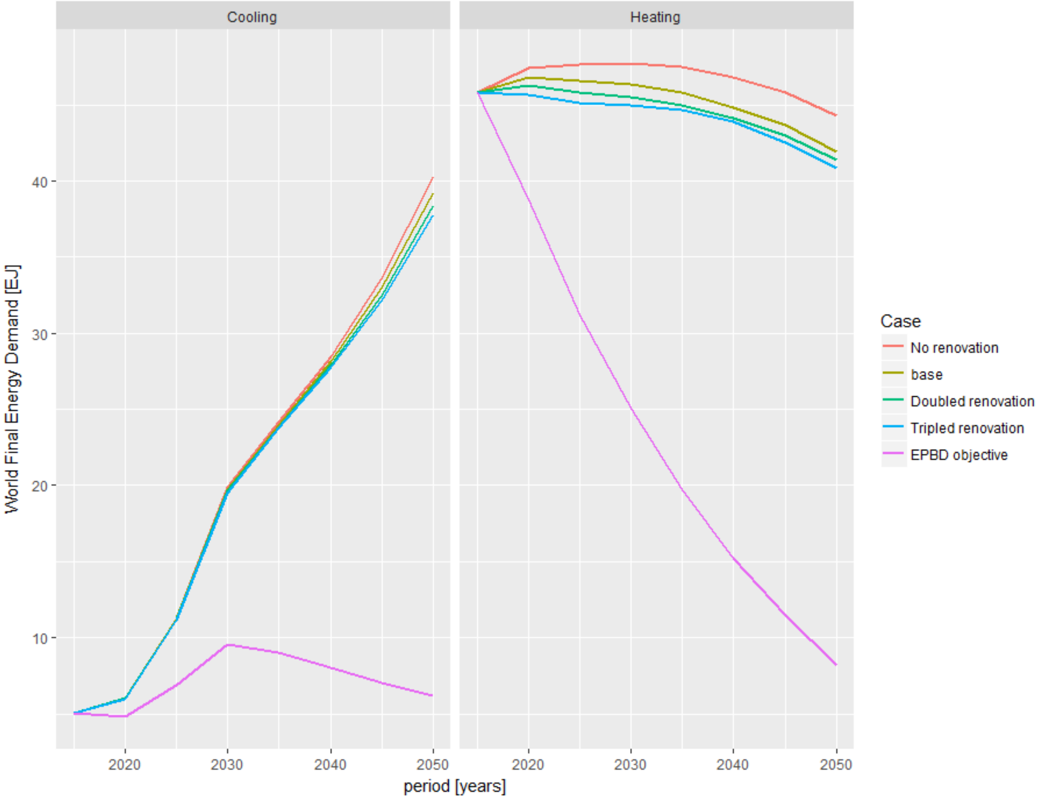

Figure 6.17: World Final Energy Demand dependence on renovation rates

case, heating and cooling FED would respectively decrease by 1 and 1.4 EJ, with the latter one showing a greater impact due to NCD region variations across these cases. For Europe, shifting to the most optimistic scenario does not lead to significant improvements, because renovation rates are higher at the beginning, but finally become lower than the baseline case ones, as figure 6.15 presented. Therefore, the impacts are counterbalanced. This is not the case for NCD, since no renovation occurs before 2040 in this region.

Maximum renovation Payback Time

The sensitivity on the PBT_{max} term of equation 4.12 is tested in this section, through two cases. Keeping in mind that increasing the building envelope thermal performance always requires a longer term point of view compared to heating and cooling equipment improvement, a minimum PBT_{max} was fixed to 15 years. Conversely, a maximum reasonable value would be 45 years, which it does not make sense to overcome, given that the new construction lifespan was chosen as 50 years. As in the renovation function section, the resulting impacts are outlined for the European region in figure 6.18.
It can be seen that increasing the PBT_{max} does not lead to significant variations, since the PWF marginal increase gets smaller when the lifespan becomes higher. Therefore, higher variations are found for the pessimistic case, with European U-values increased by 0.08 W/m^2/K compared to the baseline. The worst possible case in this sense is

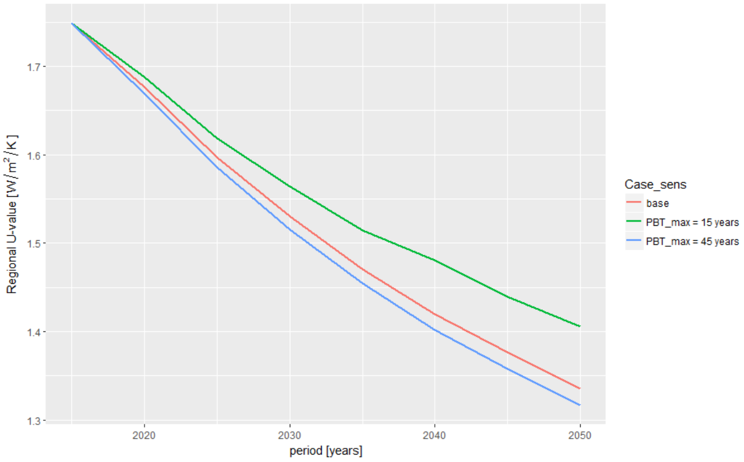

Figure 6.18: European U-value dependence on different PBT_{max}

represented by the ”no renovation” scenario shown in figure 6.14, in which the European U-value increases by 0.2 $W/m^2/K$ compared to the baseline.

6.5 Socioeconomic and climatic drivers

In this section the hypotheses related to global warming levels and main socioeconomic drivers (i.e. population and GDP) will be discussed. The SSP framework will be employed in order to provide a link with the previous model as well.

Climate

Higher levels of global warming would lead to a hotter planet, which means that the number of HDDs would decrease, while the opposite would happen for CDDs. Heating demand is directly proportional to HDD, whereas this is not the case for cooling. The latter depends on CDD in two ways: by means of a direct proportionality and through the level of cooling demand saturation (see the explanation of equation 3.3). Due to these 2 effects, increase in CDDs would lead to a high growth of cooling demand, which would probably offset the reduction in heating demand. Conversely, the opposite would happen in case of decreasing levels of climate change in the future. As already discussed in section 4.6, U-values decrease with higher levels of CDD and HDD would eventually mitigate, but not offset the growth in HDDs and CDDs, thus leading the FED to an overall increase.

SSPs

Given the discussion performed until this section, the main hypotheses on exogenous socio-economic drivers which are implemented across the SSPs will be discussed. First of all, only SSP1, SSP2 and SSP3 will be considered here, since the building stock module is currently developed for these scenarios only.

As will be seen from figure 6.26, the key message of this section is related to the importance that socio-economic drivers have on energy consumption: if the world will rapidly increase wealth levels, the increasing FED of developing countries will not make overall global consumption decrease. In the opposite scenario (SSP3), overall consumption slightly decreases, only due to the fact that large amounts of population all over the world will remain poor, with developed countries not managing to strongly reduce their consumption. In terms of global warming issue, all the 3 scenarios show that with the current trends, reduction in energy consumption will not be achieved, further threatening the planet: an increase of 50-60% of the world FED is projected in every scenario by the model.

GDP per capita shows the highest growth in SSP1, with SSP2 generally being quite close to it and SSP3 constituting the worst scenario. Population increase differs depending on the considered region. For developed countries, population shows slight changes in SSP1 and SSP2, while it generally decreases in SSP3. Developing countries instead show a strong population increase in SSP3, while only slight changes happen in SSP1 and a small increase happens in SSP2. These are the most important input data, according to which EDGE eventually computes other parameters in order to eventually obtain the FED. Variations of the most important variables is now discussed:

- Climate: SSP2 and SSP3 are assumed to lead to the same level of global warming, while SSP1 eventually leads to a slightly colder planet. In order to determine HDD and CDD, the model implements another hypothesis, based on consumers behaviour: the room temperatures at which the cooling and heating equipment are turned on, named T_{limit} in the following table:

Scenario	$\mathbf{T}_{limit,Heating}$	$\mathbf{T}_{limit,Cooling}$
SSP1	17°C	25°C
SSP2	18°C	21°C
SSP3	18°C	20°C

  The implementation of these assumptions eventually results in SSP1 having much lower CDDs and slightly lower HDDs, SSP2 and SSP3 having equal levels of HDD but lower CDDs for the former scenario.

- Floor space: a variety of different trends arises in the determination of this parameter. In SSP1, developing countries show a stronger floor space increase at the beginning, which generally reaches a peak and then decreases, due to population decrease and floor space per capita saturation with income. In the same group of nations, SSP2 eventually shows the highest amounts of floor space in 2050, with SSP3 laying in the middle of the other scenarios due to lower income rise, but higher population increase. Developed countries generally show lower floor space in SSP3, due to population decrease, and slightly higher floor space in SSP2, with SSP1 laying in the middle.

- Efficiencies: according to income levels, SSP1 shows the highest final-to-useful energy efficiencies, while SSP3 computes the lowest levels.

According to the input GDP and population data, the building stock module calculates different rates of new construction across the SSPs. Figure 6.19 outlines that due to higher population and GDP growth in SSP1 and SSP2, new construction rates are generally higher in the European region, with some slight differences across countries.

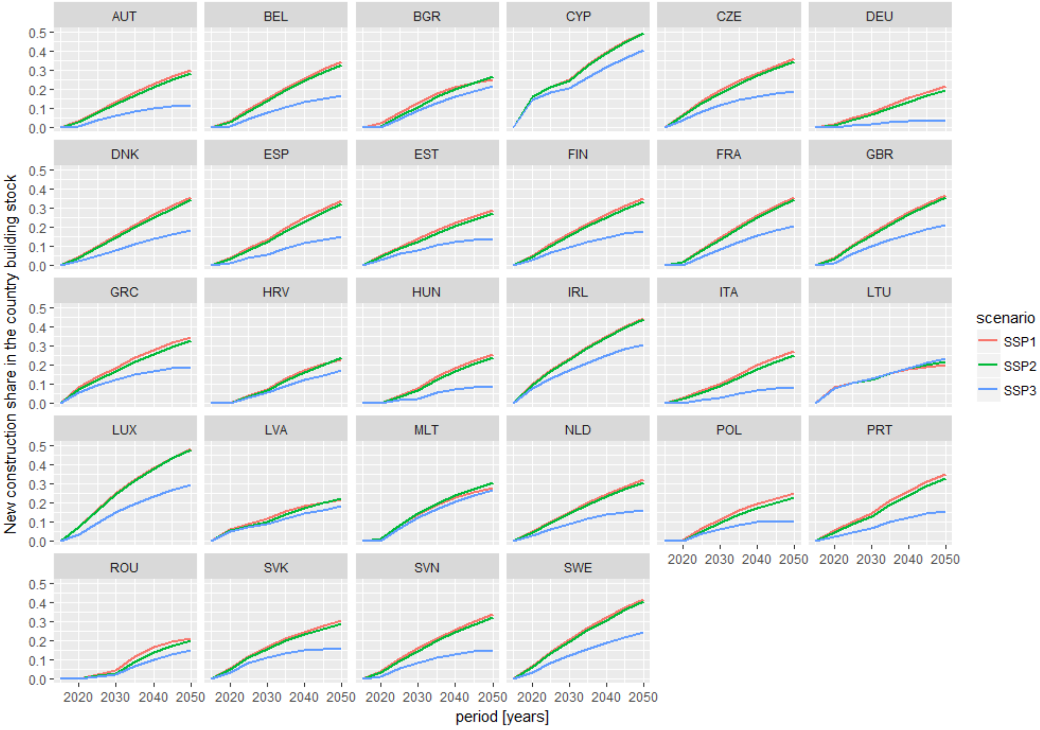

Figure 6.19: Share of new construction buildings in the total stock of European countries, for different SSPs

Conversely, looking at the world regions, developing countries show higher construction rates in SSP3, which is in accordance to what has been discussed before about population and income growth. As already outlined by figure 5.1, developed regions show much lower shares of new construction in 2050 compared to the developing ones, in all the SSPs.

The results computed by the U-values module can now be discussed. In addition to the external hypotheses discussed at the beginning of this section, this module itself employs a number of assumptions that are listed in table 6.1, implemented according to the SSP narratives:

Thus, a first overview of the U-values computations is provided by 6.21.

This figure shows that compared to the previous EDGE module outcomes (see figure 3.6), smaller differences arise across SSPs. In some cases, SSP1 performs even worse than SSP2, in terms of U-values, which is something that did not happen in the previous module. This happens because SSP1 shows lower HDD, CDD and higher final-to-useful

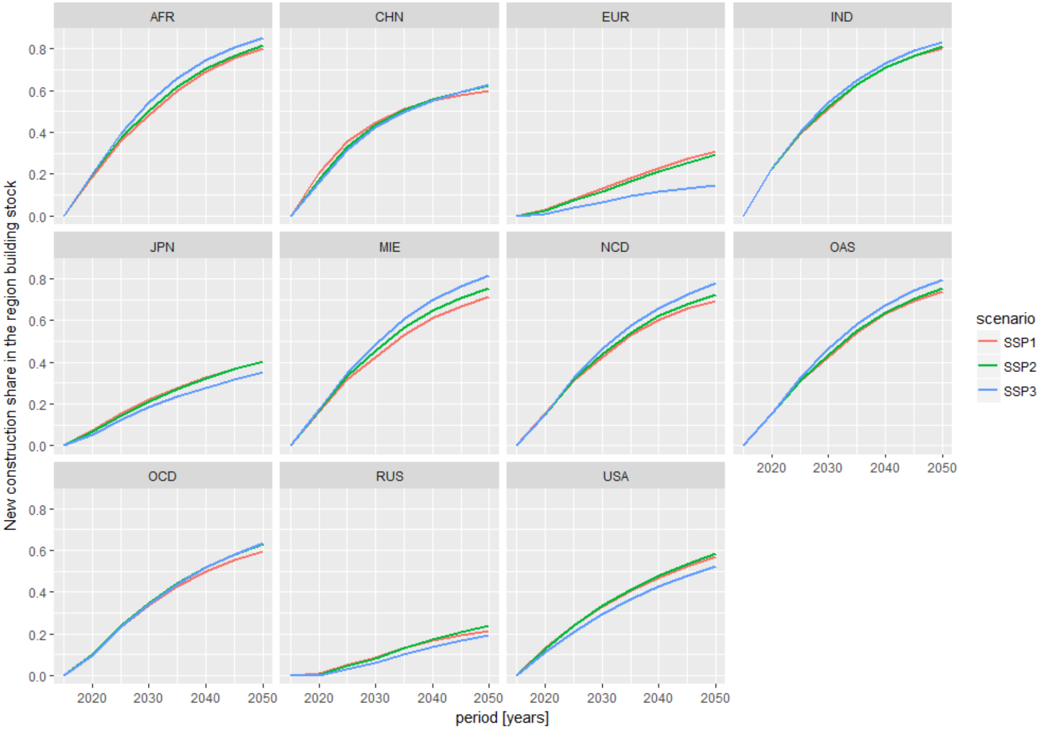

Figure 6.20: Share of new construction buildings in the total stock of world regions, for different SSPs

Variable	SSP1	SSP2	SSP3
PBT$_{max}$ [years]	40	30	20
Lifespan, new construction [years]	60	50	40
Technology cost decrease	Same decrease as SSP2, but quicker decay	1%/y decay	0.5%/y decay, no market entry of *Future window* technology

Table 6.1: Specific SSPs assumptions for the U-values module

energy efficiencies. All these factors make increasing insulation levels less convenient, as already discussed in section 4.6. However, it can be expected that lower levels of FED will be reached in the European regions, since figure 4.10 shows that overall, FED decreases with lower HDD, CDD and higher efficiencies. Due to lower HDD and CDD, the previous model would have obtained higher U-values in SSP1 as well. However, U-values were decreased by means of a γ parameter (see equation 3.5), which is SSP dependent and is lower in SSP1, as discussed in section 3.2.1.

The world regions U-values across SSPs are presented in figure 6.22.

A marked difference across SSPs arises for developing countries, with SSP1 generally performing much better than the others. Recalling that income levels grow faster in SSP1, it can be easily understood that cooling demand will also manage to strongly increase in these countries as well. This is why in regions such as India and OAS, U-values show a steep drop in SSP1, while in SSP3 they only slightly decrease. Moreover, in the NCD region, the SSP1 and SSP2 curves cross each other after 2045. This happens because this region quickly saturates its cooling demand already in 2040, then since

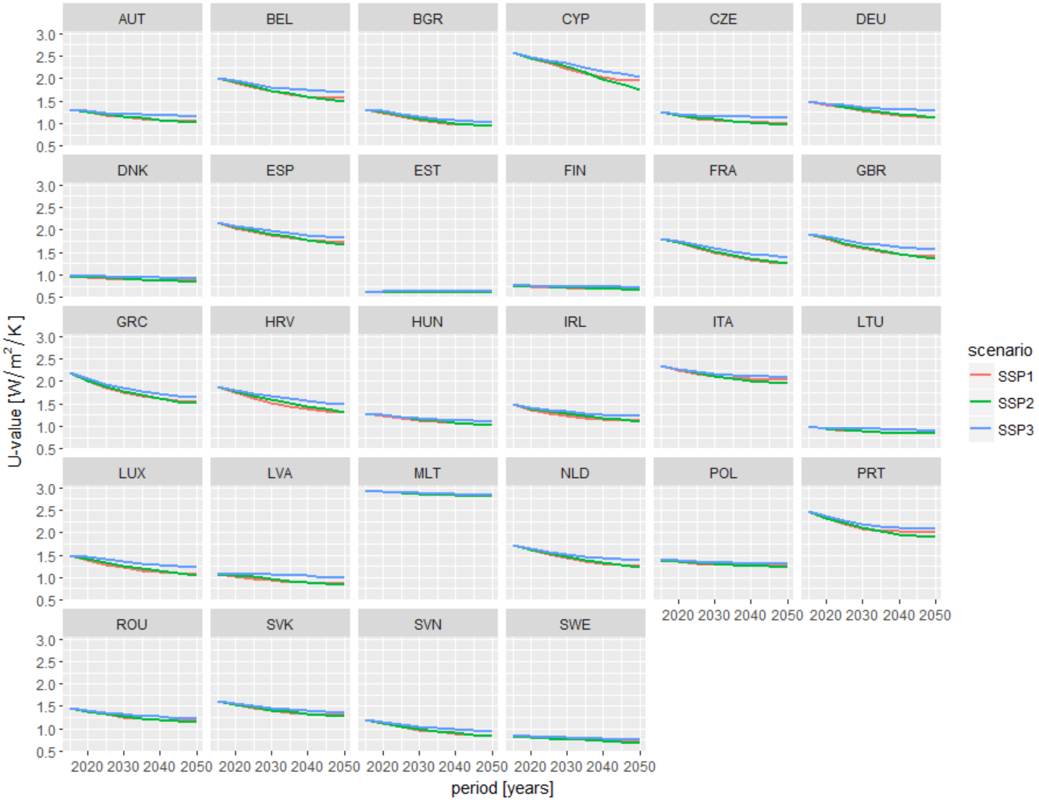

Figure 6.21: European countries U-values trends for different SSPs

CDD decrease in SSP1 (due to the assumption of lower global warming), it does not become convenient to insulate further. Conversely, CDD in SSP2 are higher, thus leading to a higher level of cooling demand when the saturation is reached (recall from equation 3.3 that cooling demand depends on CDD by means of two terms). Figure 6.23 shows the computed UED variations across SSPs.

The reasons behind U-values trends can now become clearer: looking at China, it can be seen that in SSP1, cooling demand saturation is reached before, but the level of saturation is lower compared to the other SSPs, due to lower CDDs. Conversely, SSP3 shows the highest levels of CDDs, thus in China the cooling demand reaches even higher levels than the others in 2050, yet with a slower increase due to slower GDP growth rate. Regions such as MIE and NCD manage to saturate their cooling demand in 2040 in SSP1, in 2050 in SSP2, and do reach this level in SSP3. IND and OAS strongly increase their cooling demand in SSP1, while they do not manage to even start this process in SSP3. Regions such as OCD and USA, which show significant levels of cooling demand, greatly decrease their UED in SSP1. This happens because these regions (particularly USA) are already at the saturation level for cooling demand in 2020. Thus, due to the CDD decrease, the upper asymptote of the cooling demand sigmoid curve (see 3.4) shifts downward, thus making UED decrease. For regions located in heating-based climates, differences across SSPs are quite small, but they will appear clearer later in the discussion.

Figure 6.24 shows the resulting world-level UED.

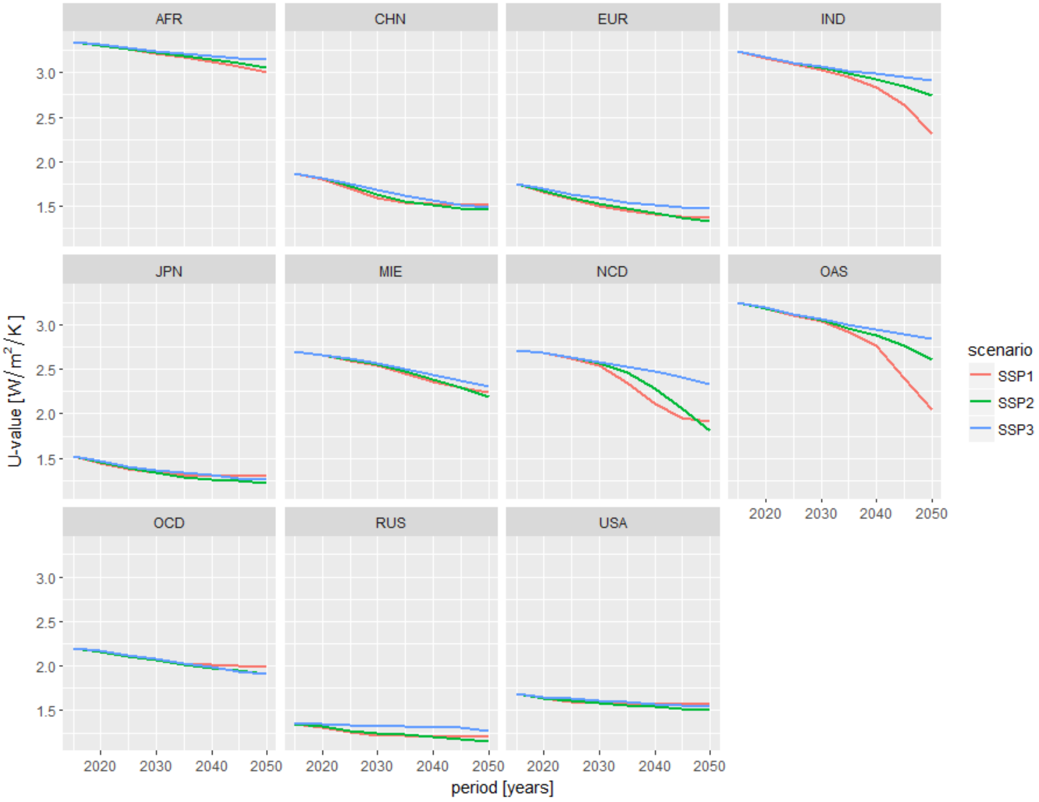

Figure 6.22: World regions U-values trends for different SSPs

Due to the great contributions of IND and OAS, cooling energy demand in SSP1 reaches higher levels than SSP2 in 2050: 149.3 against 112.7 EJ, with SSP3 showing a 77.3 EJ demand. This happens despite the fact that regions such as China, USA and OCD eventually show the lowest levels of energy demand in SSP1. Conversely, heating energy demand still does not show significant variations across SSPs, yet in this case SSP2 shows the highest levels in 2050: 37.8 EJ, with 36.5 EJ reached in SSP1 and 34.4 EJ in SSP3. This happens because SSP2 shows higher floor space and HDD levels, compared to SSP1. Whereas cooling energy demand doubles from SSP3 to SSP1, this is definitely not the case for heating consumption, which only increases by 10% from SSP3 to SSP2.

It is finally interesting to look at the computed FED, considering that efficiencies will be higher in SSP1, compared to the other scenarios. Figure 6.25 shows that cooling and heating energy demand eventually result being comparable, due to the different levels of efficiency for both end-uses, as already outlined in section 5.1.
Thanks to this, the SSP1 cooling energy demand in 2040 is actually lower than the SSP2 one. However, the contributions of IND and OAS regions from 2040 on, eventually make the SSP1 cooling demand reach the highest levels. The 2050 cooling FED shifts from 30.4 EJ in SSP3 to 39.2 EJ in SSP2 to 47.5 EJ in SSP1. It can be therefore remarked that even if in 2050 the UED in SSP1 is twice the amount of the SSP3 one, when the FED is considered, the overall increase (from SSP3 to SSP1) is only equal to 55%.

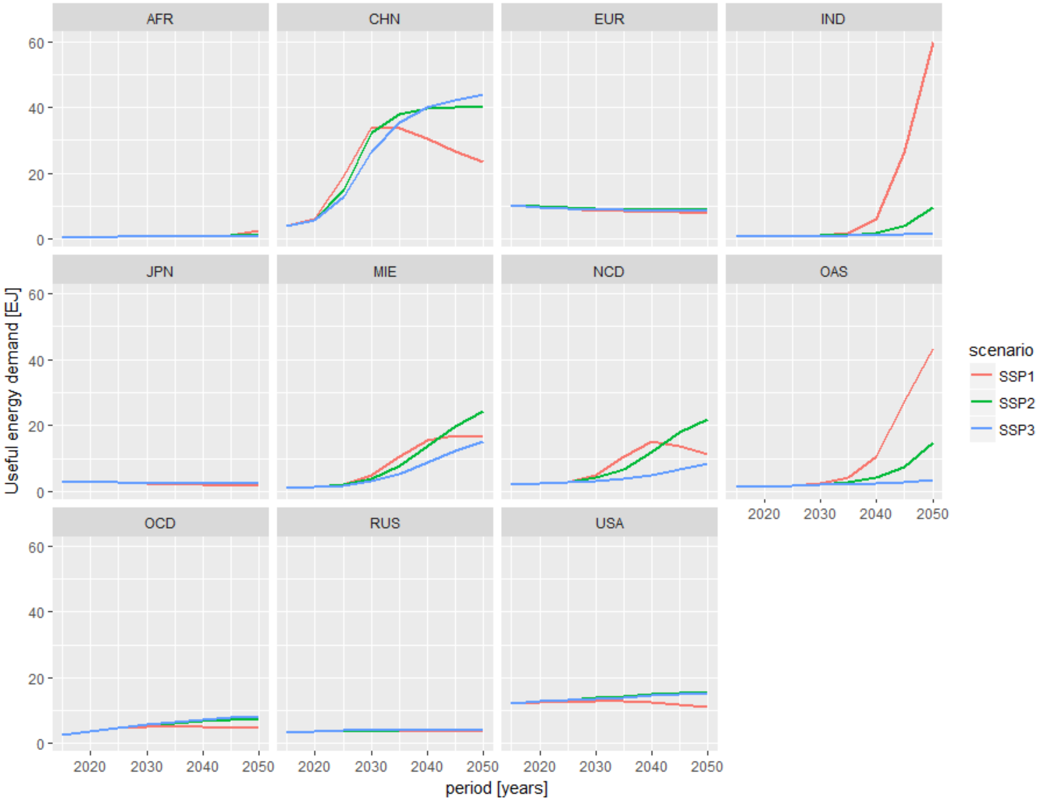

Figure 6.23: World regions Useful energy demand trends for different SSPs

Concerning heating demand, the impact of different levels of efficiency is quite clear, with widening gaps across SSPs over time. SSP1 eventually reaches 34.4 EJ, with SSP2 and SSP3 respectively getting to 41.9 EJ and 46 EJ. This is also due to reduced heating FED in developing regions, which due to higher income growth abandon the inefficient use of traditional biomass for space heating. Therefore, whereas higher income growth in SSP1 globally increases cooling demand, the opposite happens for heating demand, which is reduced by increased final-to-useful energy efficiencies.

Finally, the overall balance of FED across SSPs is shown in figure 6.26, in which the contributions of different groups of regions are outlined.

It can be seen that SSP1 and SSP2 overall lead to the same levels of FED, which is respectively equal to 81.9 EJ and 81.1 EJ, with SSP3 showing a much lower level of consumption: 76.4 EJ in 2050. Contribution of low and middle income countries to the FED are higher in SSP1, while China shows a greater relative importance in SSP3 (holding 27.2% of the total FED), together with developed regions. In SSP1, the increased equipment efficiencies make FED of developed regions decrease by one third (Europe and High Income countries FED decreases from 29.3 EJ to 20.3 EJ in 2050 in this scenario), but this effect is more than offset by the increasing FED of low and middle income countries.

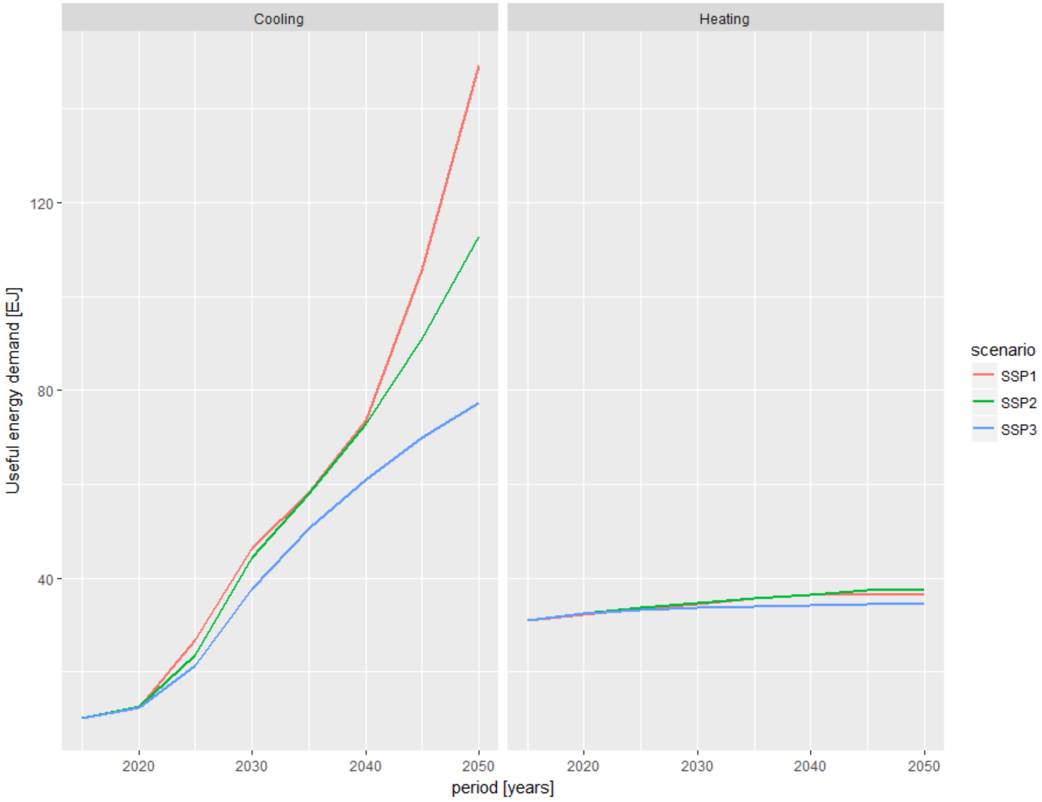

Figure 6.24: World Useful energy demand trends for different SSPs

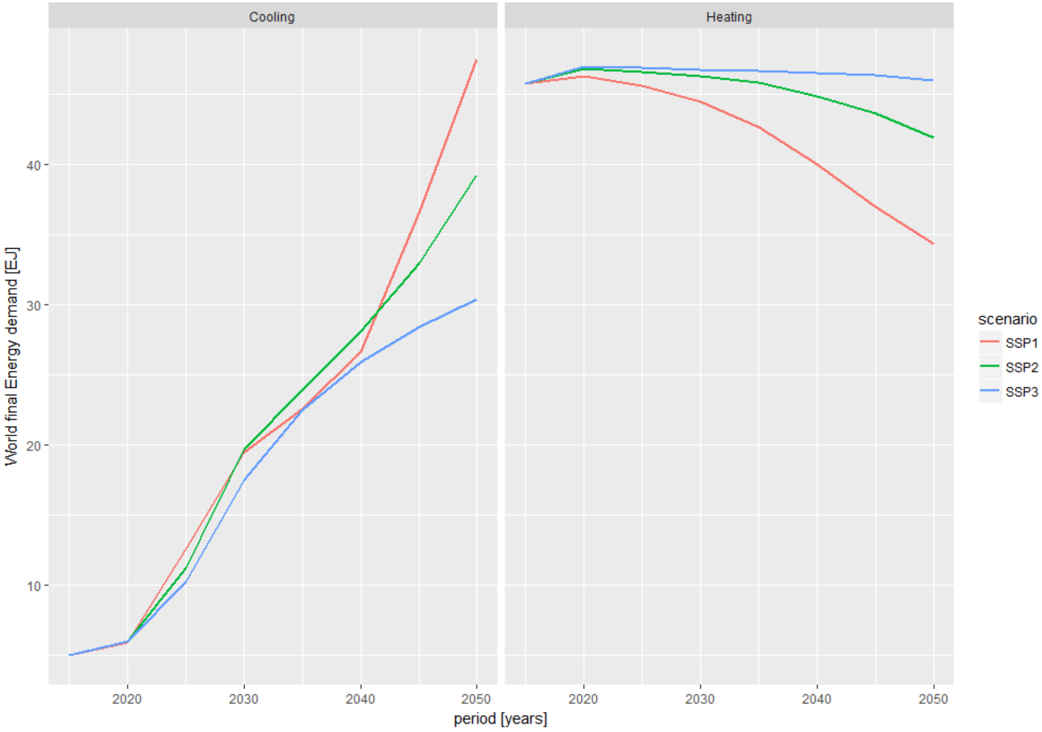

Figure 6.25: World Final energy demand trends for different SSPs, by end-use

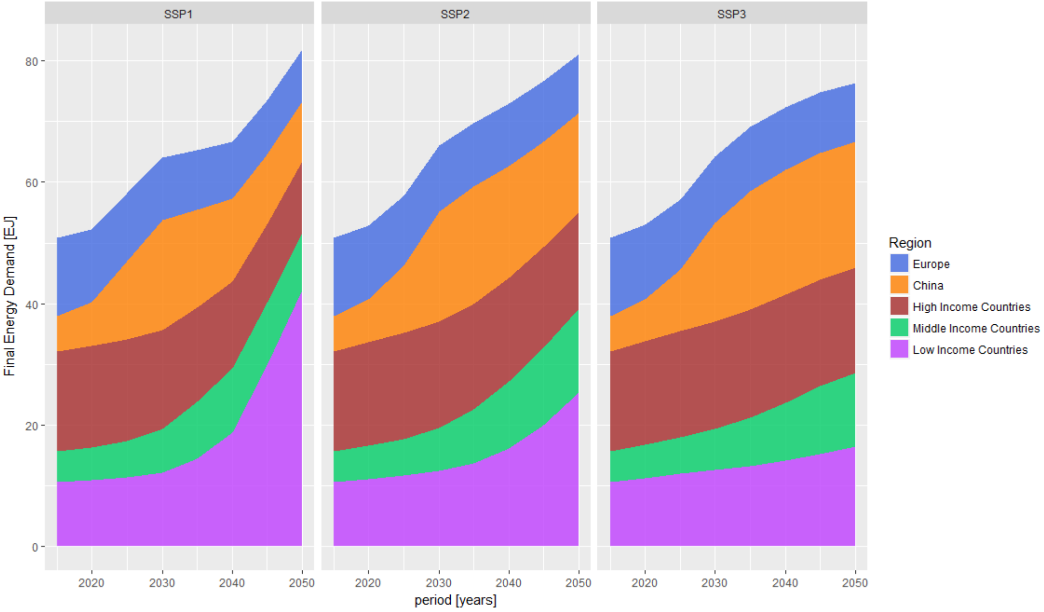

Figure 6.26: World Final energy demand trends for different SSPs, by region

6.6 The most optimistic cases

As a conclusive case for the sensitivity analyses that were performed in this chapter, this section will present the implementation of the most optimistic cases, coupled with the highest energy price increase, tested in section 5.3, for Europe. This will therefore represent to what extent the gap with the EPBD policy objectives can be reduced. The implemented cases are related to the most optimistic technology cost decrease implemented in [31], which is 2%/y, the highest energy price growth scenario (BPIE_{high} in section 5.3), progression to optimal technology allocation (i.e. convergence to λ=0.1 in 2050, as tested in section 6.2) and tripled renovation rate case of section 6.4. No improvement of discount rates was performed, since the levels resulting from the calibration are already quite low. Since the energy increase study was applied in Europe only, the implementation of such an optimistic case will not be tested at the world level.

Figure 6.27 outlines the resulting European FED trends for the most optimistic scenarios, both implemented separately and together.

It can be seen that once these different measures are jointly realized, the EPBD objective is actually reachable, at least until 2030. Indeed, implementing all of these optimistic cases leads to multiplications of benefits: for instance, the probability of renovation to happen is favoured by both convergence to an optimal market choice, technology cost decrease and rise in energy prices, whereas tripled renovation rates further increase the penetration of such measures. The remaining gap in 2050 amounts to 1.6 EJ. It should now be analyzed why such a gap cannot be reached. Therefore, figure 6.28 looks at the regional U-values decrease.

It clearly appears that most of the regions follow the aggregated European trends, with a widening gap when approaching 2050. The only significant deviations are shown by

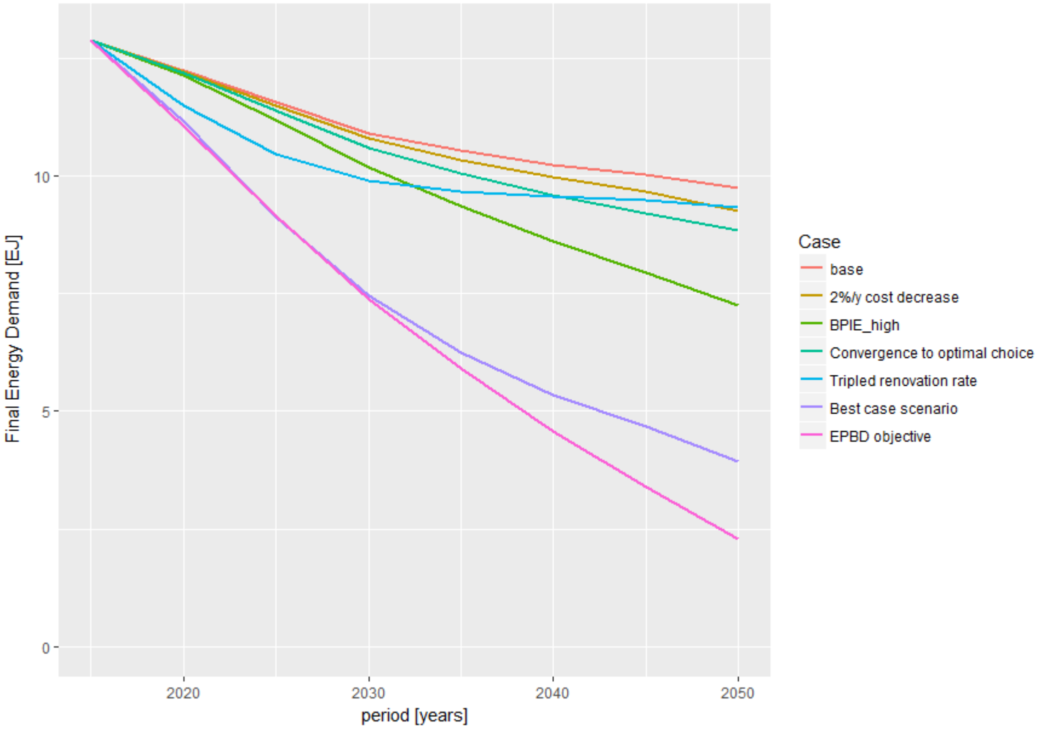

Figure 6.27: Europe Final Energy Demand trends according to the most optimistic scenarios

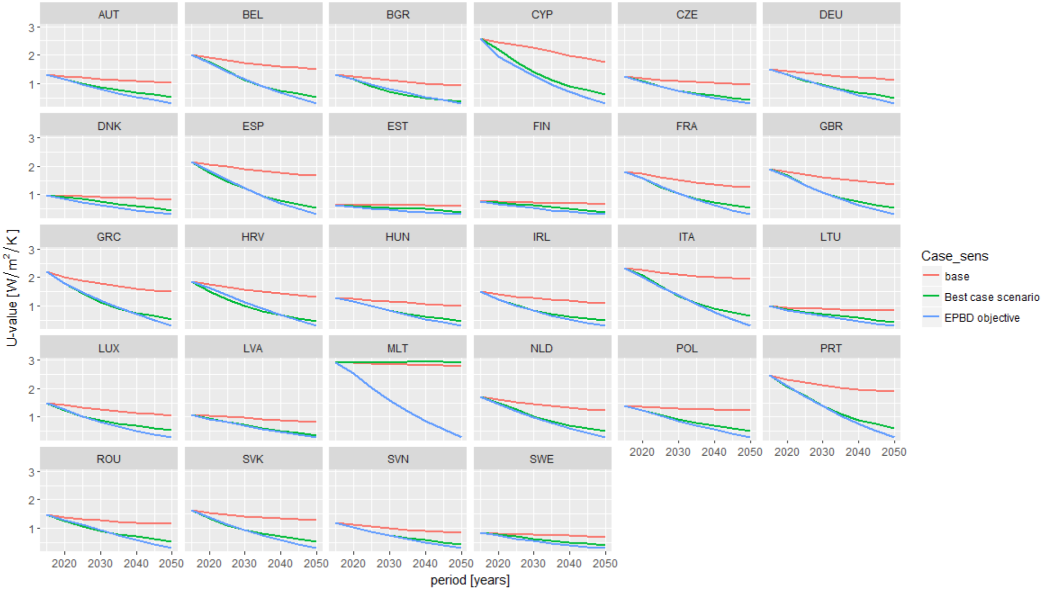

Figure 6.28: Computed U-values of European regions

Malta, which actually increases its U-values in the optimal case, because EDGE computes HDD and CDD levels which are so low that it never becomes convenient to insulate. Actually, shifting towards a higher logit parameter shifts the choice further towards choosing high U-values. However, the weight of this country in the European building stock is totally negligible. Therefore, figure 6.29 presents the computed renovation rates at the European level according to the analyzed scenario.

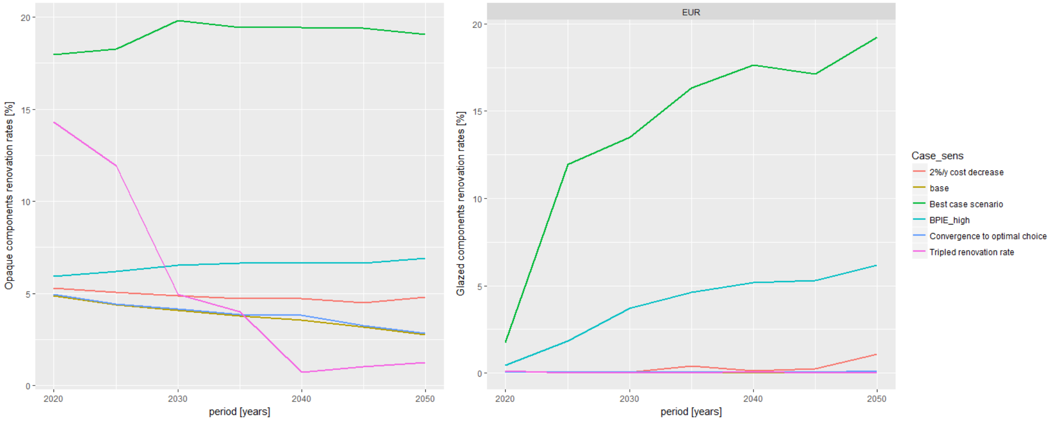

Figure 6.29: Computed renovation rates across different scenarios

Concerning opaque surfaces, renovation rates are steadily around 4.5-7% in most of the cases, with the *Triple renovation rate* trend which has already been discussed in section 6.4. In general, implementing more optimistic assumptions makes renovation rates increase compared to the baseline. This is evident in the best case scenario, which steadily keeps rates of 18-20% in all the considered period. Regarding glazed components, the only scenario that manages to reach visible renovation of windows is the one that assumes a strong price increase. Indeed, figure 6.27 also shows that this is the most impacting measure. In the best case scenario, significant renovation rates for windows are also achieved, yet reaching very high levels only after 2030 (recall that the EPBD objective amounts to 3%/y, which mean 15% every 5 years). This might be the reason why eventually U-values do not decrease to nZEB levels. Hence, figure 6.30 finally presents the vintages-level U-values, for the European region.

It appears that newest vintages do not really keep track with the required pace, but it seems reasonable due to their already low U-values. Eventually, what really matters is increasing insulation levels of oldest vintages. It actually appears that these are renovated at even higher rates than what the EPBD requires. However, their U-values trend seem to eventually flatten over time, leading to the overall curve which was depicted by figure 6.27. The reason behind this trend is due to the way the model updates the vintage U-value (see figure 4.5). In order to be clear, an example will be provided. Assuming a renovation of a vintage showing a starting U-value of 2 W/m^2/K, leading to a U_{ren} of 0.2 W/m^2/K, with a constant refurbishment rate of 20%/(5 years), the resulting U-values at the following timesteps would be:

$$\begin{gathered}
U_{t+1} = U_t * 0.8 + U_{ren} * 0.2 = 1.64 \\
\mathrm{U}_{t+2} = 1.64 * 0.8 + U_{ren} * 0.2 = 1.35 \\
\mathrm{U}_{t+3} = 1.35 * 0.8 + U_{ren} * 0.2 = 1.12 \\
\mathrm{U}_{t+3} = 1.35 * 0.8 + U_{ren} * 0.2 = 0.94
\end{gathered}$$

Then, proceeding in the same way over time, it can be seen that marginal decreases actually reduce over time, eventually leading to the flat curve depicted by figure 6.30 for the oldest vintages. This also explains why such high levels of renovation rates

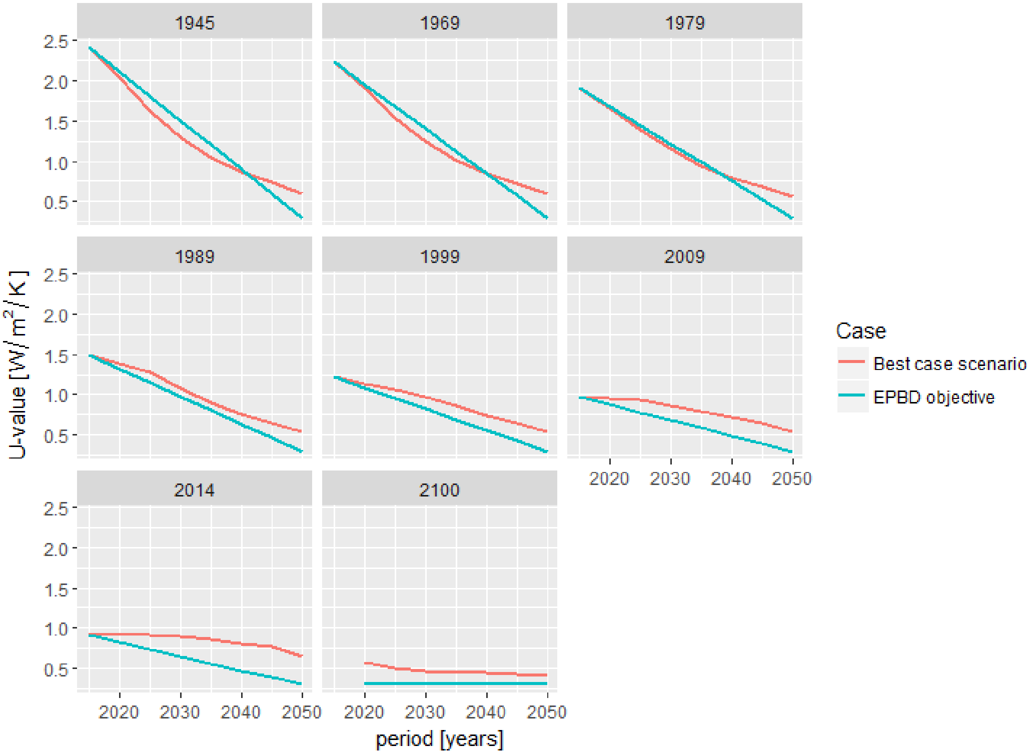

Figure 6.30: European U-values trends by vintage

are shown by figure 6.29 in the best case scenario: basically, the model renovates the same vintages at every timestep, because it always finds convenient to do so. If shares of renovated buildings were separately accounted for in the model, keeping a 20% renovation rate would mean that across 25 years, all the stock would get renovated. However, this was not the chosen approach in this work, as already discussed in section 4.3.3.

Therefore, it can be concluded that the results do not catch up with the EPBD objectives just because of limitations in the calculations of the model. It actually results that at the beginning (2015-2030), in the best case scenario it is profitable to reach such levels. Lower market heterogeneity may be reached by regulatory policies, which impose the installation of the best performing technologies, while energy price increase may be reached by applying higher taxes on energy, as was discussed in section 2.1. Increasing renovation rates is still a challenge for policymakers, as was discussed in section 2.1, while higher cost decreases would be reached, *given that there is a steeper learning curve as the volume of activity increases*, as [31] indicated.

Chapter 7

Conclusions

Following the research questions outlined in chapter 1, conclusions will be drawn in section 7.1, while suggestions of future works for improving the current model are outlined in section 7.2.

7.1 Conclusions

Building stock and U-value modules coupling

A higher detail on the estimation of FED across different world regions was reached by involving building stock dynamics in the computation of regional U-values development over time. In developed countries, relatively low population and income growth will not foster high new construction rates and the currently existing building stock will as a result still hold a 75% share in 2050 in regions such as Europe. Therefore, renovation of the current building stock can have a big effect. When considering renovation investments, increasing insulation levels of opaque surfaces is generally convenient, while window replacement is rarely profitable and does not happen in the baseline estimations.

Conversely, high population and income growth in developing countries will lead to increasing shares of new buildings, as well as increasing floor space and a very strong cooling demand growth. Since, according to the new model results, developing countries still have to construct most of the building stock that will be standing in 2050, immediately implementing building codes can lead to significant energy demand reductions in the short and long term, given the long lifespan of buildings.

UED is expected to slightly decline in Europe, due to the construction of highly efficient buildings and renovation of oldest vintages, with around 80% of the 2050 energy demand still attributable to the currently existing buildings. Renovation will be less impacting in the USA, but higher levels of demolition will be implemented in this region. Eventually, 50% of the 2050 energy demand will be attributable to new construction buildings. This holds true for China as well, which is expected to show an eight-fold increase in UED from 2015 to 2050, becoming the highest energy consumer region in the world. Renovation mechanisms will not strongly decrease energy demand in this country, due to the very low share of pre-1980 vintages in the future building stock. Developing countries will generally show very low levels of UED, until they start increasing their cooling demand due to rising income levels. The new model shows that 75-80% of their 2050 building stock will be constituted by new buildings. At the global level, heating energy demand will slightly increase, while cooling will show a 10-fold growth from 2015 to 2050, mostly due to China, middle and low income countries. In terms of final energy, increasing levels of equipment efficiency will eventually make the overall heating demand decline, while a huge growth in cooling demand will happen in any case. This eventually results in a 60% increase in FED compared to 2015 levels.

EPBD objectives

In Europe, FED is expected to decrease by 20% by 2050, if the current trends are followed. Given the hypotheses of this model, the implementation of the EPBD is expected to decrease the 2015 levels of FED by 80% in 2050. Half of the energy savings from the implementation of the EPBD in Europe will be related to the renovation of the pre-1980 vintage buildings, while only one fifth of it will be related to more efficient new construction buildings. The implementation of the European policy in the world would make the 2050 total FED further decrease by 10%: from 81 to 72.5 EJ.

Implementing the EPBD all over the world would make the overall final heating demand decrease by 37 EJ with respect to the 2015 levels, while cooling demand would actually reach a peak and then decline, keeping in 2050 similar levels of 2015. Therefore, the 2050 FED would be approximately equal to 15 EJ: an overall decrease of 80% compared to the expected 2050 level. Most of the cooling demand savings would come from low and middle income regions, which will implement very high rates of new construction buildings. Accordingly, China on its own would additionally save 6.5 EJ by constructing only nZEB buildings from 2015 on. All over the world, most of the regions show that at least 50% of the 2050 FED savings would be due to the implementation of a nZEB new construction stock, with this percentage raising to 80% in regions such as India and Africa.

Energy price increase

Expected energy price increase in the European region range around +2%/yr. If this assumption is implemented into the model, then additional 1.5 EJ would be saved from the 2050 FED in Europe. If a stronger price increase is implemented, the gap among the EPBD objectives and the expected trends decreases from 7.5 to 5 EJ, thus it is reduced by one third. Subsidies on energy prices do not basically matter in the European region: only 0.5% of the 2050 FED would be saved if they are removed. This percentage instead raises much more at the global level, where around 3% of the 2050 FED would be saved, with Middle east providing 55% of the additional energy savings.

Impact of parameter uncertainty

The effect of the uncertainty of the key parameters on the projected results has been tested. By means of testing ranges of technology cost decrease from 0 to 3%/y, it is estimated that each additional reduction of 1%/y eventually leads the total FED at the world level to decrease by 1 EJ in 2030 and 4 EJ in 2050. Cost decrease for opaque technologies results to be more important than for windows, mostly due to the greater share of the former components in the building envelope.

The impact of assumptions in the computations of technology market shares differs across world regions. If the optimal technology is chosen, then developing countries will be shifted towards higher levels of insulation, due to their low levels of energy demand. Conversely, the opposite happens for developed nations. Within the 2015-2050 period, some regions change their response to the logit parameter since they shift from low to high levels of income. Therefore, since heating FED mostly comes from developed regions, it is strongly decreased by 5.4 EJ in 2050 when an optimal technology choice is performed. For the same case, cooling FED reduction only amounts to 2.5 EJ, since poor regions actually show higher levels of insulation, thus higher cooling demand.

The effect of different assumptions on developing countries discount rates decrease over time is only important for non-OECD countries, which manage to reach high income levels across the considered period. Thus, they are more penalized if their discount rate is assumed to not decrease. Regions such as Africa and India show high discount rates in any case, since their income level remains low, thus not stimulating increasing energy demand. Overall, the global 2050 FED increases by 2.1 EJ if no discount rate decrease is implemented, while it decreases by 2 EJ when a quicker reduction is assumed to happen. Concerning developed countries, increasing average discount rates to a 7% level causes a global FED increase by 2.9 EJ in 2050, while convergence to a 3% level would cause the FED to be reduced by 3.2 EJ. Heating demand is more affected in this case, since it mostly comes from developed regions.

Different assumptions on the renovation rate functional dependence on PBT do not show great importance. Changing the lifespan of refurbishment investment becomes highly significant only when this parameter is decreased: in this case, a progressive shift towards a no renovation scenario happens. Different levels of renovation rate strongly impact heating energy demand, since Europe is the region which is affected the most by this assumption. Total FED in 2050 changes from +3.5 EJ if no renovation happens to -2.4 EJ if renovation rates are tripled. In the latter case, European insulation levels show a stronger increase in the short term, while they slightly change later. This happens because once the building stock gets strongly renovated at the beginning, it does not become convenient to further decrease U-values in the future, thus renovation rates strongly drop.

Assumptions on the main socioeconomic drivers generate different dynamics across regions, which finally lead to similar levels of FED in 2050. If the world development follows the SSP1 narrative, then developed countries will strongly reduce their heating demand, due to a less intensive use of heating equipment and to stronger technological development. However, developing nations will strongly increase their cooling consumption, due to increased wealth levels. Conversely, in an SSP3 scenario, developed regions would not reduce much their consumption, while poor regions will not significantly increase their income levels, thus generating a much smaller growth in global cooling demand. These trends eventually result in SSP1 showing the highest 2050 FED (81.9 EJ) and SSP3 presenting the lowest (76.4 EJ).

Finally, the EPBD target was shown to be ambitious but reachable. However, this happens only when combining the best cases reported in the literature with increasing energy prices and renovation rates. The remaining gap of 1.6 EJ results to be caused by limitations on the model calculations, which do not account for the shares of renovated buildings.

7.2 Future work

The method presented in this paper allows for the simple incorporation in long-term energy models of the buildings stock dynamics affecting renovation and new construction investment decisions. Although the new has shown interesting insights in to European and Global dynamics, several refinements could improve the model further. The main points to be improved are here summarized:

- Improve the connection with the current EDGE model, in order to better match 2015 FED, which is currently overestimated by 4 EJ.
- Differentiate between renovated and non-renovated building shares within vintages, in order to improve the smoothness of transition when low U-values are reached.
- Improve the representation of available technologies, by differentiating on cooling and heating climate needs. The current model only implements increasing insulation levels in order to reduce FED, which is the most suitable measure only for heating-based climates.
- Improve the representation of technologies, by differentiating on new construction and renovation costs and options, as IEA suggests [2]. For instance, it was remarked that improving energy efficiency levels of existing dwellings is generally costlier, unless it happens within a favourable opportunity, when the building is entirely renovated. Moreover, low-e coating application on existing window is the best option for renovation, compared to their replacement.

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Appendices

Appendix A

Extension to the global level

In order to extend the model to the global level, a literature research on U-values, classified by component type as in the EU database, was performed. For some countries the results of housing surveys were available, while others did not have anything like this. It is therefore a challenge to estimate country-level U-values only by means of indications from several papers, but this work represents a first attempt in this direction. For the oldest vintages, when no information was available, U-values were increased using the time coefficients outlined in table B.2. Envelope U-values are calculated as an average of walls, roof, floor and window U-values (in W/m^2/K), following the procedure of [7].

United States

Several housing surveys were performed in the U.S., however few information could be found regarding insulation levels. The collected data mostly regard energy consumption rather than U-values. The most precise indications in this sense are represented by a commercial buildings survey, which outlines insulation levels classified by vintages (until a pre-1980 group) and climate zones [111]. As outlined in section 2.3.2, residential and non-residential sub-sectors show similar levels of insulation in Europe, thus the same will be assumed for the U.S.. Considering the climate zones where most of the energy demand comes from, average country-level U-values were computed, translated in W/m^2/K from the american units and they are summarized in table A.1.

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	2.45	1.8	1.5	1.5	5
1945-1969	2.0661	1.468	0.9772	1.1192	4.7
1969-1979	1.7182	1.136	0.4544	0.7384	4.544
1979-1989	1.5791	0.9656	0.3692	0.6816	4.3
1989-1999	1.5399	0.9088	0.3692	0.6816	4.2
1999-2009	1.4757	0.852	0.3692	0.6816	4
2009-2014	1.3936	0.7384	0.3408	0.7952	3.7

Table A.1: United States U-values, deduced from [111]

Russia

Some indications were found on Russian building codes in [112]. This study oulines the currently required U-values depending on the climate zone of the country (classified by means of HDD), divided for walls, roof, windows. Since in EDGE Russia shows HDD being around 5000 K*day, the standards for 4000 and 6000 HDDs from this paper were averaged. Moreover, the same study outlines typical U-values for the pre-1979 vintages and their evolution over time, to eventually reach the current standards. Another source [113] outlines typical Moscow U-values for walls and windows, highlighting that the thermal performance of buildings constructed between 1954 and 1979 do not change much (as happens in Europe). No information on floor U-values was found, thus U-values of former soviet countries such as Estonia were compared to obtain reasonable values. The implemented U-values, divided by component, are summarized in table A.2.

Vintage	**Envelope**	**Walls**	**Roof**	**Floor**	**Windows**
pre-1945	1.625	1.6	1.6	1.6	3.5
1945-1969	1.625	1.2	1.2	1.2	2.9
1969-1979	1.625	1.2	1.2	1.2	2.9
1979-1989	1.375	1	0.9	1	2.6
1989-1999	1.2	0.8	0.7	0.7	2.6
1999-2009	0.855	0.5	0.3	0.32	2.3
2009-2014	0.705	0.32	0.23	0.32	1.95

Table A.2: Russian U-values, deduced from [112, 113]

China

Considering the country-level indications, [105] assumes a U-value of 1.7 and 2.0 W/m^2/K respectively for urban and rural buildings in 2005. The highlighted U-values would be then comparable to European ones (in 2014, the average EU U-value ia 1.69 W/m^2/K [35]). However, this is contradicted by a 2003 article [114] outlines that U-values in Chinese buildings are 2-3 times higher than comparable levels in developed countries. Regarding the rural-urban gap, [102] outlines that rural buildings are very inefficient compared to urban houses. [115] indicates that in 2012, rural houses accounted for 60% of the total floorspace area of China and that urbanization rates are projected to strongly increase. Therefore, the oldest vintages are presumably located in rural zones, while most of the recent new constructions is probably situated in cities. Moreover, China is generally divided into 5 climatic zones (from severe cold to hot summer, warm winter zone). Most of the population which is not living in the severe cold zone, however 40% of China total urban building energy use comes from northern heating regions. With both the climate and rural/urban dimensions considered, data on U-values were researched. From [116, 117], it can be seen that severe cold regions show U-values which are less than half of the warmer zones ones, for all components. Given that Shanghai is located in the hot summer cold winter region and its U-values are in the middle of both zones insulation levels, this city will be considered as a representative average of Chinese climatic zones. Data on U-values development across vintages was found in [118]. U-values will be then raised, especially for older vintages, in order to keep into account the shares of rural buildings. Therefore, the assumed U-values are synthetized in table A.3

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	3.15	2.4	2	2.4	5.8
1945-1969	2.65	2	1.6	2	5
1969-1979	2.45	2	1.3	2	4.5
1979-1989	2.1	1.7	1	1.7	4
1989-1999	1.75	1.4	0.8	1.4	3.4
1999-2009	1.6125	1.2	0.75	1.2	3.3
2009-2014	1.525	1.15	0.7	1.15	3.1

Table A.3: Chinese U-values

Japan

Japanese standard building codes outline requirements in terms of maximum allowed U-values [119], which makes then difficult to understand which may be the actual U-values levels in this country. In any case, the requirements seem to be quite strict, especially for opaque surfaces. [120] highlights that Chinese buildings heat losses through walls are 3 times higher than comparable Japanese houses, while loss through windows is twice as high. Calculating U-values according to this indication would lead Japan to have a super-efficient building stock, which is unreasonable. However, coupling this indication with the one from [114], outlined in the previous paragraph, leads to the consideration that european and Japanese U-values are probably comparable. This can be further confirmed if their building codes are compared [121]. This is the assumption that was made in table A.4.

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	2.42	1.84	1.86	1.74	4.25
1945-1969	2.26	1.65	1.67	1.63	4.1
1969-1979	1.85	1.24	1.1	1.29	3.77
1979-1989	1.46	0.85	0.76	0.94	3.3
1989-1999	1.2	0.7	0.64	0.77	2.69
1999-2009	0.94	0.54	0.36	0.58	2.26
2009-2014	0.94	0.5	0.35	0.5	2

Table A.4: Japanese U-values

Middle East

Middle East countries building stock generally shows installation of single-glazed windows [122]. Indications on U-values of roof, walls and floor components for typical buildings vary from 1 to 2 W/m^2/K, according to several sources [123, 122, 124]. [125] outlines that in Gulf countries, building codes were introduced from 1984. Looking at the hottest regions in Europe, U-values were deduced for the oldest buildings. A slight linear decrease for opaque surfaces U-values was applied, with a stronger shift in 1980 due to the application of building standards. while no reduction was considered for windows U-values. Results are summarized in table A.5.

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	3.525	2	3.3	3	5.8
1945-1969	3.4	2	3	2.8	5.8
1969-1979	3.175	1.8	2.5	2.6	5.8
1979-1989	2.95	1.7	2	2.3	5.8
1989-1999	2.775	1.6	1.5	2.2	5.8
1999-2009	2.575	1.4	1	2.1	5.8
2009-2014	2.5	1.2	1	2	5.8

Table A.5: Middle East U-values

India, Africa and Other Asian Countries

Developing regions do not show particular policies regarding insulation levels. India is the only country which issued building codes for commercial buildings, implementing U-values of around 0.5 W/m^2/K for opaque components (floors excluded) and improved windows, from 2007 [126]. However, no residential building policy seems to have been implemented. In "Other Asian countries" region, the greatest population shares are related to Bangladesh and Pakistan and no building policy was found to be applied there. It should be remembered that a large part of the population of these countries lives in slums, with percentages reaching 30% of the urban population in India , for instance [38]. Therefore, the question of what might be a suitable U-value for a slum dwelling arose. A study performed in a slum building in Kenya outlines that U-values are around 7 W/m^2/K for the roof, 3 W/m^2/K for walls and single-glazed windows are installed [127]. This is in line with what IEA outlines: U-values ranging from 3 to 10 W/m^2/K for totally uninsulated opaque surfaces [2]. [128] even highlights that common slums roofing types include iron sheet materials, with a thermal conductivity of 37 W/m/K and thickness of 3 mm. This would lead to an enormous U-value.

However, it should be remembered that most of the energy demand in these countries will certainly be represented by cooling. Poor households do not install air conditioning, as was already assumed in EDGE (see section 3.2. Therefore, assuming enormously high U-values does not make sense, because space heating and cooling demand are directly proportional to this parameter (see equations 3.2 and 3.3). Implementing high U-values would mean that heating and cooling demand increase accordingly, which does not reflect reality since poor households presumably live in energy poverty conditions as well. Therefore, estimations on current U-values of traditional north-african houses were used as an indication [129]. Table A.6 summarizes indian U-values, assuming a slight decrease from 2000 on due to the policy implementation. The african and other asian countries U-values are not presented here, because they are equal to the indian ones, without any decrease for the newest vintages.

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	3.475	2.4	3.3	2.4	5.8
1945-1969	3.475	2.4	3.3	2.4	5.8
1969-1979	3.475	2.4	3.3	2.4	5.8
1979-1989	3.475	2.4	3.3	2.4	5.8
1989-1999	3.475	2.4	3.3	2.4	5.8
1999-2009	3.15	2.2	3	2.4	5
2009-2014	3.025	2	2.7	2.4	5

Table A.6: Indian U-values

Other non-OECD countries

This region is mostly constituted by latin american countries, with cooling-based climates. As already outlined before, in this kind of climates very low insulation levels are present. This is indeed confirmed by a brazilian paper [130]. Therefore, implemented U-values, summarized in table A.7, reflect this situation, without being too high since latin american countries are not as poor as african ones.

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	3.15	2.4	2	2.4	5.8
1945-1969	3	2.1	2	2.1	5.8
1969-1979	2.875	1.9	1.9	1.9	5.8
1979-1989	2.8	1.8	1.8	1.8	5.8
1989-1999	2.725	1.7	1.7	1.7	5.8
1999-2009	2.65	1.6	1.6	1.6	5.8
2009-2014	2.65	1.6	1.6	1.6	5.8

Table A.7: Non-OECD countries U-values

Other OECD countries

This aggregation involves countries belonging to very different climates. Indeed, the greatest included regions are Canada, Australia, Mexico and Turkey. The U-values of Mexico were found to be similar to the ones of latin-american countries, while turkish U-values are close to middle east levels. Therefore, these nations show generally high U-values. Moreover, they constitute around 75% of the total population of this region. However, Canada (which holds around 15% of the population) shows really high insulation levels. Roof U-values range from 0.26 to 0.2 W/m^2/K, walls and floor U-values vary among 0.5 and 0.4 W/m^2/K depending on the vintage [131]. Regarding Australia, which approximately holds the remaining 10% of the population, building codes were found to require quite low U-values for any type of climate [132]. Therefore, the U-values summarized in table A.8 were computed by decreasing the NCD U-values, according to the population shares fo Canada and Australia.

Vintage	Envelope	Walls	Roof	Floor	Windows
pre-1945	2.615	1.92	1.5	2.04	5
1945-1969	2.49125	1.68	1.5	1.785	5
1969-1979	2.39	1.52	1.425	1.615	5
1979-1989	2.28	1.44	1.35	1.53	4.8
1989-1999	2.17	1.36	1.275	1.445	4.6
1999-2009	2.06	1.28	1.2	1.36	4.4
2009-2014	2.01	1.28	1.2	1.36	4.2

Table A.8: Other OECD countries U-values

Appendix B

Regression analysis

In this chapter, details on the implementation of the performed regression analyses are outlined.

Residential and Services sub-sectors-regression

Correlations between U-values of residential and non-residential sub-sectors have been checked again, both at the envelope, component and vintages levels, through the determination of the intercept α and the slope coefficient β, according to the following equation:

$$U_{residential} = \alpha + \beta \cdot U_{non-residential} + \epsilon \tag{B.1}$$

If U-values of both sub-sectors are distributed in the same way, then α must be equal to 0 and β to 1, while the ϵ term represents a mean-zero random error term, measuring the difference between the estimation and the actual value of the response [133]. The regression results showed that the value of β was always ranging from 0.9 to 1, with high levels of significance (i.e. p-value always lower than 10^{-7}), while the value of α showed higher variations, ranging from 0 to 0.3, with very low levels of significance in all the cases (i.e. p-value always between 0.1 and 1). Hence, a regression was run considering all the available data, that is, all the components and vintages. Results are shown in table B.1 and indicate that the intercept α is significantly enough close to 0, while the slope β is significantly close to 1. Standard errors [1], are quite small. Thus, from these results, it can be deduced that when the level of U-values is small, (that is, lower than 2 W/m^2/K), the residential sector shows slightly greater U-values, while the opposite happens at high U-values levels. However, the variations between these two subsectors are very small. Therefore, even if some variations in the balance between residential and non-residential U-values may occur if different groups are considered, it can be concluded that no significant differences arise between the two sectors, at the aggregated level.

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[1] The standard error meaning can be outlined when related to confidence intervals. A 95% confidence interval is a range of values that contains, with 95% probability, the true unknown value of the considered coefficient. For a linear regression, the 95% confidence interval of a coefficient β takes the form of (β-2·SE,β+2·SE) [133]

Coefficient	**Estimate**	**Standard Error**	**Level of significance (p-value)**
α	0.10441	0.03493	0.00331
β	0.9411	0.01846	10^{-16}

Table B.1: Overall regression results

Components U-values weight-regression

The following figure outlines the regression results: it can firstly be seen that the intercept α is not equal to zero, however this value is not significantly negative, since its p-value is around 0.02 and its standard error corresponds to about 0.03-0.04 for both cases. Therefore, a 95% confidence interval of the α coefficient would contain 0. Instead, the other coefficients are strongly significant (p-value lower than 10^{-9}), with a SE being at most equal to 0.035. The red line indicated the 25% share, which would result from an equal weight of all the coefficients. Even if the analysis was performed from the same database U-values [7], the impact of floor greatly differs among 2008 and 2014. Moreover, walls appear to be the most important component in 2008, while in 2014 windows and roof U-values show the highest coefficients. It is difficult to find an explanation for these variations. Since the effect of thermal bridges has been neglected in equation 2.3, a positive value of the intercept would be expected, so that the envelope U-value is actually higher than what would result from the aggregated components, yet this does not happen. Performing the same regression and looking at the resulting coefficients across different vintages may yield some hints for explaining these trends. However, restricting the analysis to a single vintage (or even groups of

Figure B.1: Intercept and coefficients results vintages) results in low levels of significance of the coefficients, due to lower amount of data. Even though both the 2008 and 2014 analyses were computed for 28 regions and 6 vintages (thus having 168 data for each component U-value), there is still some uncertainty in the determination of the intercept.

Energy Efficiency drivers-regression

Data were collected from 2008 to 2014, therefore some levels of renovation may have happened in the considered buildings. Within this analysis, it is assumed that the current U-values represent the levels of insulation that the buildings had when they were constructed, considering negligible the effect of renovation. Another assumption is related to linearity between predictors and response. Moreover, both databases outline U-values levels with very wide timesteps (at least 10 years), therefore the predictors data must be averaged for each vintage. To understand which variables should be investigated, it must be kept in mind that all the predictors should not be collinear, in order to avoid misleading results. In fact, if this happens, it would be difficult to separate out the individual effects of collinear variables on the response and a lot of uncertainty would be involved in the estimation of the i-th regression coefficient β_i: their standard error would increase, causing the t-statistic to decline, which may eventually lead to a failure in the rejection of the null hypothesis: $\beta_i = 0$ [133]. Details on the implementation of the regression are here explained:

1. U-values data are regressed over vintages. Therefore, three data sources are available: one from the TABULA database, two from the European commission database, which performed a collection of data both in 2008 and 2014. Since it has been outlined in section 2.3.2 that few differences arise from the comparison of residential and non-residential sub-sectors, only the former one has been considered. In the TABULA database, U-values related to pre-1950 vintages were aggregated into a single group, given that most of the data related to the predictors were not available before that year and, as was outlined in section 2.3.1, U-values did not decrease much until the seventies.

2. According to the indications outlined in 2.3.1, historical oil prices development was considered, as a variable related to energy prices. The annual average crude oil price, in $/barrel, with the inflation adjusted to July 2017, was downloaded from [36]. In order to consider the development over different vintages, four different variables were tested: the peak oil price, the average of the 2 peaks, the average vintage price, the delayed average vintage price (i.e. the 1970-1980 vintage was assigned the oil price of the previous period, that is 1960-1970, in order to analyze the importance of delay in the policy response to oil prices).

3. Policy impacts: data were downloaded from the MURE database [37], looking at summary tables of policies by targeted end use (space heating was considered) for households were considered. Data are divided into "status" (which can be either ongoing, completed, proposed or unknown) and "semi-quantitative impact"

(which depend on the estimated amount of energy savings from the selected policy: high is assigned to measures leading to savings greater than 0.5% of the sector energy consumption, medium for 0.1% to 0.5% savings, low for less than 0.1% savings [134]). Depending on the three levels of impact, a level of 1 to 3 was assigned to each policy, while a value of 1 was assigned to unknown impact measures. This amount was then spread over the vintages, depending on the year in which they were launched and concluded.

4. Urbanization and population density: data were downloaded from the World Bank development indicators database [38] and were averaged for each vintage and they were available from 1960 on. Regarding the 1950-1960 vintage, data were assumed to be equal to the 1960-1970 period. Urbanization rates are expressed in percentages, while population density in people/km^2.

5. The variable related to income is the GDP per capita, from [35], which was averaged for each decade.

6. Climate: HDD and CDD levels were downloaded from Eurostat [35] and were averaged by decade. Data were available until 1974: for the previous decades, the same level of the 1970-1980 vintage was assumed, since in any case there is no significant variability over decades, for the analyzed data.

7. The variable related to the time dimension is simply the average of the upper and lower limits of the considered vintage.

Firstly, considering collinearity issues, HDD and CDD are certainly related. However, the former one represents a much more significant predictor of U-values than the second, therefore only the HDD data will be included from now on. Among the four variables related to energy costs, the average decade oil price resulted to be the most significant predictor. This is probably due to the fact that U-values are classified into groups of 10 years, therefore the effect of either yearly peak prices or the delay in the countries response to prices cannot be captured, since the latter happens in a period which is lower than 10 years. Moreover, population density was found to be a worse predictor than urbanization rate and it was discarded, probably because the former is not only linked to the presence of big cities. Moreover, policy indicators had to be discarded as well, due to their low levels of significance in all the cases. Indeed, despite their importance in driving U-values development is certainly recognised, it is not easy to evaluate their impacts. There were multiple sources of uncertainty in the way impacts were computed and spread over vintages in this regression: this is why their coefficient is not significantly different from zero.

The final ranges of coefficients estimation (depending on the considered building component) for the different databases are summarized in table B.2, divided into opaque surfaces (i.e. roof, walls and floor), glazed surfaces (i.e. windows) and envelope estimations. The TABULA database does not show information at the aggregated envelope level: trying to aggregate the components U-values would lead to further

Database	Coefficient	Opaque	Glazed	Envelope
Tabula	alpha	(34;49.42)	73.5	-
	HDD	(-4.76;-2.16)*10^{-4}	-6.54*10^{-4}	
	Time	(-2.4;-1.6)*10^{-2}	-3.46*10^{-2}	
EU commission, 2008	alpha	(34.39;42.44)	50.82	42
	HDD	(-3.75;-2.73)*10^{-4}	-6.41*10^{-4}	-4.6*10^{-4}
	Time	(-2.03;-1.64)*10^{-2}	-2.33*10^{-2}	-1.98*10^{-2}
EU commission, 2014	alpha	(35.05;40.34)	59.78	45.55
	HDD	(-3.83;-2.7)*10^{-4}	-6.94*10^{-4}	-4.55*10^{-4}
	Time	(-1.93;-1.67)*10^{-2}	-2.76*10^{-2}	-2.15*10^{-2}

Table B.2: Estimations of the regression coefficients

uncertainty in the results, since the share of components areas are not differentiated across vintages, thus it has not been done. In each of the analyzed cases, the coefficients estimations were highly significant (i.e. p-value lower than 10^-3).

Looking at the values, it can be seen that the order of magnitude of the estimated coefficients does not vary across databases. As expected, the coefficients related to climate and time are negative. Glazed components show a higher value of both the intercept and the coefficients, especially the one related to climate. This makes sense, since in pre-1950 vintages, almost only single-glazed windows are present, with a U-value which is around 5.8 W/m^2/K, while the latest glazed components show U-values as low as 1 W/m^2/K, which represent triple-glazed windows and are installed especially in the coldest climates. U-values for opaque surfaces diminished over time as well, but they decreased from around 3 W/m^2/K to 0.5 W/m^2/K. Therefore the total decrease over time of windows U-value is almost two times compared to the opaque surfaces one. Moreover, climate plays a great role in determining the thermal performance of glazed surfaces. Recalling figure 2.1, it can be seen that for the newest vintages, U-values related to opaque surfaces range over a much narrower span compared to the windows ones. Indeed, decreasing U-values to very low levels is much easier for opaque surfaces. Therefore, triple-glazed windows are very expensive and are currently not used in warm European countries, leading to the remarked higher variation in U-values, as section 2.5 outlines.

2008-2014 analyses-regression

Looking at table B.2, it can be noticed that there are few differences among the estimations related to 2008 and 2014 of the European commission database. Apparently, the coefficients related to 2014 are higher, in absolute terms, than the ones related to 2008. If some renovation of the oldest buildings happened, it would be expected that the magnitude of the time coefficient becomes lower. Therefore, it can be reasonable to look at how the thermal performance of the same vintages changed among these two years. Firstly, the envelope U-values related to 2014 were regressed, using the corresponding 2008 levels. Both the slope and intercept are significantly different from zero.

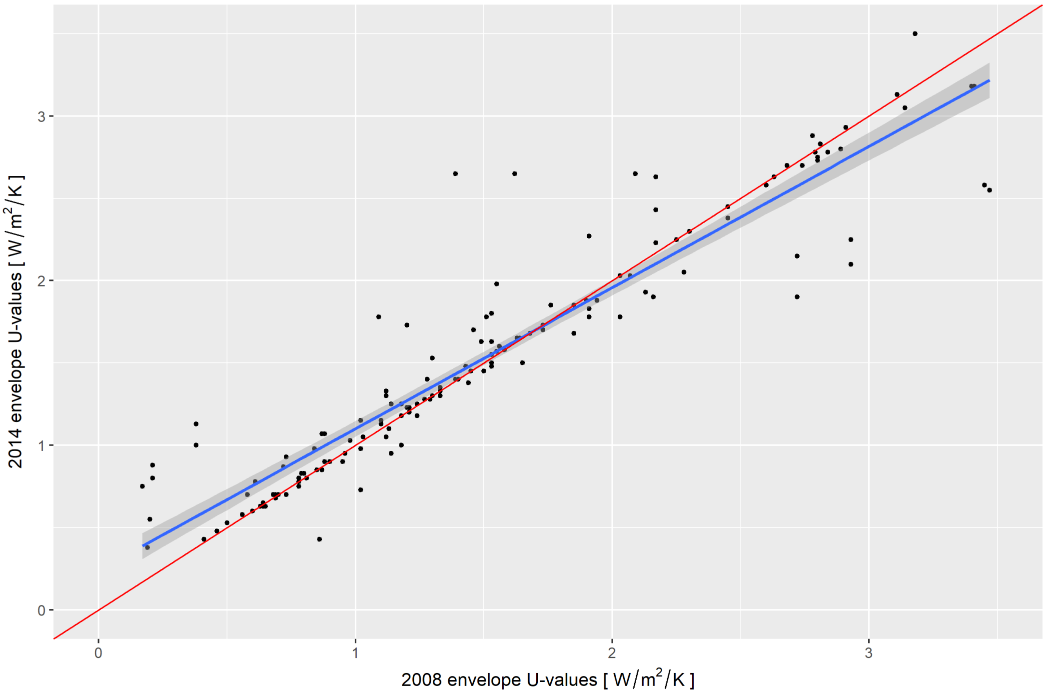

Figure B.2: Regression between envelope U-values related to 2008 and 2014, with regression line (blue) and bisector line (red)

It can be seen from figure B.2 that for the best performing buildings (U¡1 W/m^2/K, related to the newest vintages) U-values actually increased, while the opposite happened for the worst performing buildings (linked to the oldest vintages). The latter effect might be due to the renovation of the worst performing stock, while the former might be related to ageing of the building envelope for the newest buildings. However, it must be remembered that data collection differences might have happened as well, leading to variations in the results, as already outlined in section 2.3.1. In any case, there is no marked shift towards either an improvement, or a worsening of U-values. Improvement of country-level U-values from 2008 to 2014 is probably due to new construction buildings and demolition of oldest vintages.