Examining future mitigation pathways for residential building sector heating and cooling demand

Scenario development and analysis on TIMER

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Supervisor

Vassilis Daioglou, PhD

Copernicus Institute of Sustainable development &

PBL Netherlands Environmental Assessment Agency

Second Reader

Detlef van Vuuren, Prof.

Copernicus Institute of Sustainable development &

PBL Netherlands Environmental Assessment Agency

Internship Supervisor

David Gernaat, PhD

PBL Netherlands Environmental Assessment Agency

Efstratios Mikropoulos

e.mikropoulos@students.uu.nl & emikropo@gmail.com

Abstract

The building sector consumes more than half of electricity, almost one third of the global energy produced and is responsible for almost one third of the global energy-related CO2 emissions. The anticipated future situation is even more dire with the building demand significantly rise due to the expected population and GDP growth followed by an increase in living standard (especially in developing countries). One way to reduce the energy demand (and thus the emissions) with no expense in comfort, is through improved thermal insulation in the buildings' shell. Hitherto the efforts towards an energy-efficient building stock cannot offset the increase in energy demand, so additional development should be driven via technological improvements, regulations and policy initiatives.

In this thesis we developed a stylized bottom up system dynamic global model is developed as part of IMAGE (an Integrated Assessment Model). The model simulates decisions on insulation investments and the resultant building stock quality (indicated via the useful energy intensity of buildings). Furthermore, we examine the effect of insulation on the residential energy use for heating and cooling and the associated CO_2 until 2100 and under different socio-economic developments. Finally, we investigate climate policies in the form of subsidies, energy standards and a carbon tax are applied to the model and their efficient on reducing the projected demands and emissions as well as their associated costs (under each above-mentioned future development).

Analysing the results, we found that effect of policies differs across the geographical regions, and under the various examined socio-economic pathways. In general, the carbon tax can successfully reduce the CO_2 emissions, but not the heating demand of the residential buildings (which is some occasions increases). Contrary, higher demand (and sometimes cooling) reduction can be achieved by the other two measures, depending on the characteristics of each scenario, but the respective emission reduction achieved is insignificant. The reason is a rebound effect, which due to the reduction on the heating and cooling demands activates a fuel switching towards a less "clean" fuel mix. So, it becomes evident that for an optimum result, and to achieve the 1.5^{o}C or 2^{o}C target (set by the Paris Agreement) towards a decarbonized future, a mixture of policies should be utilized.

Outline/Contents

1. Introduction

Global effort is essential to keep the average temperature rise in low levels. Towards this direction, the Paris Agreement was signed in 2016. The Paris Agreement's long-term goal is to mitigate the climate change by keeping the increase in the global average temperature to well below 2 °C (above pre-industrial levels) and preferably to limit the increase to 1.5 °C. The so called 1.5°C target is expected to substantially reduce the risks and the effects of climate change. The transition to a decarbonized future should start well before 2030 and until that year marked emissions reductions (compared to today) should be achieved (Rogelj et al., 2018). If the intense efforts begin later than 2030 the (almost) zero net emissions by 2050 associated with the 1.5°C threshold will not be achievable, even if the pledges under the Paris Agreement were increased in scale and ambition (regarding emission mitigation) (Rogelj et al., 2018).

The building sector nowadays consumes more than half of electricity, and almost one third of the global energy produced. Furthermore, it is responsible for 28% of the global energy-related CO_2 emissions (Dulac et al., 2013; Aberel et al. 2017; Atanasiu et al., 2013). With the building-related CO_2 emissions rising by nearly 1% per year since 2010 (Atanasiu et al., 2013), the recent emissions of 2018 have risen to an all-time high (IEA, 2019) [b]. Both direct and indirect residential sector's emissions are expected to further grow (alongside with the buildings energy demand) over the next decades adding additional stress on the energy system and the environment globally (Daioglou, et al., 2012; Clarke et al., 2014; Dulac et al., 2013; Aberel et al. 2017). Furthermore, forces/drivers such as the increase in population, global economic development, and the increase in average living-standards are responsible for a constantly growing building sector, which will continue to grow over the coming decades (Dulac et al., 2013). UN Environment estimated that in the next 40 years there will be approximately 230 billion square meters of new builds (Aberel et al. 2017). These developments connect the building stock to issues such as air pollution, environment degradation, climate change, resource depletion and energy security. However, at the same time there is a huge potential to reduce the energy consumption and CO_2 emissions by recognizing the problem's magnitude and propose suitable pathways.

To limit global warming to 2°C (above pre-industrial levels) a reduction of emissions in the building sector of about 50-75% by 2050 (compared to 2010 emissions) and almost 100% by 2100 must be achieved (Clarke et al., 2014). The 1.5°C target suggests for a more rapid emission reductions in the buildings sector of 85-95% by 2050 (almost net zero emissions) (Knobloch et al., 2018; Atanasiu et al., 2013).

Heating is responsible for the most direct emissions of the sector (Knobloch et al., 2018) and in combination with the cooling demand constitutes a major part of energy consumption regarding the building stock (**Figure 1)**. So, targeting them could greatly benefit the energy system. The Global demand for heating could be fulfilled more (energy) efficiently and without reducing comfort by an improved thermal insulation of the buildings' envelope (Lucon et al., 2014). There are several options regarding the application of insulation on new and renovated buildings. Apart from windows (windows with high thermal resistivity provide good insulation), there is cavity insulation, a method where insulative material is inserted inside a wall (it is possible only when there is a gap layer between bricks inside the wall), external insulation and internal-wall insulation, where a layer of insulation is applied on the exterior or interior of the building. Cavity insulation is less expensive (less labour work and material), but also less efficient as the inside-wall layer is thinner than the insulation layer created by the two other methods (Petersdorff et al., 2005). Benefits of insulation application include fuel poverty alleviation, health benefits, increased energy security, increased employment, higher rental and resale values and air quality improvement (Atanasiu et al., 2013).

The energy efficiency of new buildings has significantly improved during the last decade (driven by technological improvements, regulations and policy initiatives). However, the existing building stock mainly consists of older, less efficient buildings that consume significant amounts of energy (Harrison et al., 2017). Considering the high average lifetime of buildings (usually around 80-100 years) the less-efficient buildings will continue to burden the energy system for many years. Thus, their renovation becomes essential to advance towards the 1.5^{o}C (or even the 2^{o}C) target. Hitherto the combined improvements towards more sustainable buildings (in new constructions and renovations) have already led to less energy intensive buildings but the measures are not taken fast enough to counter the rapid growth of the building stock, so the total building-related energy demand and emissions are constantly rising (as already mentioned).

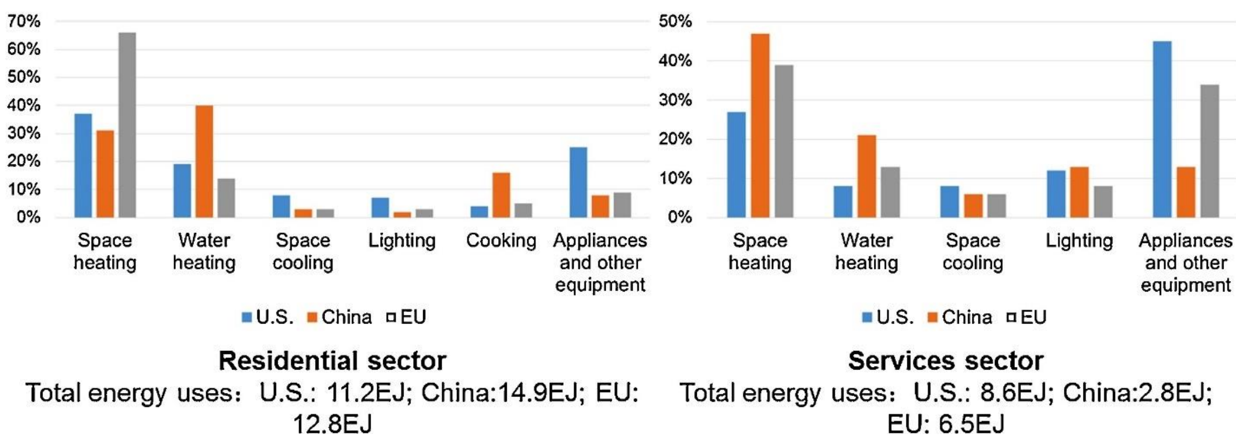

Figure 1. *Breakdown of building energy end-uses in the U.S., China and the E.U., 2010. (Cao, X. et al. 2016).*

There is much untapped potential in the building sector. Policy instruments aimed at investments in sustainable buildings could reduce the sector's CO_2 emissions (IEA, 2019) [b]. Incentives like grants and subsidies, tax relief, equity finance, loans and debt finance, guarantees encourage sustainable behaviour through financial rewards. Moreover, mandatory policies and regulation "force" an upgrade in the buildings shell (but only in new and renovated buildings), and a taxation on energy use (i.e. a carbon tax) indirectly push towards the improvement of the buildings' envelope (as a mean of fuel use reduction) (Knobloch et al., 2018; Harrison et al., 2017; Ritchie et al., 2017; Atanasiu et al., 2013).

This thesis focuses on the need of a decarbonized future, and by utilizing a dynamic simulation model (TIMER/IMAGE) it examines possible mitigation pathways (policy mechanisms described above) under various future developments (socio-economic pathways). For the integration of insulation in TIMER model through a decision mechanism a sub-model was developed during my internship. This sub-model is the combination of the Building-Stock model and the Renovation model and improves the existing REMG (part of TIMER) (further details on all these models and frameworks is presented in section 3). Furthermore, the possible pathways and actions are compared in terms of costs and efficiency (regarding energy demand and CO_2 emissions mitigation). The results help explain the potential, drivers and constraints of energy efficiency improvement offered by the insulation of buildings. This will further highlight the dynamics which drive energy demand and emissions of this sector. Finally, it will contribute to the development and expansion of the TIMER model, and the broader IMAGE model, which offers a more holistic view of the energy system and the environment as a whole.

As heterogeneity is a basic element of the energy sector the share of floor area between residential and non-residential buildings varies considerably across countries. Heterogeneity in the sector also originates from the different urban and rural population classes and furthermore the income classes (income quintiles) that are apparent thorough the world. However, the majority of the existing building stock, as well as the projected future one is (and will be) composed by residential buildings (European Commission, 2018). In this report the residential building sector is examined, but the results provide insight on potentials also for the non-residential sector. The projections will be both global and regional and until 2100 (the regions used are the ones represented by the IMAGE framework and they are presented in Appendix I).

The report is structured as follows. First the research question and sub-questions which this research aims to answer are displayed (section 2). Then the relevant background theory is presented (section 3). The next section focuses on the methodological steps taken to answer these sub-questions and the main objective of this paper (section 4). The expected results for each step are illustrated in section 5. Finally, the discussion on the findings and the conclusion follow (sections 6 & 7).

2. Research questions

As already mentioned, the potential improvements in the global building stock through investments, and the resulting changes in residential building heating and cooling demand is examined under several socio-economic pathways (future developments) with and without the presence of several climate mitigation scenarios (section 3.4. provides information about the socio-economic pathways). Then the effect of specific mitigation strategies will be simulated and assessed. Therefore, the main research question is:

"How can improvements in residential buildings envelope help towards reducing heating and cooling energy intensity and CO2 emissions across different socio-economic pathways and climate change mitigation scenarios?"

A set of sub-questions are developed to meet the main objective of this research.

1. How can the improved sub-model (Building-Stock and Renovation model) lead to different heating and cooling demand across differing socio-economic pathways?
2. How do the results concerning heating intensity compare with a version of the model lacking an explicit representation of renovation and efficiency improvement?

3. How do policies aiming at expediting efficiency improvement in buildings affect choices in renovation and efficiency improvements in residential buildings?
4. How could these policies contribute to GHG emission reductions and climate change mitigation?
5. How do renovations contribute to reducing heating and cooling demand and subsequent CO_2 emissions from the residential sector in climate change mitigation scenarios?

Sub-questions (1) is aimed to examine different future developments under the three possible socioeconomic pathways (SSPs). Sub-question (2) investigates the results of the new/improved model compared to the older version of TIMER and REMG. Sub-question (3), (4) and (5) examine the effect of policies (climate and energy efficiency policies), under possible pathways of development, towards a decarbonized future.

3. Background Theory

Section 3 displays the backbone of this report and the basic theories on which it elaborates upon. My thesis is based on a continuation of an internship conducted at PBL, at which I developed a sub-model responsible for renovations (and the application of insulation in general) in the residential buildings sector. Therefore, for a better understanding of my methodology and findings, a short description on this sub-model is presented here.

3.1. Long-Term Scenarios and Integrated Models

Integrated Assessment Models (IAM) aim to link the main features of society and economy to the biosphere and atmosphere (Clarke et al., 2014). This scientific modelling represents interactions among important human systems like the energy system, economy system, land use, agriculture and technology development.

By projecting key characteristics of transformation pathways (to mid-century and beyond), IAMs attempt to inform policy makers often in the context of climate change and climate change mitigation. IAMs are usually simplified, stylised numerical approaches that take a set of inputs (depending the type of IAM this could be societal drivers, population growth and economic growth, technology deployment, economic parameters etc.) and produce output regarding energy system and land use transitions, climate change mitigation pathways and economic effects of these pathways and emission projections (e.g. CO_2 ppm concentration by 2050).

The decision making in an IAM is economy based, aiming towards a minimized economic cost around climate change mitigation targets. However, there are various types of IAMs differentiated in terms of foresight, representation of trade, representation of technological trade, economic interaction, flexibility and sectoral/regional technology and GHG detail, and thus, each producing different future scenarios (Clarke et al., 2014). Three big categories of integrated models are simulation (recursive-dynamic), intertemporal optimization and general equilibrium models. A recursive-dynamic model makes decisions at each point in time based on the information in that time (model run), in contrast to optimization models which assume perfect foresight (all future decisions are taken into account in today's decisions). The last (perfect foresight models) are more likely to result into higher emission reductions, allocated more efficiently over time, and acquired through lower costs/expenses, as it implies fully rational and educated decisions and provided the "theoretical" optimum solution. General equilibrium models (full-economy models) on the other hand, are more suited in describing the economic system and the economic interactions between sectors. That allows a better understanding in ripple effects (e.g. from a mitigation policy), in contrast to partial economic models which utilise economic growth and activity as an input. However, the last focuses more on a detailed representation of key systems (in this case the energy system).

Apart from IAMs, there are also other approaches to examine the transformation pathways, as qualitative scenario methods and aggregated modelling tools (e.g. cost-benefit analysis tools). These approaches provide a more in-depth detail and information about important aspects, as economic cycles or the operation of electric power systems (Clarke et al., 2014). However, in modelling there is a trade-off between detail and a large-scale description, so these methods lack in terms of their timeframe and scope (compared to the integrated models).

3.2. IMAGE, TIMER and REMG

In this research a recursive dynamic energy model (IMAGE-TIMER) is used to examine the effect of insulation under different socioeconomic pathways. **IMAGE** (Integrated Model to Assess the Global Environment) is an ecological-environmental IAM framework (structure is illustrated in **Figure 2**) that simulates the environmental consequences of human activities worldwide by representing interactions between society, the biosphere and the climate system (PBL,2014; PBL,2019). It is framework of soft and hard-linked sub models representing human systems like, the energy system, the land-use system, agricultural economy, climate, biodiversity, international climate policy etc. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes (like global warming) that result from interacting socio-economic and environmental factors. **TIMER** is the part of IMAGE the energy-system model of IMAGE. It analyses the long-term dynamics of energy conservation and the transition to non-fossil fuels within the integrated modelling framework and explores long-term trends for energy-related greenhouse gas emissions. Important components of the various sub-models (parts of IMAGE) are: price-driven fuel and technology substitution processes, cost decrease as a consequence of accumulated production ('learning-by-doing'), resource depletion as a function of cumulated use (long-term supply cost curves) and price-driven fuel trade. TIMER models market inertia, technology heterogeneity, and many other dynamics in energy systems (for example, through multinomial logit equations, multiple options are chosen for an energy function, each with a different market share), achieving this way relatively increased realism in its projections compared to optimization models. The TIMER model projects the supply and demand of primary and final energy. This is based on information concerning energy resources, and projections of the demand of different energy services (i.e. heating, travel, industrial output, etc) across a number of sectors: Industry, transport, residential, services, agriculture, and other. The model also includes energy conversion sectors such as power generation and hydrogen production.

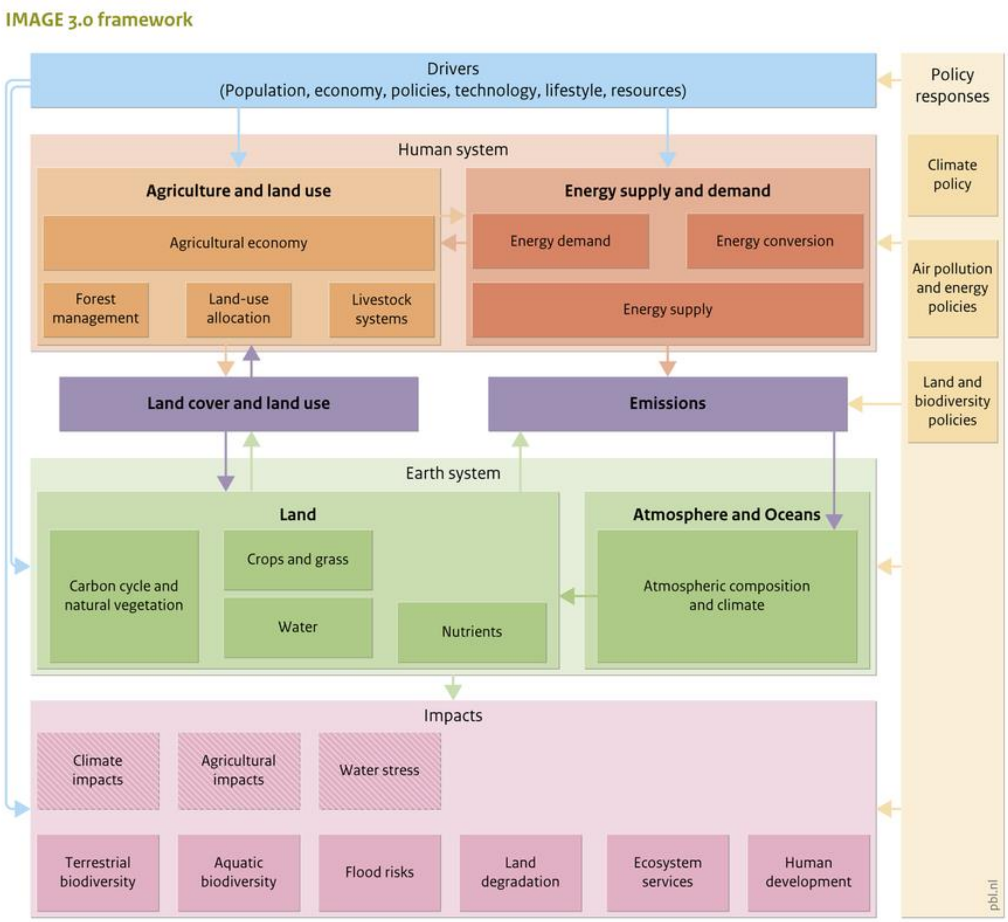

Figure 2. *Schematic of the IMAFE 3.0 framework (PBL, 2014).*

While the results of this research are based on the full TIMER model, the bulk of the work is based on the residential energy demand module of TIMER (the Residential Energy Model-Global, REMG). **REMG** is a bottom-up model simulating the global residential energy demand in a recusrive-dynamic fashion. The basic outline of the residential model is shown in **Figure 3** (Daioglou, 2010).

First there are drivers such as population, GDP, floorspace, household size, electrification, discount rates and perceived costs. These drive the energy demand function (for the residential sector) for cooking, water and space heating, space cooling, lighting and appliances (e.g. washing machines, televisions, etc.). First the useful energy demand is estimated (that is the energy demand needed to meet the demand function, i.e. GJ of heat or Watts of lighting). Afterwards, by allocating the fuels for each of these demand functions, the final energy demand is determined (i.e. the demand of fuels after conversion efficiency of technologies has been accounted for). The said fuel allocation is based on the total costs (fuel costs and costs for the production of the energy carriers), through a multinomial logit, and finally the market share of the energy carriers is estimated. The REMG model provide a very detailed description of the energy system, since it distinguishes between regions (see Appendix I), and population income classes (for more detail the classes see 2.3.1). The final energy demand is linked to the rest of the TIMER model in order to determine primary energy demand and changes in energy prices due to depletion of resources. Thus, feedbacks from the energy demand of other sectors and overall primary energy supply (and conversion to intermediate energy carriers such as electricity) are fully accounted for.

REMG makes all its calculations across 26 regions (see Appendix I), and 5 income quintiles across urban & rural households. Thus, it able to represent important dynamics accounting for regional differences in climate characteristics, income inequality and socio-economic heterogeneity. This makes it one of the most detailed global long-term models for the residential sector, able to investigate long term climate change mitigation strategies, currently available.

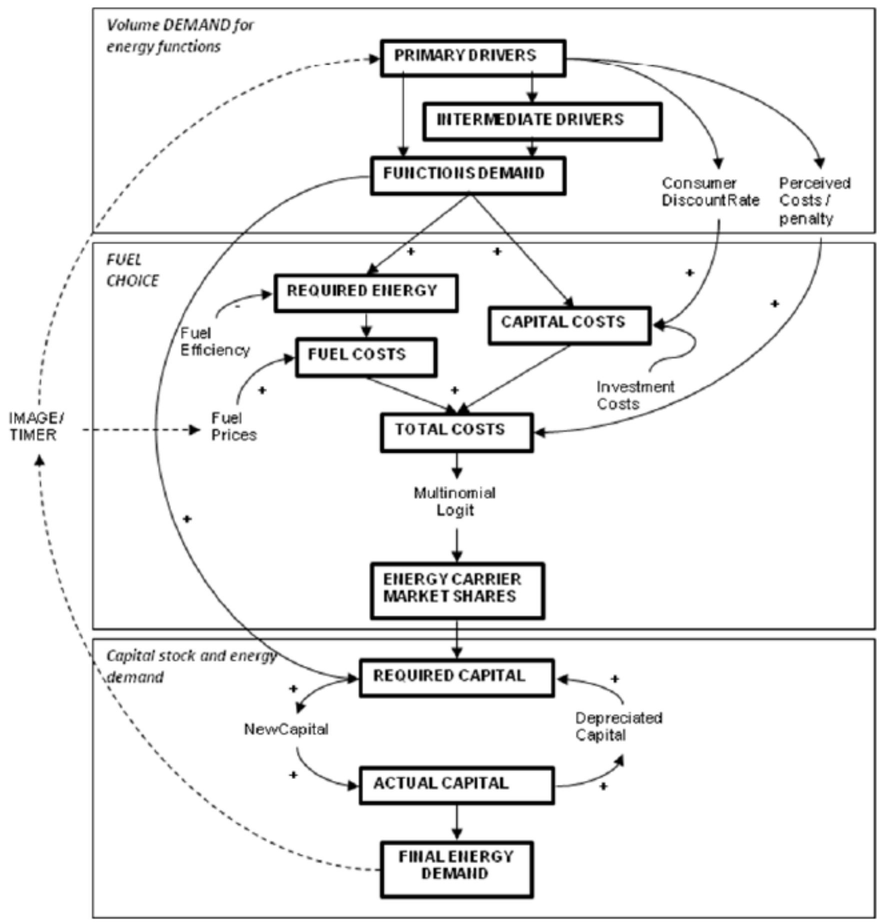

Figure 3. *Casual relation diagram of main indicators of REMG model (Daioglou, 2010).*

3.3. Building-Stock and Renovation model.

As already mentioned, the insulation in buildings plays an important role of the residential energy demand and its reinforcing has the potential to highly mitigate the energy demand and contribute to the decarbonization of the energy system (Daioglou, 2010; Clarke et al., 2014; Dulac et al., 2013; Aberel et al.

2017). So, it is essential for a model simulating residential demand and its future development to have a proper representation of the buildings shell quality (insulation application). REMG originally incorporated the buildings shell efficiency improvements until 2100, by assuming a steady improvement of the buildings' quality (decrease in useful energy intensity, measured in energy demand per floorspace and heating degree day – kJ/m^2/HDD). But this non-dynamic way of insulation representation lacked the detail and accuracy in order to incorporate the decisions actors have to take which drive improvements in efficiency, and also did not provide much room in examine possible future developments concerning improvements of existing building stocks.

In my internship at PBL a global Building-Stock model was developed, based on floorspace projections from TIMER. This Building-Stock model estimates the input and output flows of the building stock, distinguishing the buildings per region, quintile (income class) and age, thus making further modelling developments possible. furthermore, 4 building types incorporated in the model are stand-alone houses, semi-detached houses, apartments and high-rises. Afterwards, a second model was developed simulating the human decisions on use of insulation in new and renovated buildings. This unlocks the possibility in TIMER for buildings to apply insulation improving their shell's energy efficiency and thus reducing their heating and cooling demand. The Renovation model assumes 6 different insulation levels, of different dynamic costs and efficiency, and the allocation of them in buildings (during construction and renovations) is economy based. Ultimately the investments in insulation taking place and the building's stock average useful energy intensity unlit 2100 are projected (also the intensities per category of building – old, new, renovated, abandoned etc.). Combing these two models into REMG (and thus TIMER), the final **sub-model** (**Figure 4**), can calculate the building sector demand for heating and cooling, and their respective emissions. In this section the two models developed during my internship are briefly described. For a better insight on the model's mechanism a review of the internship report is suggested.

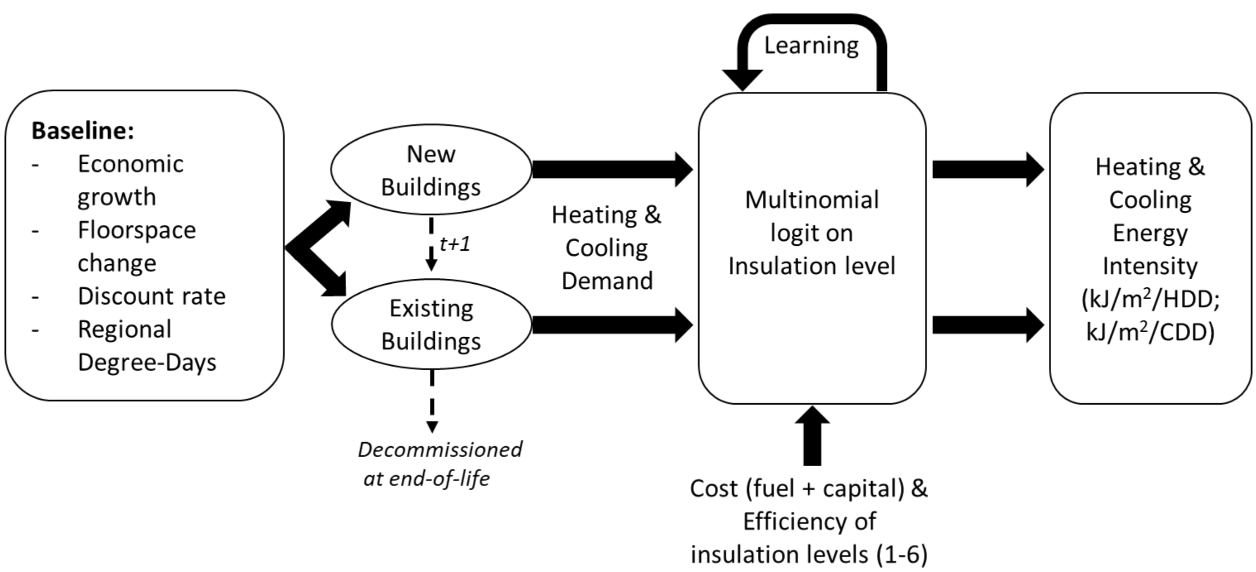

Figure 4. *Schematic of methodology used to project investments in building insulation, and the effect on cooling and heating demand of new and existing buildings. Note that all calculations are done per Region, Urban/Rural demographic, Income quintile, and Building type (Daioglou et al., 2019)*

3.3.1. Building-Stock model

The first model simulates the inflows and outflows of the global building stock from 1971 to 2100. The flows depend on projections of floorspace (Daioglou, 2010) in combination with buildings lifetimes and shares of building types found (Deetman, 2019). The change of floorspace in each region is examined and labeled as **New Buildings** in case of an increase, and as **Abandoned** in case of a decrease. The abandoned buildings are composed of the oldest existing buildings of the stock (assumption that the older buildings get abandoned). In addition to the abandoning process, the buildings in the stock get decommissioned (**Decom. Buildings**) due to old age, with the use of a normal distribution, close to their average lifetimes (decommissioning is simulated after the buildings lifetime ± 5 years, under the condition that the building has not been abandoned in a previous year). The decommissioned, due to old age buildings, are rebuild in the same year to cover the need for floorspace. Considering all the above, the change on the building stock is:

$$Change\ in\ BuildStock(t) = Total\ New\ Buildings(t) = New\ Buildings(t) + Decom. Buildings(t),$$
$$if\ \Delta(foorspace) > 0$$

$$Change\ in\ BuildStock(t) = Reduce\ in\ Buindings(t) = Abandoned(t) + Decom. Buildings(t),$$
$$if\ \Delta(foorspace) < 0$$

Equaiton 1.

and the building stock in year t is:

$$\boldsymbol{Building\ Stock(t)} = Building\ Stock(t-1) + Change\ in\ Buildings(t) - Decom. Buildings(t)$$

Equation 2. Where: Decom. Buildings are the decommissioned buildings. t represents the year (between 1971 and 2100) while all other parameters are in m^2.

Note: The 'abandoning' of buildings each year is modelled assuming that buildings that were decommissioned are not going to be rebuilt (they are abandoned). In case the amount of abandoned buildings is greater than the (available) decommissioned buildings (of the same year), no buildings are rebuilt, and an additional amount of buildings is removed from the building stock. This amount consists of average (in terms of energy intensity) buildings that would be decommissioned the coming years (next year or more, depending the amount needed). These assumptions are the base for energy calculations of the average useful energy intensity of the building stock.

By "converting" the floorspace to the building stock and its components, steps needed for calculating the heating and cooling energy demand and the building shell characteristics are now possible. These steps are presented in the next sub-section.

3.3.2. Renovation model

As already mentioned, the renovation model is created in an attempt to forecast the changes in heating intensity of new and older dwellings (by retro-fitting) via insulation, and thus reducing the energy consumption of existing and new buildings in the future. There is a variety in buildings shell efficiencies (low and high efficiency buildings, ZEB[1], historic buildings etc.) depending on the region, the areas (urban/rural), the population density and the economic quintiles. Furthermore, old buildings can be retrofitted to a point where their efficiency match the efficiency of new buildings. So, it is essential to have a dynamic and detailed description of the building stock. This analytical representation of the stock and the insulation process and its application (and depth) provides also an opportunity for exploring different socio-economic and climate policy scenarios (towards the decarbonization of the residential sector).

This model simulates the investment decisions of the actors based on the relative cost of improving the energy efficiency of building shells. The buildings shell improvement (or renovation) can take place in two chronological periods a building, firstly during the dwelling construction (considering only the extra costs of this appliance), and secondly when/if a building gets renovated, as insulation can be added to its shell. The actors' decision on insulation investments is based on a multinomial logit equation which compares the relative costs of the insulation levels and allocates the market shares of the different options. The insulation options are categorized into 6 general groups, each being progressively more efficient (less heat transmittance) and more expensive. Through this decision model investments in new and retrofitted buildings are estimated and through them changes in the buildings stock quality are projected. The necessary steps are briefly described below:

a) Formation of the different energy-efficiency classes.

In this model 6 different insulation paths are considered. The paths from 1 to 6 increase in insulation depth (and cost) with 6th having the most insulation, while the 1st is a "no-insulation" option. When the 1st option is applied in new buildings, minimum energy standards are used, and when applied in the renovation phase the buildings keep the average useful energy intensity they had at this point in time (no extra insulation). The model distinguishes between 4 building types and assumes that they consist the whole global building stock. So, the 6 insulation levels for a building are estimated using the U-Values of the surfaces (walls, roof, floor and windows) and the dimensions of the 4 prototype dwellings (their main characteristics are presented in Table 1). Additionally, an annual adjustment in U-values of each insulation level is made to simulate an autonomous energy efficiency improvement (AEEI) in the insulation measures.
Then, using the prototype building characteristics and the adjusted U-values, the heat loss coefficient of buildings is calculated and from it, its useful energy intensity:

$$Q_{new,renovated} = \sum (UValue_{surface} * Surface)$$

$$UE\_intensity_{new,renovated} = Q_{new,renovated} * Conv\_factor$$

Equation 3 & 4. Where:
- *New,renov:* suffix indicating the two cases, new buildings and renovated buildings
- *Q: Heat loss coefficient (W/K/m^{2}floorspace)*
- *U_Value:* Thermal transmittance *(W/K/m^{2}surface)*
- *Surface:* Surfaces where insulation is placed (*m^2)*
- *Conv_factor: Convesrion factor = 86.4 – factor that converts W/K/m^2 to kJ/HDD/m^2*
- *UE_intensity$_{new/renovated}$:* Useful energy intensity of new/renovated building

Table 1. *Characteristics of 4 prototype houses describing the 4 different building types simulated in the sub-model (detached, semi-detached, apartments and high-rise).*

	Floors	Height per floor (m)	Windows	Further assumptions
Detached	2	3.3	20% of external walls	cubic
Semi-Detached	2	3.3	20% of external walls	cubic, 3 in a row formation (→2/3 of total walls are external)
Apartments	3	3.3	20% of external walls	cubic, in formation of 4-big cube shape (→1/2 of total walls are external)
High-Rise	8	3.3	20% of external walls	cubic, in formation of 4-big cube shape (→1/2 of total walls are external)

b) Determine the renovation costs and the total heating costs for each energy-efficiency building.

First, the investment costs for the different building "intensity-classes" are determined. These are expected to lower with the passing of years, due to the learning curve effect, as cumulative production increases (Blok, 2009). The progress ratio (PR) used for the learning effect should be between 0.7 and 0.95 (the value used changed between different socio-economic pathways, see section 4). So the cost per level is calculated similarly to the loss coefficient.

$$Investment\ Cost_{new,renovated} = \sum (Cost\_surface_{new,renovated} * Surface)$$

Equation 5. Where:

- *Cost_Surface:* Cost of insulation per surface *($\$_{2010}/m^2_{surface}$)*
- *Investment Cost$_{new/renovated}$: Total cost of the investment (insulation) ($\$_{2010}/m^2_{floorspace}$)*

Note: For insulation level 1, investment cost is zero, as the minimum required insulation (or no insulation) is applied.

The investment costs calculated are annualized through an annuity factor. As mentioned before, the discount rate used in this annuity factor is calculated inside the TIMER model (Daioglou, 2010). The lifetime of the investment is generally assumed to be 30 years, but in renovations it depends on the remaining lifetime of the building (as the remaining lifetime of the renovated building can be less than 30 years).

$$Investment\ Cost\ Annual_{new/renovated} = Investment\ Cost_{new/renovated} * crf$$

Equation 6. Where:

- *crf:* capital recovery factor (=1/annuity factor). $crf = DiscountRate/1 - (1 + DiscountRate)^{-LT}$
  - (LT – investments lifetime, 30 years or less depending of buildings remaining lifetime)
- *Investment Cost Annual $_{new/renovated}$: Annualized total costs of the investment (insulation) ($2010/$m^2$floorspace)*

Finally, the fuel costs are added and thus the relative costs required across different "intensity-classes" are estimated. Fuel cost are important in the allocation process, since the higher the insulation level, the investment increases but this is followed by less heating demand (less fuels).

c) Allocation of the Market shares for each "intensity-class" building.

This is based on a multinomial logit function which allocates market shares for different renovation depths based on their relative costs. This function is used throughout the TIMER model to determine investment decisions in different energy demand sectors.

$$MS_{new/renovated} = \frac{e^{-\lambda * RelativeCost_j}}{\sum_i e^{-\lambda * RelativeCost_i}}$$

Equation 7. Where:

- $MS_{new/renovated}$: The market shares of different intensity-classes
- *λ:* the logit parameter indicating the price elastic of substitution (equal to 2 in IMAGE-TIMER for the residential sector investments).

Finally using the market share for new and renovated buildings, the different "intensity-classes" groups are formed for each year. For the new buildings the market share is multiplied by the total amount of new buildings, and for renovations the respective market share is multiplied with the "suitable for renovation" number of floorspace. The last comprises of buildings older than 30 years old (to ensure that the insulation applied in the construction has been fully utilized (insulation lifetime is assumed to be 30 years).

$$NewBuild_i = Total\ New\ Buildings * MS_{new}$$

$$Renovated\ Build_i = Suitable\ Buildings * MS_{renovated}$$

Equation 8 & 9. Where:

- *i:* suffix indicating the level of insulation (intensity class)
- $New\ Build_i$: New buildings per level of insulation (m^2)
- $Renovated\ Build_i$: Renovated buildings per level of insulation (m^2)

d) Estimation of the building stock's (average) useful energy intensity

At this phase, the average energy intensity of the building stock is calculated. This is a necessary step to estimate its final energy consumption for heating. First, the average energy intensity of new and renovated buildings each year is estimated using the market shares of "intensity classes" and the suitable for insulation buildings (phase 3):

$$\boldsymbol{UEint(t)_{Building\ Stock}} = \frac{\sum_{1971}^{t}(UEint_{BS\_0} + UEint(t)_{NewBuild} - UEint(t)_{AbandBuild} - UEint(t)_{DecomBuild} + UEint(t)_{RenovatedBuild})}{Building\ Stock(t)}$$

Equation 10. Where:

- *$UEint(t)_{BS\_0}$: The building stock in year 1970 multiplied by its useful energy intensity (considers the stock prior to the model's timeframe) (kJ/HDD)*
- *$UEint(t)_{NewBuild}$: The amount of new buildings in year t multiplied by their useful energy intensity (kJ/HDD)*
- *$UEint(t)_{AbandBuild}$: The amount of new abandoned in year t multiplied by their useful energy intensity (kJ/HDD)*
- *$UEint(t)_{DecomBuild}$: The amount of decommissioned buildings in year t multiplied by their useful energy intensity (kJ/HDD)*
- *annual amount of decommissioned buildings until the year of the run (kJ/HDD)*
- *$UEint(t)_{RenovBuild}$: The amount of renovated buildings in year t multiplied by the difference of their new useful energy intensity to their prior useful energy intensity (the prior weighted intensity is subtracted and then the new is added) (kJ/HDD)*
- *$UEint(t)_{BuildingStock}$: The average useful energy intensity of the building stock in year t (kJ/HDD/m^2)*

The useful energy intensity of the building stock is the ultimate result of the renovation model (in combination to the Building-Stock model). Using this outcome, the final heating and cooling demand of the building stock is calculated in REMG. Equation 11 shows a simplified version of this calculations follows (the exact methodology which incorporates elements of fuel poverty and inability of certain households to meet their heating/cooling demand due to economic constraints can be found in Daioglou et al. (2010)).

$$\boldsymbol{HeatDemand(t)_{Building\ Stock}} = UEint(t)_{Building\ Stock} * HDD(t) * Building\ Stock$$
$$\boldsymbol{CoolingDemand(t)_{Building\ Stock}} = UEint(t)_{Building\ Stock} * CDD(t) * Building\ Stock$$

Equation 11. Where:

- *$Heating/CoolingDemand(t)_{BuildingStock}$: Is the total heating/cooling demand of the building stock in year t (EJ/PJ for global and regional results respectively)*
- *HDD:* The heating degree days in year t
- *CDD:* The cooling degree days in year t

3.4. Socio-economic pathways.

In this thesis possible future developments are examined, and for that purpose SSP1, SSP2 and SSP3 are utilized. SSP and RPC scenarios are introduced below to provide insight on the report's methodology choices and results.

The Shared Socio-economic Pathways (SSPs) represent different possible trajectories for human development using internally consistent sets of qualitative and quantitative projections (Van Vuuren et al. 2016; Van Vuuren 2017). They are differentiated across their socio-economic challenges to mitigation and adaptation to climate change. So, by using different assumptions on forces like population growth, economic growth, consumption, behavioural change, production patterns and technology developments different future development are projected. SSP1 describe a green growth strategy, SSP2 a more middle-of-the-road development pattern and SSP3 further fragmentation between regions. Finally, there is also SSP4 which assumes an increase in inequality across and within regions and SSP5 which revolves around a fossil-fuel based economic development (Van Vuuren et al. 2016). The SSPs scenarios consist of a set of baselines where climate change impacts, new climate policies and climate mitigation policies (beyond those in effect today) are not included. As population and economic growth form key determinants of further changes in energy and land-use, their projected development according to SSP1, SSP2, SSP3, SSP4 and SSP5 is illustrated below. In the thesis, only SSP1, SSP2 and SSP3 are utilised (the rest are presented just for comparison).

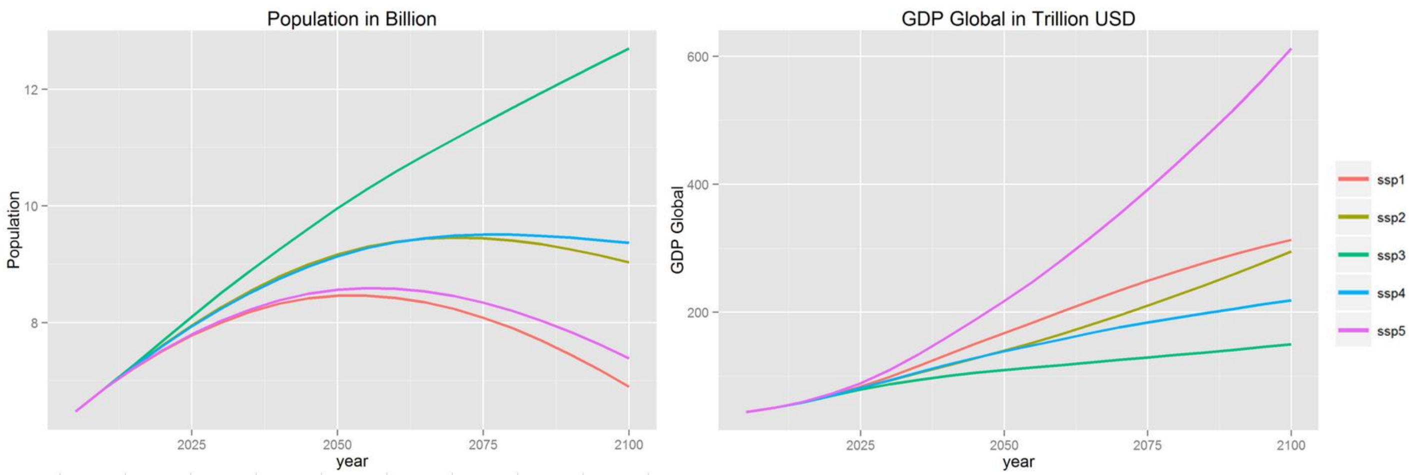

Figure 5. *Global population and economic development for SSP1, SSP2, SSP3, SSP4 and SSP5 (Van Vuuren et al. 2016).*

The Representative Concentration Pathways (RPCs) is a set of pathways developed as a basis for long-term and near-term modeling experiments (Van Vuuren et al. 2016). They have a range of radiative forcing values from 2.6 to 8.5 W/m^2 projected for the year 2100. Each RCP is named after its radiative forcing target level (estimated for 2100) leading to literature-representative group of four, RCP2.6, RCP4.5, RCP6 and RCP8.5. So RCP2.6 pathway leads to a very low forcing level (consistent with approximately 2°C global mean temperature increases by 2100), RCP4.5 and RCP6 to a medium stabilization scenario and RCP8.5 to a high emission scenario (for details see Appendix III, **Figure AP.1.).** For a better understanding of the RCPs the different projected GHG emissions under each scenario are presented in **Figure 6.**

In this thesis, RCPs pathways will not be utilised since the developed scenarios will only be products of SSPs, but the RCP2.6 radiative forcing target level will be part/goal of the scenarios (see section 4.2).

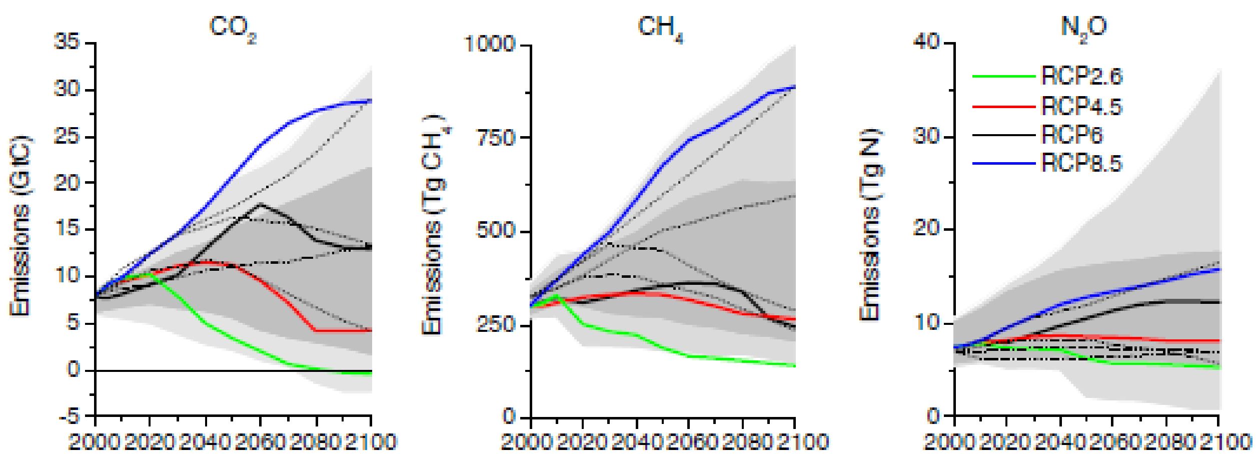

Figure 6. *Emissions of main greenhouse gases across the RCPs. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature. The dotted lines indicate four of the SRES marker scenarios. Note that the literature values are obviously not harmonized (Van Vuuren et al. 2016).*

4. Methodology

This section describes the methodological steps that are taken to meet the main research objective. First, the research design is briefly elaborated upon (section 4.1). The data collection and the scenario analysis are treated, illustrating three phases, each created to answer the sub-questions of section 3. Last, the quality of this research is discussed (4.3). The methodological steps that are followed and the linkages between them, are illustrated in the figure below.

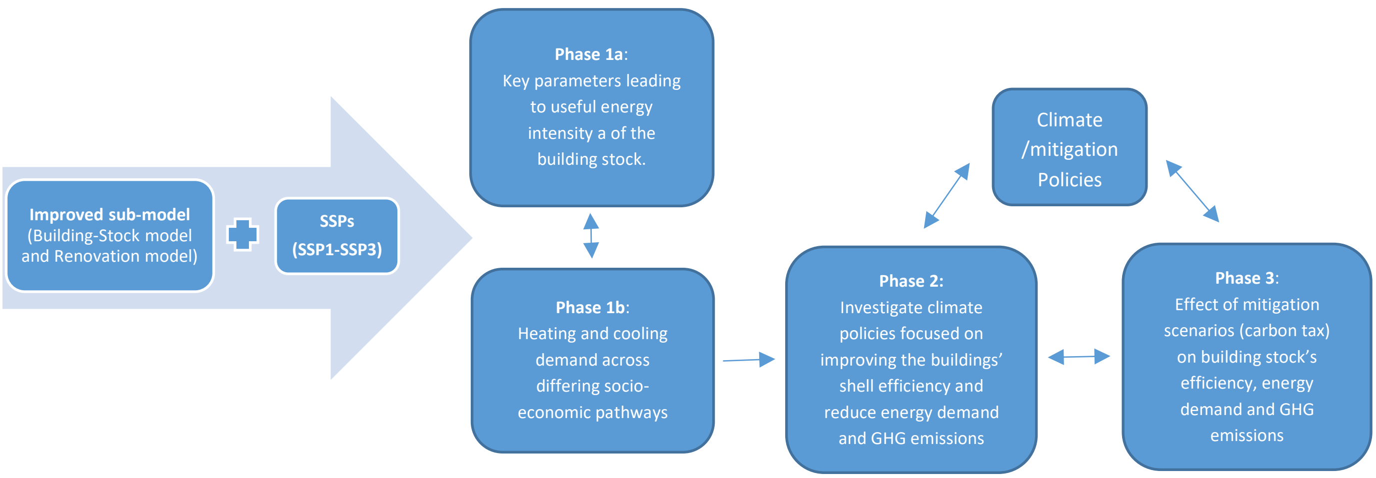

Figure 7. *Methodological steps taken to answer the research question.*

4.1. Research design

This thesis contains both qualitative and quantitative research. The qualitative research mostly focuses on gathering insights on methodologies concerning the development and analysis of scenarios, which is the first step in developing own pathways/scenarios. Quantitative research is essential through all the process. First, model input data are needed to finalize/improve the renovation decision model and afterwards other parameters will be needed for the scenario analysis that follows (section 4.2). All steps are categorized in the different phases that also relate to the sub-questions.

4.2. Data collection and analysis

Phase 1: Key parameters leading to the residential buildings stock's useful energy intensity, energy

In the first phase the improved (with an explicit representation of building efficiency improvement) TIMER model is used to project energy efficiency improvements of the residential building stock until 2100. By utilising the sub-model (combination of the Building-Stock and the Renovation model), the global average useful energy intensity of residential buildings is simulated. Afterwards utilizing further capabilities of the TIMER (and specifically REMG), the heating and cooling demand and the corresponding heating and cooling CO_2 emissions are projected. The methodology behind these calculations is briefly explained in section 2.3 (and analytically presented in my internship report).

The outcomes of this simulations should be able to successfully represent all three possible pathways examined in this research (SSP1, SSP2 and SSP3). To achieve this diversity in possible future developments certain key parameters are altered in a way that they realistically represent the storyline the pathways describe. Some of these parameters are inputs (exogenous parameters) to the renovation model and together with the suitable adjustments on them, are presented in **Table 2.** Other parameters and drivers altered under the different pathways (SSPs), like population growth, projected floorspace, GPD development and discount rates (for the different regions) are also counted in the projections calculations made by TIMER to produce suitable/robust results. Examples of these parameters can be found in Appendix II. For additional information van Vuuren's paper is proposed (Van Vuuren et al. 2016).

Table2. *Model assumptions of key parameters for SSP1, SSP2 and SSP3.*

	SSP1	SSP2	SSP3
AEEI of insulation levels (1 - 6)	fast (1.5%)	medium (0.75%)	slow (0.4%)
Experience index b (learning effect due to implementation)	strong (-0.515)	medium (-0.2)	low (-0.074)
Insulation/investment Lifetime (possibility reinvest)	reduced (20 years)	original (30 years)	original (30 years)
"Green" cost factor (for first insulation level)	strong preference (20 $\$_{2010}$/GJ)	weak preference (9 $\$_{2010}$/GJ)	no preference (0 $\$_{2010}$/GJ)

Table 2 demonstrates the input parameters of the renovation model that were adjusted under the different SSPs, to better fit in their storyline. As mentioned in Section 2.4, SSP1 describes a green growth strategy, SSP2 a more middle-of-the-road development pattern and SSP3 further fragmentation between regions. Considering this general frame of the three pathways, the exogenous parameters are polarized between SSP1 and SSP3, while for SSP2 an intermediate value is chosen. So, for autonomous energy efficiency improvement and for the experience index (b) used in the learning mechanisms inside the sub-model calculations, the theoretical extremes (Blok, 2009) are used for SSP1 and SSP3 (enhanced technological improvement and learning for SSP1), and for SSP2 intermediate middle value are used (usual progress ratio (PR) is between 0.7 and 0.95, , which correspondos to b values between -0.074 and -0.515

(since b = log_2PR) (since b = log_2PR)). Furhtermore, in SSP1 an actor can reinvest in insulation after 20 years, while in the other SSPs possible reinvestments are possible after the original investment's lifetime (30 years). The last parameter, green cost factor is a premium factor (or a penalty) used in the calculation of the investment cost, and it is added in insulation level 1. So, this factor makes the no-insulation level a relatively more expensive. The last two parameters are used to simulate a "green" preference of the actors towards higher levels of buildings efficiency, implying a more informed and environmental friendly society SSP1 than in SSP2 future development (in SSP3 there is no prefference towards a greener solution).

Finally, a comparison of the "improved" REMG with the older version of the model (the version that did not dynamically simulate the buildings efficiency improvement, but instead used it as an exogenous parameter), is beneficial at this phase. For this purpose, the useful energy intensity of the SSP2 pathway under both versions is inspected.

Phase 2: Investigate climate policies focused on improving the residential buildings' shell efficiency resulting in reduction of heating/cooling demand and GHG emissions.

The several pathways in the previous phase result into 3 different baselines, each projecting different final heating and cooling demands and heating and cooling emissions of the residential sector. Based on the paper by van Vuuren et al. (2016), the energy mitigation probably won't be enough to reach the RCP2.6 target (2 degrees scenario) and additional measures must be examined. There are several ways to mitigate the emissions of the residential sector. One option is to influence the demand side through different climate policies outlined below. In this phase policies that can potentially increase the insulation appliance in buildings and thus decrease the heating and cooling demand and corresponding emissions is examined.

First, multiple subsidies on the investment (insulation) capital costs are inspected. In principle, a subsidy lowers the price of the insulation appliance making investments more desirable increasing the buildings energy efficiency and thus lowering the demand and emissions. The subsidy policy measures will be implemented separately, across all SSPs and in various depths (increasing subsidies from 20% to 40% and 60%) starting from 2020 and maintaining them until 2100. The changes on useful energy intensities under each subsidy are initially examined and then the effect on the energy demand and on GHG emissions is compared to the baseline (the initial projection, where no policy is applied).

Then "cost-effectiveness" of each subsidy (under each socio-economic pathway) is estimated. The cost-effectiveness (or effectiveness) of subsidies is defined as the kg CO_2 abated per $ and can be calculated as the ratio of total CO_2 abated (residential heating and cooling emissions) due to the subsidy, to the total subsidy expenses:

$$Effectiveness_i = \frac{\sum_{t=2020}^{i}(kgCO_{2subsidy} - kgCO_{2baseline})}{\sum_{t=2020}^{i} Total\ Investments * Subsidy(\%)}$$

Equation 12. Where:

- i= suffix indicating the year of the run (2020 – 2100).

- Subsidy (%) = 20%, 40% or 60%
- subsidy and baseline: suffixes that refer to the corresponding scenarios

Afterwards, a minimum energy efficiency standards policy will be applied. Efficiency standards in insulation are already (indirectly) assumed in the model, as the U-Values used for calculation are already under the European minimum standard regulation. Combinations of these values, with the buildings' surfaces, consist the six insulation levels used in the model. These insulation levels improve each year (their useful energy intensity decreases) simulating that way the technological development. So, indirectly a decrease in minimum standards (corresponding to the level 1 insulation) is implied. However, the minimum energy efficiency standards policy sets a stricter, greener path were some insulation levels are prohibited. In particular, from 2020 to 2029 insulation level 1 is excluded as one option at the decision point, while from 2030 to 2100 additionally insulation level 2 is excluded as an option (shifting the minimum standards from level 1 to level 2 and 3 respectively). Implementing these minimum energy efficiency standards can potentially improve the buildings quality, lowering their useful energy intensity and thus decreasing heating and cooling demand (and heating and cooling emissions).

Phase 3: Effect of mitigation scenarios on the building's stock efficiency (insulation appliance) and on the sector's heating/cooling demand.

The climate policies so far are specifically developed to directly affect the appliance of insulation in an effort to improve the buildings stock shell efficiency, and ultimately lower the emissions. So, they focuse on the residential's sector buildings, only indirectly affecting outside systems and elements (fuel prices, technology deployment etc.). In contrast, the mitigation scenario is affecting the whole model, designed in a way to reduce all emissions (not only residential sector's) at the degree needed so the climate change to be mitigated. To do so, a "tailored" carbon tax is inserted ($\$_{2010}$ / tonne CO_2), externally created via an optimization technique, using the constraint that the final emission concentration level is consistent with radiative forcing targets of RCP2.6. The amount of the carbon tax that will be applied each year is taken from prior calculations of IMAGE (van Vuuren et al., 2016), and details on its calculation are out of the scope of this research. Carbon tax curves have been developed for SSP1 and SSP2 (**Figure 8**) but not for SSP3, as for the last the constraint could not be satisfied (the socioeconomic pathway could not meet the emission constraint under any carbon tax, i.e. the scenario is infeasible). In other words, in this thesis, mitigation scenarios (carbon tax) will be applied only for SSP1 and SSP2 and their effect on insulation investment, as well as, on the residential's sector heating/cooling demand will be examined.

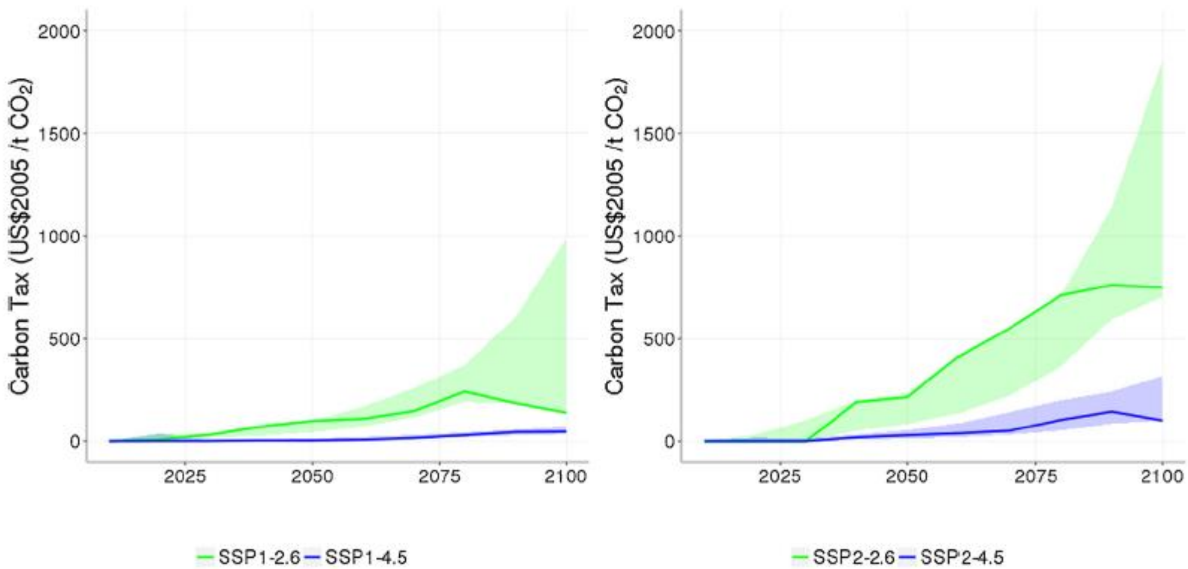

Figure 8. *Carbon price for reaching radiative forcing targets of 4.5 and 2.6 W/m2 for SSP1 (left) and SSP2 (right). The area indicates the range of results of the other IAMs for the specific SSP (Van Vuuren et al. 2016).*

In principle, the carbon tax increases the cost of the fuels used for heating and cooling in buildings. This increase is lower as the insulation level increases (the higher the level the less energy consumption), meaning that high levels of insulation become relatively more attractive, and in principle this could drive a shift towards an improved building stock efficiency.

To have a wholistic view in the mitigation scenario, its cost-effectiveness is also examined. Similarly to the subsidy sector, the effectiveness is defined as the kg CO_2 abated per $ spent toward this goal.

$$Effectiveness_i = \frac{\sum_{t=2020}^{i}(kgCO_{2mitigation} - kgCO_{2baseline})}{\sum_{t=2020}^{i} Total\ Emission\ Costs}$$

At the final stage, all policy scenarios are compared with the mitigation scenario, examining which one of them provides an easier transaction towards the RCP2.6 goal and a decarbonised future. All scenarios are gathered in **Table 3**.

Table 3. *Scenarios that will be created and examined in regards SSPs and climate policies. 20 in total.*

SCENARIOS	SSP1	SSP2	SSP3
Baseline	√	√	√
Mitigation Policy	√	√	χ
Minimum-Standard Policy	√	√	√
Subsidies (20%)	√	√	√
Subsidies (40%)	√	√	√
Subsidies (60%)	√	√	√

Note: The absence of a mitigation policy for SSP3 is due to inability of reaching the RCP2.6 goal using a carbon tax.

4.3. Research quality

To improve the research quality, reliability, replication, internal validity and external validity are important aspects to elaborate upon (Bryman, 2015). To achieve the highest possible quality in this report, these aspects have been taken into account. Reliability indicates the consistency of the measurements that are taken in a research and the replication of a research entails the accuracy on which another researcher can execute the same research (Bryman, 2015). These concepts were achieved through a clear presentation of the different concepts used in this thesis and a transparent linkage between the steps taken, ensuring that way a clear and similar (to the paper) interpretation. An effort to increase the reliability of the data used, is through triangulation, with data obtained from different sources. The internal validity describes whether the results obtained comply with the given theory (Bryman, 2015). This is partially ensured by comparing the outcome of the model with historic data collected from literature review (this only applies for the development until 2015), and with current trends (for example, growth in energy demand). Furthermore, the use of supervision, increases the internal validity. Finally, the external validity describes whether the results obtained in the research can be generalised outside the context of the research (Bryman, 2015). This research is about the energy consumption of the building sector under different future projections and pathways for mitigation. By nature, there is a high external validity, as the mitigation proposals can be applied globally. On the other hand, since global data are not always available, some assumptions are made through the report, and thus, the external validity decreases. An effort to make these assumptions as realistic as possible, is made and the reasoning is justified.

Ama thes mporeis kiolas na grapseis: As this work builds upon a given model and its software code, reliability and replication of the code changes are ensured through version management of different model revision. To achieve this extensive use of the version management software of PBL was made.

5. Results

In this section the results under different socio-economic pathways and after the application of the proposed policies are examined. Only global results for the scenarios (baselines, policy scenarios and mitigation scenarios) are presented here, while additional regional results for Wester Europe, USA and China are demonstrated in Appendix IV.

5.1. Baselines - Global

The emissions, heating and cooling demand as well as the effect of renovation varies under the different projected baselines (SSPs). These variations are driven by GPD and population which in turn affect several mechanisms and calculations that simulate and project different future outcomes concerning floor space and insulation/retrofitting adoption. This research is scoped around retrofitting of buildings and their effects on heating/cooling demand and consequent emissions, and so, only mechanisms directly affecting the results are examined.

The adoption of retrofitting and the depth of insulation directly affect the energy (heating and cooling) demand by improving the buildings envelope quality. **Figure 9** shows the differences in the amount of new and renovated buildings, and at the same time the depth of insulation measures (level of insulation) for each year until 2100 for the three examined socio-economc pathways.

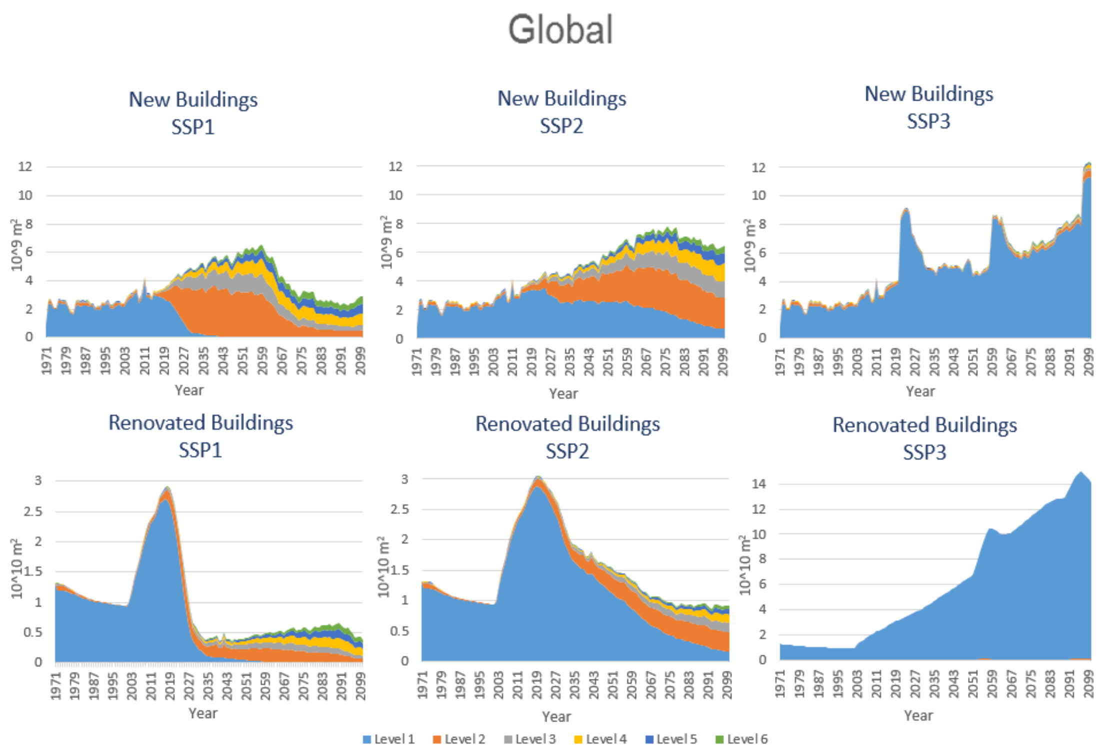

Figure 9. *Global insulation levels of residential building stock across all baselines. Top Row: Insulation levels for newly constructed buildings. Bottom Row: Insulation levels of renovated existing building.*
Reminder: *Level 1 insulation in the renovation process is a no-renovation option (the buildigs remain as their at their prior level). So, level 1 "renovated" buildings each year, are the buildings that are suitable for renovation but no action is taken.*

As expected in SSP1 the total amount of new buildings is smaller (lower population growth resulted in lower projected floor space) and the buildings' quality is better, with an increased amount of buildings shifting to insulation levels higher than 1. On the other hand, in SSP3 increased population growth leads to higher amount of new buildings, while one them no major application of insulation is noticed, as almost all buildings constist of the lowest possible level of insulation (level 1). SSP2 describes a middle-road situation, where there is still an increased need of new buildings (compared to SSP1), but the majority of them gets highly insulated as the model progress towards 2100.

The variance in buildings insulation levels between the SSPs are originates from the different investments in insulation and lead to different renovation rates and ultimately into different useful energy intensities of the building stock.

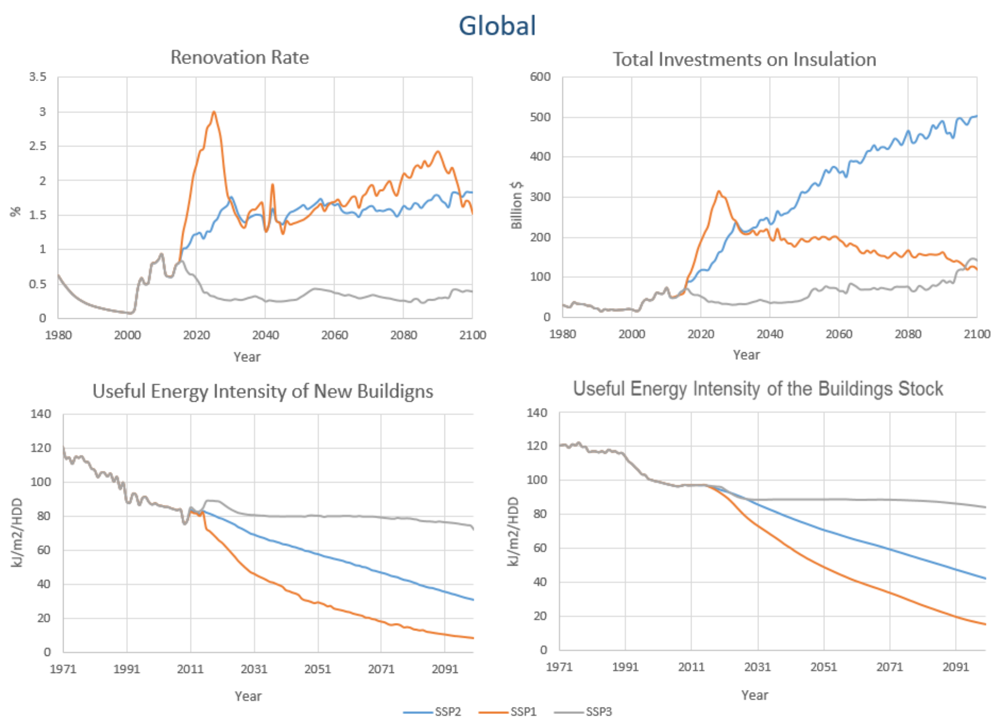

Figure 10. *Global key parameters for the formation of heating and cooling demand across all baselines. Top Left: renovation rates of buildings (renovations compared to the total building stock). Top Right: Total investments on insulation (initial investments for insulation applied in new constructions and in renovations). Bottom Left: The useful energy intensity of the newly constructed buildings. Bottom Right: The average useful energy intensity of all buildings.*

The resultant useful energy intensity represents the average quality (insulation depth) of the building stock, as it is defined as the heat transmittance in kJ (between the inside of a building and its environment) per m^2 of floorspace and per HDD (the better insulated a building the lower the heat transmittance between its interior and tis environment). The total investments (**Figure 10**) are interconnected with the useful energy intensity as by definition the higher the investments the more the insulation appliance and the better the quality of the building stock. However just comparing investments between different SSPs would result into false conclusions. **Figure 10** shows that SSP1 has the lowest useful energy intensity but not the highest investments. This "inconsistency" is caused by two basic differences between the SSPs, 1st being the different amount of insulated buildings (new and renovated) due to different floorspace projections and 2nd the different costs per renovation (e.g. level 5 insulation in year 2050 under SSP1 costs less than a level 5 insulation in the same year under SSP2 (or SSP3), due to the learning mechanism (see also section 4.2.). A relatively better indicator is the renovation rates, which demonstrates the share of renovated m^2 compared to the total stock. Still renovation rates only depict the insulations during renovations and not during the construction of buildings, so it does not provide the whole picture. As expected, SSP1 has the lowest useful energy intensity, followed by SSP2 and lastly by SSP3. The fast improvement of buildings in SSP1 is due to the high projected renovation rated between 2017 and 2030. This is connected to the theoretical potential of old, less-efficient buildings that is discussed in the introduction (renovation is a key target for achieving mitigation goals).

Useful energy intensity directly affects the heating and cooling demand of regions and through them the greenhouse gas emissions associated with heating and cooling. Heating and cooling demands and the effect of insulation are presented on **Figure 11** accompanied by the respective CO_2 emissions. To examine the effect of insulation the indicators (demands and emissions) are compared to a "counterfactual" no-insulation indicator. The last illustrates what the demands and emissions would have been if no improved insulation was applied (i.e. all buildings were of insulation level 1).

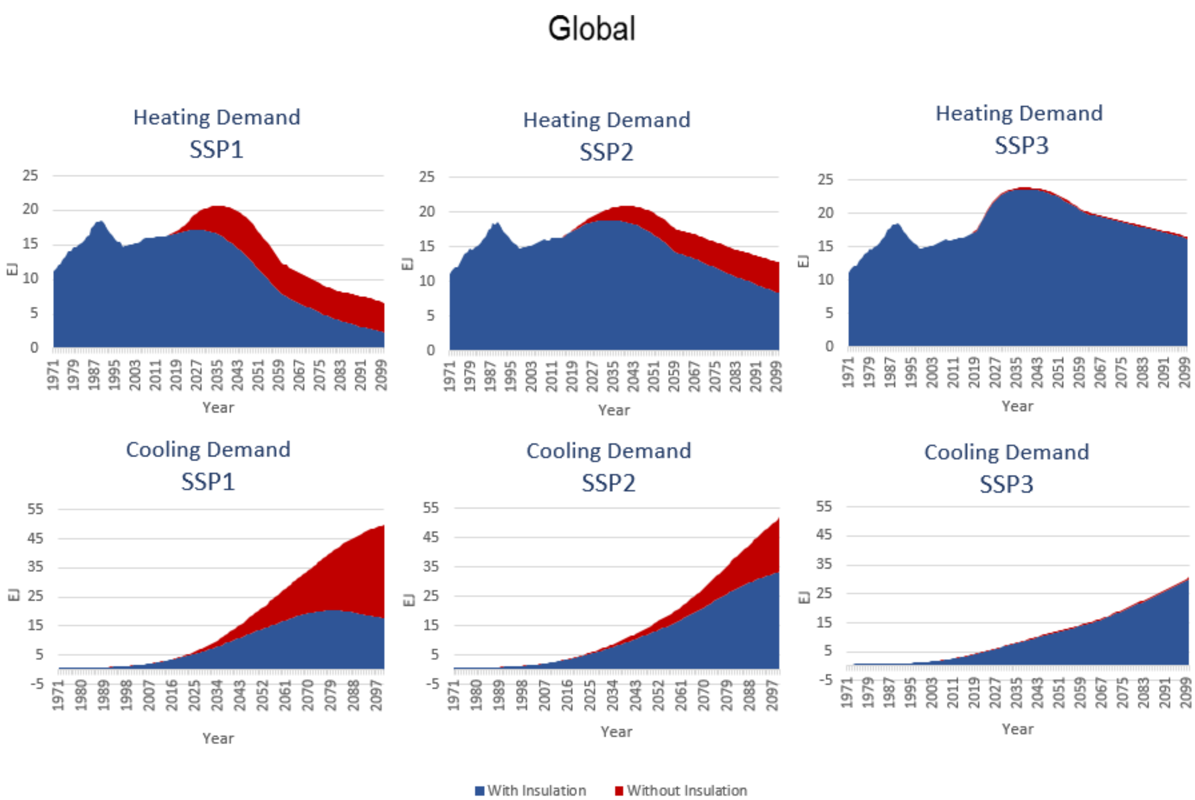

Figure 11. *The effect of insulation on heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand before and after the use of additional insulation on buildings (insulation greater than the current level 1). Bottom Row: Cooling demand before and after the use of additional insulation on buildings.*

Figure 11 demonstrates that the appliance of insulation can have a huge effect on heating and cooling demand for SSP1 and SSP2, reducing the demands by 64% and 35% respectively in 2100, while it is almost absent in SSP3 (around 2% reduction). This is correlated to the buildings' insulation levels (**Figure 9)**, as in SSP3 almost the whole building stock comprises of buildings of level 1 (the basic insulation). Heating demand follows a straightforward pathway for the 3 SSPs, before and after the appliance of insulation, with SSP1 having the lowest values and SSP3 the highest. This outcome is produced due to various factors,

like the population, the amount of floorspace, the baseline effects of climate change temperature (endogenously calculated in TIMER based on cumulative emissions affecting the HDD indicator) and the quality of the buildings (shown by the average useful energy intensity). On the other hand, the cooling demands under the SSPs portray a less direct path. Values before insulation appliance show that SSP1 ends up with a similar demand to SSP2 in 2100, but it reaches higher levels sooner (e.g. in 2050 SSP1 cooling demand is approximately 30% higher than SSP2's demand and around 50% higher than SSP3's), and both SSPs have a higher cooling demand than SSP3. This relatively low cooling demand for SSP3 is counter to its larger population growth and higher environmental temperature (higher CDD). Since SSP3 depicts a future with relatively low GDP per capita (with respect to the other baselines) across all regions, households are poorer and fewer cooling appliances are installed, while SSP1's increased GDP is followed by more cooling appliances and thus an increased cooling demand. This relation (the dependance to the installation of cooling applications) follows the cooling demands even after the with-insulation results. This is the reason SSP3's cooling demand in 2100, even though not (significantly) reduced by insulation measures, is the same as SSP2's demand. SSP1's cooling demand now get its place at the lower end since the insulation improvements there were the most intense.
Finally, the CO_2 emissions are presented in **Figure 12**.

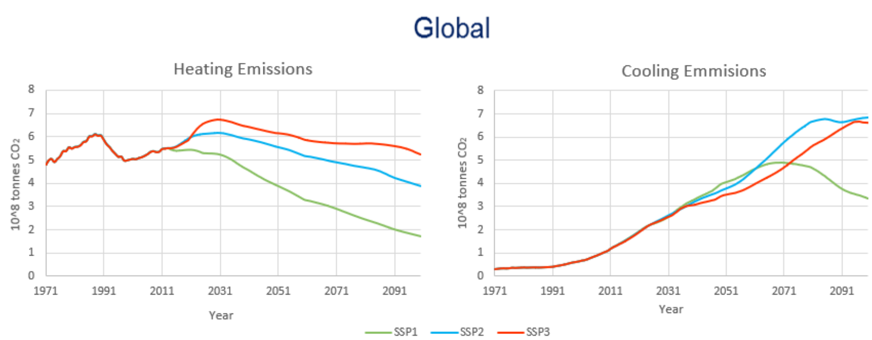

Figure 12. *Global CO_2 emissions caused by heating and cooling the residential building sector under SSP1, SP2 and SSP3.*

The heating emissions for the SSPs follow a similar pathway to heating demands, with SSP1 emissions being lower during the whole period (2015-2100) followed by SSP2 and lastly by SSP3. On the other hand, the cooling emissions follow a more complicated path. This is related to the cooling appliances mentioned above (cooling demands are not in the same order of magnitude as the useful energy intensities). In 2100 SSP2 ends with the higher cooling emissions closely followed by SSP3, while SSP1 manage to significantly reduce its CO_2 emissions through insulation. In general, the demands and emissions are connected but do not follow the exact same patterns as other factors come into play, such as the different sources of energy and the different heating and cooling appliances efficiency. For that purpose, a graph of the fuel shares used for heating follows to provide insight on the "cleanness" of the fuels. For cooling, only electricity is used (in the scope of the model fans air coolers and air condition units are used), so the emissions are indirect caused at the site of power production (power plants etc.) or are non-existing in the case of renewable energy production (LCA emissions are not included in the results).

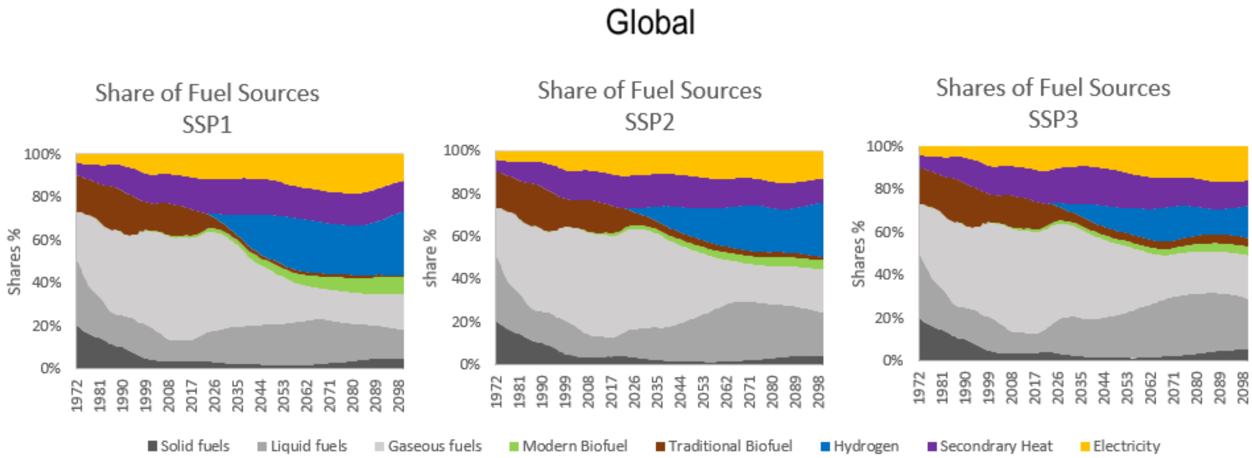

Figure 13. *Share of fuel sources used for heating the Global residential's sector buildings. Solid fuels: coal (incl. cokes and other commercial solid fuels), liquid fuel: oil as Light Liquid Fuel (LLF) or Heavy Liquid Fuel (HLF), Gaseous fuel: natural gas and gaseous fuel from biomass (BGF), coal etc.*

Figure 13 (and **Table AP.2** in Appendix III) presents the type of fuels used for heating the residential buildings and the share of the types through the years (1972-2100). The types used are solid fuel (e.g. coal), liquid fuels (e.g. oil), gaseous fuels (e.g. natural gas), modern biofuels (e.g. sugarcanes), traditional biomass (e.g. wood), hydrogen, secondary heat (e.g. central district heating) and electricity. From the above fuels, solid fuels, liquid fuels and traditional biomass as considered the less "clean" (in terms of GHG emissions), while modern biofuel and secondary heat sources are the "clean" options. Gaseous fuels are somewhere in the middle (less emission than solid and liquid fuels). Hydrogen and electricity could go both ways, depending on the way they are produced (could be sustainable hydrogen and electricity production from wind turbines, hydropower, PV panels, or they could be produced by the combustion of fossil fuels). **Figure 13** suggests that in all baselines there is a shift toward cleaner provision of heating fuels, as solid, liquid and gaseous fuel and traditional biomass usage drops, while replaced by the "clean" options. However, the shift in SSP1 is earlier and more intense, followed by SSP2 and lastly by SSP3. This outcome is consistent with the concept of the different SSPs, with SSP1 being the greener, SSP3 the fragmented, and SSP2 the middle-of-the-road socio-economic pathway.

As a final step, a comparison of the improved sub-model with the older of REMG is shown in **Table 4**. The values presented for REMG are used as exogenous parameters for the model, while the respective sub-model values are endogenously dynamically simulated. Furthermore, the REMG intensity values until 2015 are "calibrated" to historic data, as they are calculated via calibrated final energy demand, floor space and HDD. On the other hand, the sub-model values are all estimated inside the model (the calibration is applied afterwards at the estimated heating and cooling demands), so differences between them are expected even for historic values. The sub-model intensities are slightly decreasing each year, as the model assumes a continues (small) technological development and reduction in costs. Contrary, the REMG intensities slightly decrease in the beginning, then increase again around 2020 and start to decrease again at 2050. According to literature (Atanasiu et al., 2013; Harrison et al., 2017) a continuous reduction of the useful energy intensity is more realistic, as the trends show fluctuations in heating demands, but the intensities are shown to improve each year (see also section 1).

The differences between the sub-model and the older version of REMG are not limited at SSP2, but are present in all pathways and for all results (heating/cooling demands etc.).

Table 4. *Scenarios that will be created and examined in regards SSPs and climate policies. 20 in total.*

SSP2		
Year	REMG	Sub-model
1981	124.6	117.4
1990	120.1	116.5
1995	105.7	106.1
2000	104.0	99.7
2005	104.4	97.4
2010	84.4	97.3
2020	95.1	94.5
2030	101.3	86.9
2040	101.4	78.7
2050	100.3	71.5
2060	97.0	65.4
2070	93.0	59.9
2080	88.5	53.9
2090	85.0	48.0
2100	81.5	42.1

5.2. Subsidies - Global

The amount of insulation installations depends on its cost and its effectiveness (as by increasing the effectiveness, the fuel expenses drop). The total relative cost can be influenced by several factors, as the investment cost, the capital recovery factor (discount rates), the fuel costs and the learning effect (indirectly). In this section a reduction on the cost of insulation through a subsidy policy is examined. By making the investment cheaper for the users there is an increase on the insulation appliance, and thus a reduction on energy demand and emissions, is expected. Toward this outcome subsidies of 20%, 40% and 60% on the initial investments are applied and their effect is examined. These subsidies are individually applied from 2020 onwards.

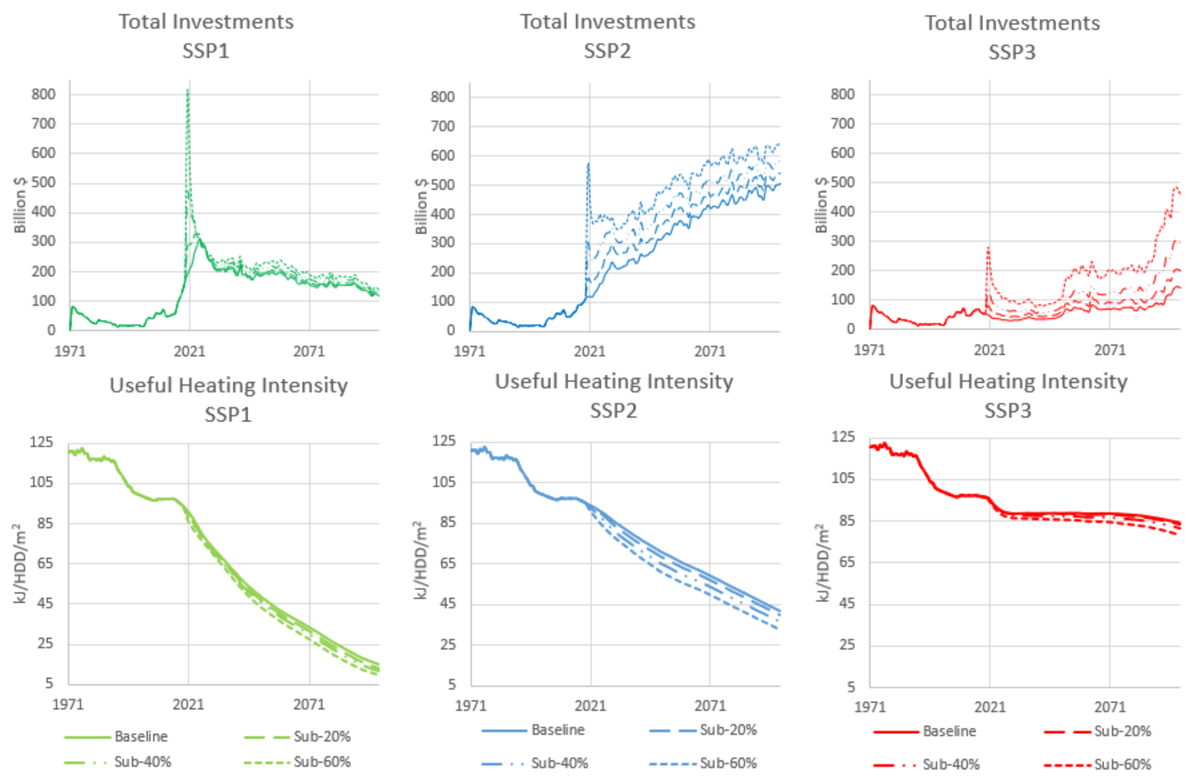

Figure 14. *Total investments on insulation and the useful energy intensity of the buildings stock after the introduction of a subsidy measure. The subsidies applied are 20%, 40% and 60% of the initial investment. Top Row: Total investments across the SSPs for the baselines and the subsidy scenarios. Bottom Row: Average useful energy intensity across the SSPs for the baselines and the subsidy scenarios.*

Figure 14 verifies the increase of the total investments (more installations and higher levels of insulation used in the buildings) and the decrease in the corresponding useful energy intensity (improvement of the building stock). As already mentioned in the previous chapter, the total investments are related to the amount of insulation application and the cost of each appliance, and these two factors differ among the SSPs. So, SSP1 investments being lower compared to SSP2 and SSP3 does not imply that less investments took place, but that their cost was less (mainly due to the optimum learning rate factor applied to this baseline). Also, from the graph we can see that the change in the total investments in SSP1 is less than SSP2 and SSP3, as the investments were already relatively cheap and decreasing their cost was not as effective as in the other cases. Especially in SSP3, were the insulation levels have the highest costs and the GDP projection is the lowest, the subsidy measure is a major decisive factor for installations. This will be clearer in the further analysis of the demands and emissions. Another interesting observation concerns the connection between total investments and useful energy intensity improvement which varies across the SSPs (the reduction is not relatively the same). The reason behind that is the different parameters assumed in **Table 2** (especially technology developments and learning rates). Due to these differences the six insulation levels' are different across the pathways, with SSP1 levels being the most effective (highest thermal resistance) and the cheapest, followed by SSP2 and then by SSP3 (e.g. level 1 in SSP1 is has lower useful energy intensity and costs than respective level 1 in SSP2, which in turn is more effective and cheaper than the same level in SSP3). So, the increase in total investments does not necessary result into the same decrease in the useful energy intensity (for details see **Table 5**). In this case it happens the SSP with the most investments (SSP2) to be the one with the highest progress (but the one does not entail the other).

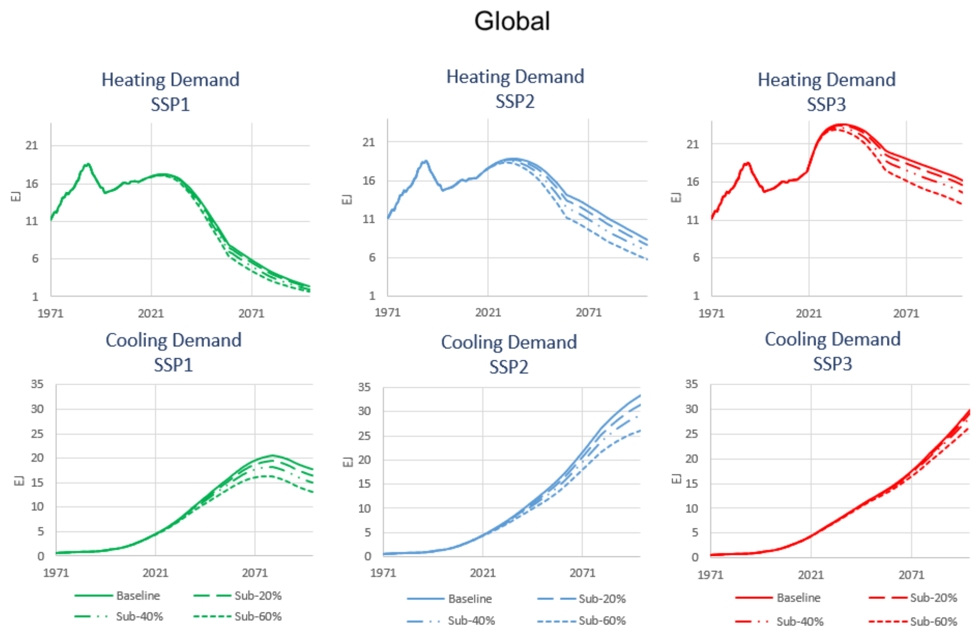

Figure 15. *The effect of subsidies on heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand before and after the implementation of subsidies. Bottom Row: Cooling demand before and after the implementation of subsidies.*

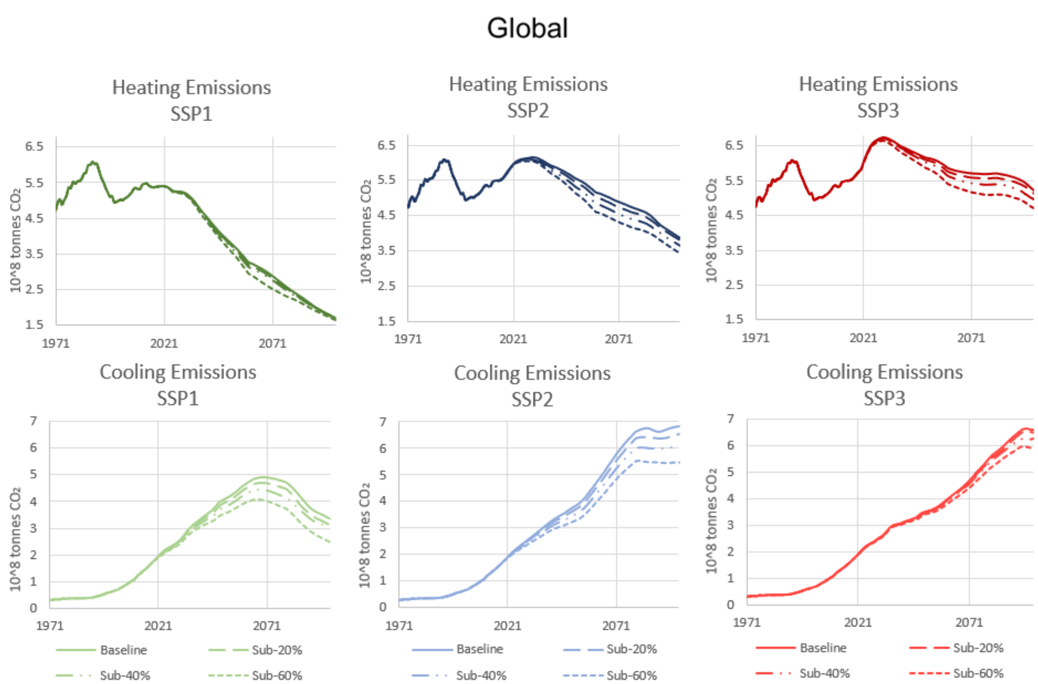

Figure 16. *The effect of subsidies emissions caused by heating and cooling of the residential sector under SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the implementation of subsidies. Bottom Row: Cooling emissions before and after the implementation of subsidies.*

As can be seen in **Figures 15 & 16** in all occasions higher subsidies lead to lower energy demands and CO_2 emissions, but the overall effect varies across the baselines. For example, we can see that in SSP1 further investing in insulation does not significantly change the outcome, as people have already heavily invested even in the absence of the subsidy (baseline). For a better understanding of the effect of the subsidy policy and the relation between useful energy intensity with heating and cooling of the buildings a table follows illustrating all improvements for chosen years (after 2020, since this is the starting point of the subsidy).

Table 5. *The reduction of demands and emissions across the SSPs under the three subsidy policies.*

	Mitigation (%)	Subsidy 20%			Subsidy 40%			Subsidy 60%		
		2050	2075	2100	2050	2075	2100	2050	2075	2100
SSP1	Useful Energy Intensity	2%	5%	9%	6%	11%	20%	10%	19%	35%
	Heating Demand	3%	7%	9%	6%	15%	19%	11%	27%	31%
	Cooling Demand	3%	5%	7%	7%	11%	16%	13%	19%	26%
	Heating Emissions	1%	2%	2%	3%	4%	1%	6%	12%	5%
	Cooling Emissions	3%	5%	7%	7%	11%	10%	13%	20%	26%
SSP2	Useful Energy Intensity	4%	4%	6%	8%	10%	13%	14%	17%	22%
	Heating Demand	3%	7%	8%	7%	15%	19%	13%	26%	32%
	Cooling Demand	3%	4%	5%	8%	10%	12%	14%	17%	22%
	Heating Emissions	2%	3%	2%	4%	7%	5%	7%	12%	11%
	Cooling Emissions	3%	4%	4%	8%	10%	11%	14%	17%	20%
SSP3	Useful Energy Intensity	1%	1%	1%	2%	2%	3%	4%	5%	7%
	Heating Demand	1%	3%	4%	4%	8%	10%	8%	16%	20%
	Cooling Demand	0%	1%	2%	1%	3%	5%	3%	6%	11%
	Heating Emissions	1%	2%	2%	2%	5%	5%	5%	10%	10%
	Cooling Emissions	1%	1%	1%	2%	3%	5%	3%	7%	10%

There are many conclusions that can be extracted from **Table 5**. First, as the policy shifts to higher percentages of subsidies, more insulation is applied (more actors insulate their buildings and in higher insulation level) and this results to higher reductions on energy demands and emission. The decrease in useful energy intensities result into a similar reduction in heating and cooling demand, but a strictly linear dependence is absent (e.g. in SSP2 the reduction in useful intensity in 2100 is 22%, but the heating demand reduction goes up to 32%). This behaviour shows that improvement on the quality of buildings can stimulate dynamic mechanisms resulting into a more than proportionally decrease in the demands[1]. Furthermore, reduction in demands and reduction in emissions is even further apart. Heating emission abatement is always significantly lower than the corresponding heating demand abatement, suggesting that there is a limiting factor in place. This factor is the choice of fuels (fuel mix), as by lowering the

[1] One of these mechanisms originate from the difference in the way the global useful energy intensity and demand are calculated. Global useful energy intensity is the weighted average of the intensities of the 26 regions (with the weighting factor being the floor space), while global demand comes from the summation of the demands of these regions. Thus, since the floor space of a region is disproportional to its demand, there can be differences in the absolute changes on these parameters.

demand, fewer fuel is needed, and that leads to a new balance were "less clean" options become relatively more attractive[2]. Ultimately the net reduction is lower than it would be if the same fuel quality was used. On the other hand, cooling results seem more interconnected (almost same reductions for demands and emissions) indicating that the cooling fuel (electricity) is more inelastic (electricity production in subsidy scenario follows a similar pattern than the baseline scenario).

Higher subsidies lead to higher energy and emission mitigations, but the "effectiveness" is not proportional to the expenses, meaning that after a point the marginal CO_2 reduction is insignificant. For that reason, the cost-effectiveness of the subsidies applied under the policies is examined (see **Equation 12**).

Table 6. *The effectiveness of subsidies across the SSPs. It is defined as the ratio of CO_2 mitigation to the expenses used for this purpose (in this case in the form of subsidies).*

	Effectiveness of subsidies (kg CO_2 /$)								
	SSP1			SSP2			SSP3		
Year	**Sub-20%**	**Sub-40%**	**Sub-60%**	**Sub-20%**	**Sub-40%**	**Sub-60%**	**Sub-20%**	**Sub-40%**	**Sub-60%**
2025	0.028	0.031	0.036	0.073	0.056	0.041	0.051	0.048	0.045
2050	0.218	0.235	0.256	0.152	0.139	0.137	0.338	0.302	0.285
2075	0.478	0.508	0.547	0.220	0.215	0.238	0.525	0.496	0.450
2100	0.679	0.739	0.806	0.246	0.224	0.260	0.617	0.615	0.528

Note: *The year in the table signifies the cumulative mitigation until this specific year.*

Table 6 show the effectiveness for the various SSPs. In SSP1 more subsidies result into an increase in effectiveness while in SSP3 the opposite phenomenon is present. SSP2 presents both behaviours depending the year examined. This variation in the effect of subsidies denotes how sensitive the system is. Another important observation is that the subsidy policy is the most effective in SSP1, which is the pathway where CO_2 mitigation is relatively less essential (since the CO_2 emissions in SSP1 are the lowest). This is due to the insulation levels of SSP1 being cheaper and more effective (with the lowest useful energy intensity), so, by increasing the amount investments (billion $), a lot high-quality insulation appliances take place. However, subsidy policy is still beneficial for SSP3, where the reduction on costs is important to stimulate the insulation investments (without a policy measure insulations levels higher than 2 are almost non-existent).

To have a wholistic view of the subsidies as a policy measure, the free riding effect across the baselines should also be examined. The free riding effect is a negative aspect revolving subsidies, in which part of the subsidies are given to actors that would invest anyway in the "technology" (Blok, 2009). In our case, investments present without the existence of subsidies are projected by the baselines. So, the free riding effect can be estimated as the 20% of the total investments in the baselines and is the part of subsidies expensed to no purpose ("misused" investments).

[2] In REMG there is a fuel decision model (similar to the renovation model discussed in this report) which allocates the types of fuels based in their relative costs (combines the fuel prices and the technologies used).

Table 7. *The cumulative free riding effect across the SSPs in trillion $$_{2010}$ and the ratio of this effect/amount to the total investments.*

	trillion $	Subsidy 20%			Subsidy 40%			Subsidy 60%		
		2050	**2075**	**2100**	**2050**	**2075**	**2100**	**2050**	**2075**	**2100**
SSP1	Free Riding	1.36	2.25	2.99	2.73	4.50	5.98	4.09	6.75	8.96
	Ratio	19%	19%	19%	35%	35%	35%	47%	48%	49%
SSP2	Free Riding	1.37	3.30	5.65	2.75	6.60	11.30	4.12	9.90	16.95
	Ratio (%)	16%	17%	18%	27%	30%	32%	33%	38%	41%
SSP3	Free Riding	0.24	0.60	1.07	0.48	1.19	2.14	0.72	1.79	3.20
	Ratio (%)	15%	15%	15%	22%	22%	21%	21%	22%	21%

Note: *The year in the table signifies the cumulative free riding effect until this specific year.*

SSP1 demonstrates the highest relative free riding effect (ratio), as it is the pathway with the most insulation applications even without a subsidy. The ratios presented (free riding effect to total amount of investments),19%, 35% and 48% are close to the actual respective subsidies applied, constituting this measure impractical (since most of the expenses are misspent). The situation for SSP2 is a bit improved with the ratios being a bit lower, but still a large amount of invest money (on subsidies) is worn through the free riding effect. On the other hand, SSP3 results seem promising. Especially for the 60% subsidy scenario only one third of the subsidies is misspent to free riders (50% of the total subsidy is misused in 40%-subsidy scenario, while the 20%-subsidy scenario is similarly impractical as the rest (for SSP1 and SSP2)).

Summing up, from the scope of cost-effectiveness subsidy policy in SSP1 is the most promising, but it is followed by high rates of free riding. The high effectiveness is caused by the high-quality buildings that accompany SSP1 (optimum technological learning) and the low prices (optimum learning). On the other hand, the effectiveness of subsidy policy in SSP2 is the lowest (from 2050 onward) followed by a high rate of free riders. Subsidies increase the total investments (billion $) only by a small amount, and now each investment is a bit more expensive (less insulation appliance) and less efficient than in SSP1, resulting in a worse efficiency. Finally, SSP3 seems to be the most suitable pathway to benefit from a subsidy. In its baseline (no policy) almost no investments take place, so the subsidy policy resulted in a significant increase in insulation investments, with a relatively low riding effect (for 40% and 60% subsidy scenarios), and at the same time significant CO_2 reduction (high effectiveness).

Overall the subsidy policy successfully decreases the residential buildings' heating and cooling demand but is not well fitted to reduce the corresponding emissions (with the bottleneck being the heating emissions as shown in **Table 5.**). In the end of the "Results" section it will be compared to the other policy examined in this report.

5.3. Standard Policy - Global

The way the model estimates the insulation appliance there is already an internal minimum standard policy, as there is a minimum in the insulation level than can be chosen. So, in other words, first level insulation represents the minimum standards required in insulation in a specific year. As the model advances towards 2100 these minimum standards increase (decrease in useful energy intensity of the insulation levels) due to technology improvements, resulting in improved new and renovated buildings. By further reinforcing these minimum standards through a standard policy, the residential sectors' energy demand and emissions can be significantly reduced. In this section a standards policy excluding level 1 insulation from 2020 onward and level 2 insulation form 2030 onwards is examined. Naturally the standards policy possibilities are not limited to this example, but this simplified simulation provides an insight on the mechanism and its benefits.

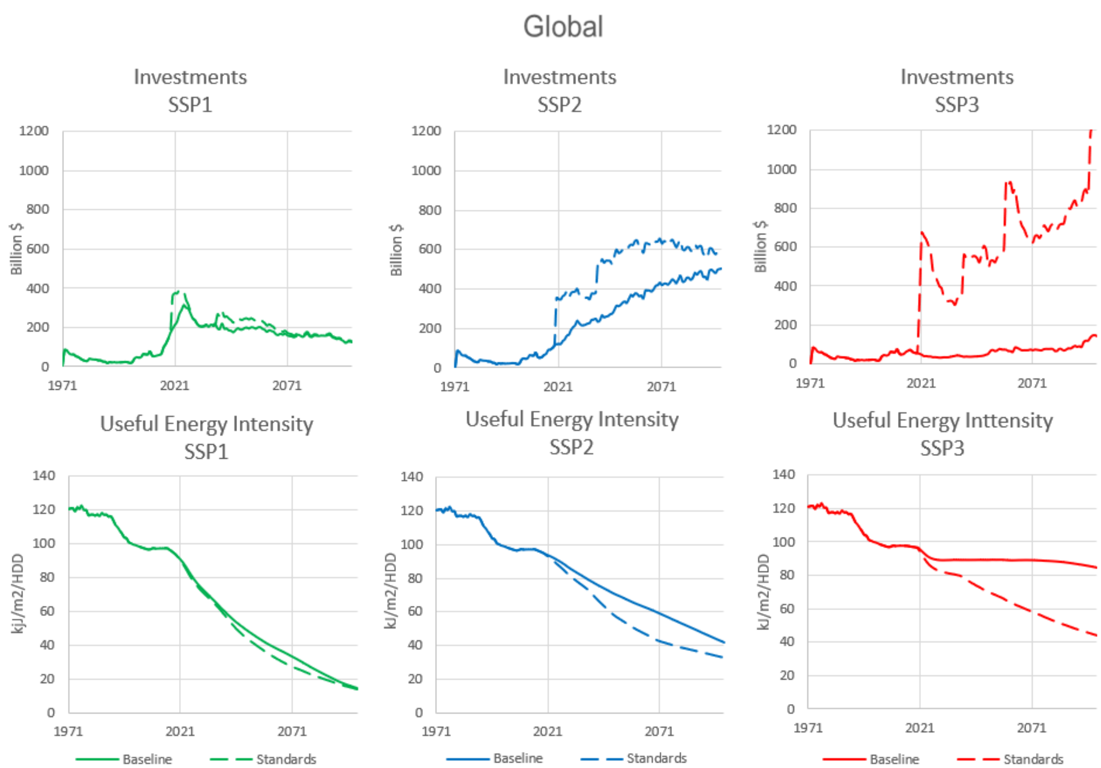

Figure 17. Total investments on insulation and the useful energy intensity of the buildings stock after the introduction of the standards policy measure. The standards policy excludes the level 1 insulation option from 2020 inwards and the level 2 insulation option from 2030 onwards. Top Row: Investments across the SSPs for the baselines and the standards scenario. Bottom Row: Average useful energy intensity across the SSPs for the baselines and the standards scenarios.

Figure 17 demonstrates the effect of the standards policy on the insulation investments and thus in the useful energy intensity. Excluding the level 1 and later the level 2 option has the least effect in SSP1, since the majority of the projected investments are of higher levels. In the opposite end, forcing level 3 or higher insulation in SSP3 has the maximum effect, since this is the pathway with the worse buildings' quality (almost all buildings consist of level 1 and 2 insulation). A huge increase in investments in SSP3 leads to a significant decrease in the useful energy intensity of the building stock. A lower but still significant increase in investments is observed in SSP2 followed by an increase in the building stock quality. More information about these improvements can be found in the pivot table in the end of this section.

The realized declines in useful energy intensities result into a decrease in energy demands and the corresponding heating and cooling emissions. The new developments can be seen in **Figure 18 & 19**.

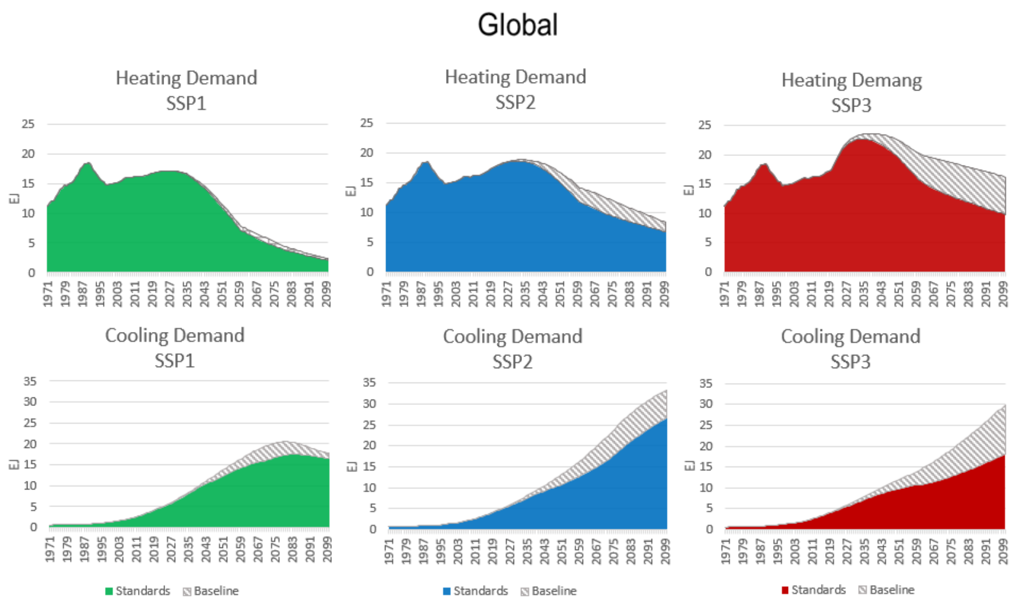

Figure 18. The effect of standards policy on heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand before and after the implementation of the standards policy. Bottom Row: Cooling demand before and after the implementation of the standards policy.

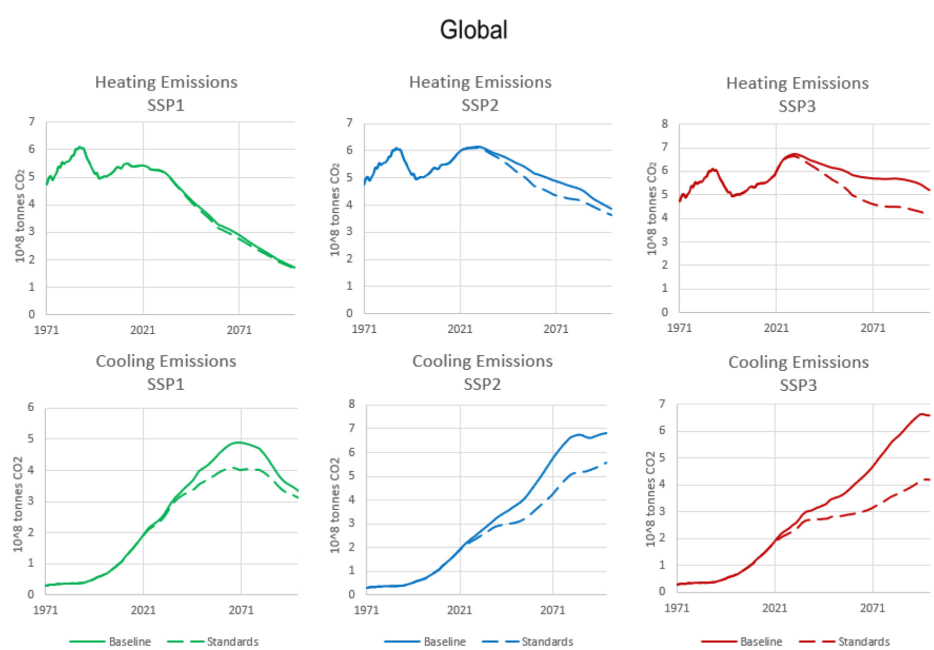

Figure 19. The effect of standards policy on heating and cooling emissions under SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the implementation of the standards policy. Bottom Row: Cooling emissions before and after the implementation of the standards policy.

As anticipated, the heating and cooling demands drop significantly, especially in the SSP3 pathway, followed by a smaller reduction on emissions. For a more precise analysis, **Table 8.** below presents the reduction on demands and emissions in specific years.

Table 8. *The reduction of demands and emissions across the SSPs under the standards policy.*

Mitigation (%)	SSP1			SSP2			SSP3		
	2050	**2075**	**2100**	**2050**	**2075**	**2100**	**2050**	**2075**	**2100**
Useful Energy Intensity	11%	19%	9%	18%	28%	23%	20%	37%	48%
Heating Demand	4%	13%	12%	9%	22%	19%	12%	30%	39%
Cooling Demand	10%	17%	7%	18%	25%	20%	17%	33%	39%
Heating Emissions	2%	4%	2%	6%	11%	6%	9%	20%	21%
Cooling Emissions	11%	16%	7%	19%	25%	18%	19%	34%	36%

As mentioned before, pathways with many 1 & 2 insulation levels are affected the most, so the SSP3 has shows the greatest improvements (followed by SSP2). The relation between the mitigations is similar to the subsidy scenario. Demands and useful energy intensity have a non-linear relation, with the heating demand decrease overcoming the corresponding useful energy intensity in one occasion (SSP1-2100). Heating emissions declines less than the heating demand suggesting that the fuel mix used for heating is again less “clean” than in the baselines (see also section 5.2. where a similar phenomenon is noticed and explained). The cooling demand and emissions are better synced (almost the same) indicating that the electricity is produced in a similar way than in the baselines (small differences in the mitigations, so small differences in the cleanness of the fuels).

Comparing the reductions of **Table 8.** to the corresponding pathways of **Table 5.** can be seen that for SSP1 the results of the standards policy are similar to the SSP1 20%-subsidy and 40%-subsidy. On the other hand, SSP2 results are similar to the more expensive SSP2 60%-subsidy scenario. Finally, for SSP3 the mitigations are greater than any subsidy scenario examined in this report. However, forcing expenses in households could create societal issues like increase in poverty (this is further discussed in section 6).

5.4. Mitigation Scenario - Global

In the Subsidy section the relative cost of insulation levels, and thus the amount of insulation installation during the model timeframe, was manipulated through subsidies on the capital investment. Another way to affect the relative cost of the investment is through the fuel costs and specifically through a carbon tax. By inserting a carbon tax, the lower an insulation level is the more it is affected (since the low the level the higher the useful demand and the higher the need in fuels). So, by altering the relatives costs in favour to the high insulation levels, a shift towards a decrease in useful energy intensities is expected (improved building stock quality). In turn those improvements result in a decrease of heating and cooling demand and emissions.

The policy measures so far (subsidies and energy standards) were developed to directly affect the appliance of insulation and thus improve the buildings stock, so they focused on the residential's sector buildings. In contrast, the mitigation scenario is tailored in a way to mitigate the climate change. The creation of a carbon tax suitable for climate change mitigation, as well as the details behind its creation (It is developed through an optimization technique), is out of the scope of this research. Only the effect of the mitigation scenario on the residential sectors' useful energy intensity, demands and emissions is examined, while general references to mechanisms behind specific behaviours are briefly discussed when it is necessary. It should be reminded that in SSP3 no carbon tax could achieve a decarbonized future, so this sections only refer to SSP1 and SSP2.

The applied carbon tax in the mitigation scenario is presented in **Figure 20** coupled with the total emission costs caused by this taxation. The carbon tax and emission costs in SSP2 are higher since more emissions must be abated in order to mitigate the climate change in this pathway.

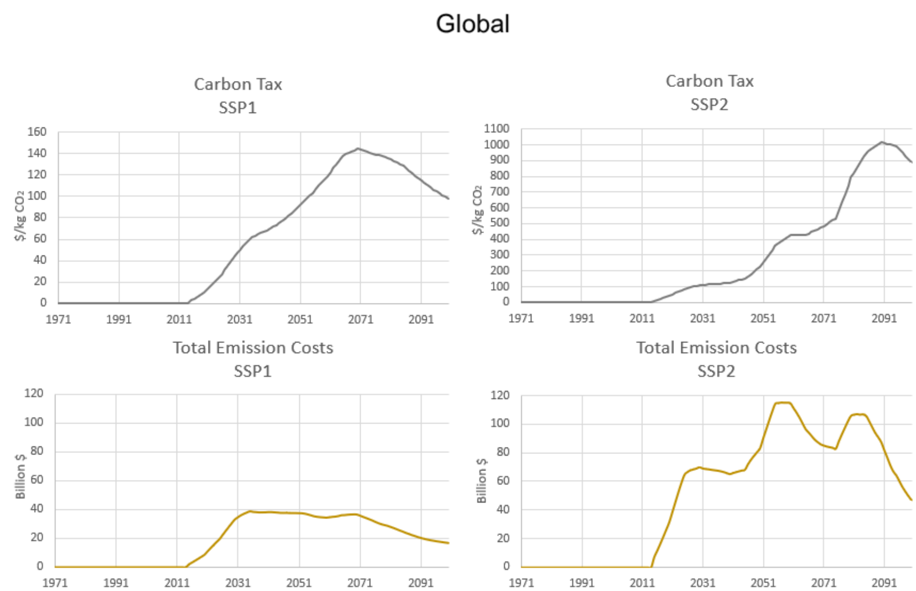

Figure 20. The implemented carbon tax and the total emission tax costs under SSP1, SP2 and SSP3. Top Row: The annual carbon tax ($/kg CO_2) starting from 2015 onwards (note different scales). Bottom Row: The total emissions costs (Carbon Tax X CO_2 Emissions) derived from heating and cooling the residential sector buildings.

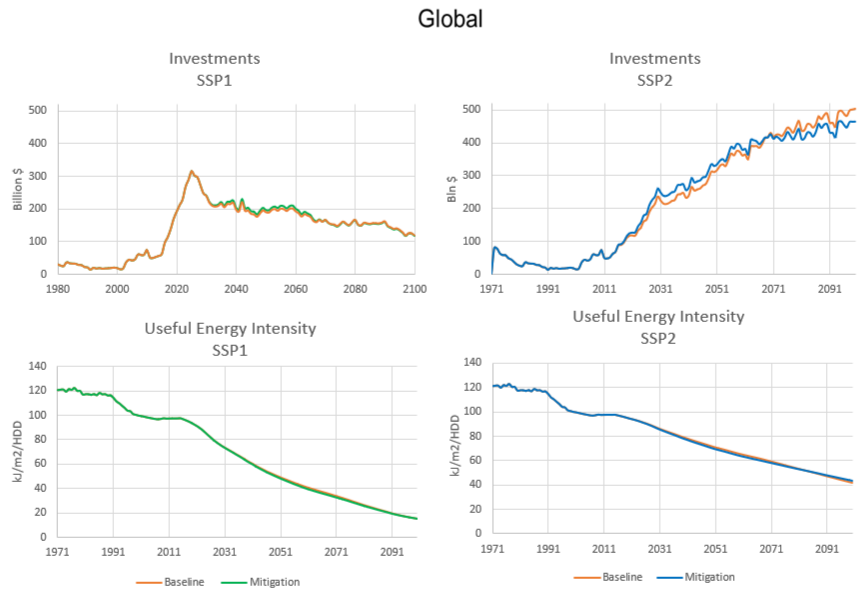

Figure 21. Total investments on insulation and the useful energy intensity of the buildings stock after the introduction of a carbon tax. The mitigation policy inserts a dynamic carbon tax in CO_2 emissions affecting the structure of the whole system. Top Row: Investments across the SSPs for the baselines and the mitigation scenario. Bottom Row: Average useful energy intensity across the SSPs for the baselines and the mitigation scenario.

Figure 21 shows that the insertion of a carbon tax slightly increases the investments in insulation until around 2070, while after that the investments under SSP1 remain the same as the baseline's, while under SSP2 they slightly drop. Moreover, the useful energy intensities only present negligible differences in both SSPs. Further examination of the results revealed that the carbon tax only changed the fuel prices by a small margin, which in combination with the relatively high investment costs of the insulation (with respect to fuel cost, see equations 6 and 7) , resulted in a total relative cost of the investment approximately the same. In other words, the outcome of this scenario was a building stock of the same quality as in the baselines.

A similar useful energy intensity does not entail similar heating/cooling demands and emissions, since now the system inputs and balance differ. This is described by **Figure 22 & 23** which follow, and illustrate the demands and emissions under the SSPs.

To better understand the results a switch between emissions and demands is best suited. **Figure 23** projects a decrease in heating and cooling emissions across both pathways (an expected outcome since this is the utility of the carbon tax). In an attempt to limit the increase in the costs of fuels (due to the carbon tax), there is a switch towards cleaner fuels, compared to the baseline fuel shares shown in **Figure 13** (the cleaner a fuel, the less tax is applied to it), leading in a decrease in emissions. Furthermore, there was a shift into more efficient (and more expensive) heating and cooling appliances, in an effort to increase the conversion efficiencies and thus decrease the emissions. So, there is a positive mechanism in place, promoting less final energy demand and cleaner fuels. However, **Figure 22** presents a slight increase in heating demand for SSP1 and a significant increase for SSP2. This contradictory outcome is due to the realization of the climate change mitigation. As the projected average temperature of the earth decreases (the increase of temperature is mitigated), HDD increase, ensuing an increase in heating demand (negative mechanism). In combination the positive and negative feedback mechanisms result in a net increase of the heating demand. On the other hand, regarding the cooling demands, there are two positive feedback mechanisms, decrease of average temperature and increase in conversion efficiencies, resulting in a significant demand reduction in both SSPs. The effects described were more intense for the SSP2 pathway, since there the changes were vaster and the mechanisms more drastic.

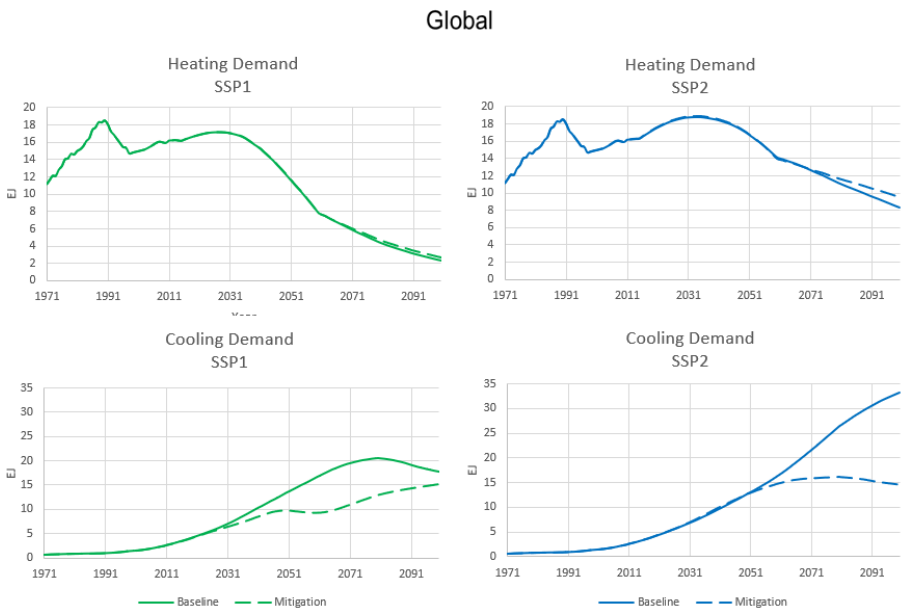

Figure 22. *The effect of the carbon tax (mitigation scenario) on heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand before and after the implementation of the carbon tax. Bottom Row: Cooling demand before and after the implementation of the carbon tax.*

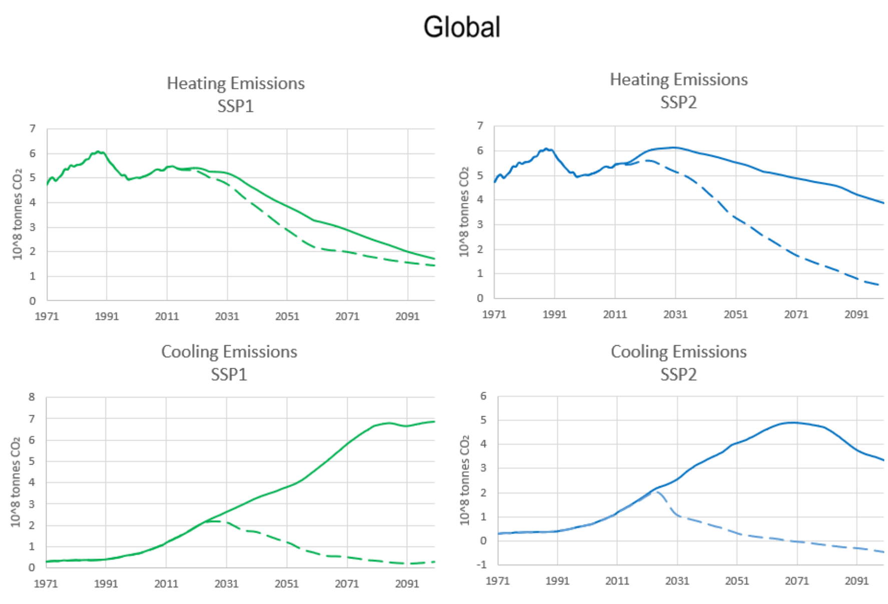

Figure 23. *The effect of the carbon tax (mitigation scenario) on heating and cooling emissions under SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the implementation of the carbon tax. Bottom Row: Cooling emissions before and after the implementation of the carbon tax.*

Table 9. *The reduction of demands and emissions across the SSPs under the mitigation scenario. A negative value denotes an increase.*

Reduction (%)	SSP1			SSP2		
	2050	**2075**	**2100**	**2050**	**2075**	**2100**
Useful Energy Intensity	2%	3%	0%	2%	2%	-4%
Heating Demand	0%	-3%	-12%	0%	-2%	-15%
Cooling Demand	27%	41%	14%	1%	33%	56%
Heating Emissions	24%	29%	16%	40%	68%	86%
Cooling Emissions	66%	93%	96%	91%	100%	100%

Table 9 presents numerically these reductions for specific years. As explained above, the mitigation scenario is not effective in reducing the residential buildings' heating demand (in most cases an increase is observed) while it is quite effective in reducing the cooling demand. The emissions are furher reduced due to the combination of "cleaner" fuels and more efficient technologies. The carbon tax successfully decreases the cooling emissions to (around) zero in both SSPs. Regarding the heating emissions, a significant decrease is viewed in SSP2 (up to 86% in 2100), while this decrease is smaller in SSP1, as the respective emissions are already highly mitigated in the baselines (vast amount of insulation appliance in the baseline of SSP1).

Table 10. The effectiveness of the mitigation scenario and the mitigation costs across the SSPs. Its effectiveness defined as the ratio of CO_2 mitigation to the expenses used for this purpose (in this case in the form of CO_2 taxes). The mitigation costs is the reverse index of the effectiveness and it describes the cost to reduce the CO_2 by one kg.

	Effectiveness (kgCO2/$)		Mitigation Costs ($/kgCO2)	
Year	**SSP2**	**SSP1**	**SSP2**	**SSP1**
2025	1.12	1.15	0.89	0.87
2050	4.49	4.88	0.22	0.21
2075	6.07	9.43	0.16	0.11
2100	7.81	14.21	0.13	0.07

Note: *The year in the table signifies the cumulative effectiveness until this specific year.*

The cost-effectiveness of the mitigation policy is increased as the years progress, despite the decrease in the carbon tax after a point (see **Figure 17**). The reason that the measure becomes progressively more effective is that the improvements of the building stock achieved in a year will continue to influence the demand until the improved buildings decommission (after many years). The carbon tax is more effective for the SSP1 pathway, while it is comparatively more needed in SSP2 (since it is a pathway with originally more emissions. However, **Figure 23** suggests that the final emission levels of the SSPs are similar and that both carbon taxes achieve their "ultimate" goal (set by RCP2.6.), although the process was significantly more expensive for SSP2 (**Figure 17**). Comparing the "effectiveness" of the carbon tax with the "effectiveness" of subsidies it can be concluded that the cumulative improvements in mitigation scenario create an environment where the CO_2 mitigation is relatively cheap for both SSP1 and SSP2. Finally, the mitigation costs index is also included in **Table 10**. Also named as shadow price, it is the reverse of the effectiveness and describe the $ needed for the mitigation of one kg of CO_2.

5.5. Comparison of the Policy Scenarios - Global

In this section all the policy measures above are examined and compared in an attempt to distinguish the most effective one for the mitigation of the residential sector's buildings heating and cooling demand and emissions. The policies examined have unique specifications and different approaches could be used (different carbon tax, different subsidies, increased standards). The comparison present in this report is regarding the specific choices illustrated above and its outcome will refer to only those. Furthermore, there are a lot of uncertainties involved (e.g. future energy prices), so the comparison's outcome reliability is limited, but it will give an insight in the potential of the policies.

First the several demand and emission reductions across the SSPs are gathered in the tables bellow (Mitigation scenario only includes only results for SSP1 and SSP2).

Table 11. *The reduction of demand and emissions under SSP1 for the all scenarios. A negative value denotes an increase in the amount.*

SSP1 Reduction (%)	Heating Demand			Cooling Demand			Heating Emissions			Cooling Emissions		
	2050	2075	2100	2050	2075	2100	2050	2075	2100	2050	2075	2100
Subsidy-20%	3%	7%	9%	3%	5%	7%	1%	2%	2%	3%	5%	7%
Subsidy-40%	6%	15%	19%	7%	11%	16%	3%	4%	1%	7%	11%	10%
Subsidy-60%	11%	27%	31%	13%	19%	26%	6%	12%	5%	13%	20%	26%
Standards	4%	13%	12%	10%	17%	7%	2%	4%	2%	11%	16%	7%
Mitigation	0%	-3%	-12%	27%	41%	14%	24%	29%	16%	66%	93%	96%

Under SSP1, the mitigation scenario (carbon tax) is the most effective in reducing the heating and cooling emissions (16-29% and 66-96% reduction respectively depending the year). It also scores high in the cooling demand category, close to subsidy-60%, but the reduction drops as the model progress towards 2100 (due to already high investment in insulations). However, it performs poorly regarding heating demand, which increase. The subsidies scenarios have diverse results depending the subsidy applied. As expected the higher the subsidy the higher the mitigation of energy demand and emissions (due to more insulation appliances), so for the comparison with other scenarios Subsidy-60% is used. Subsidy-60% is very successful in reducing the heating and cooling demands and cooling emissions by 2100, but not as much successful in lowering the heating emissions. Finally, the standards policy under SSP1 has little effect on all parameters since in this pathway actors have already heavily invested in high insulation levels even without a policy.

Table 12. *The reduction of demand and emissions under SSP2 for the all scenarios. A negative value denotes an increase in the amount.*

SSP2 Reduction (%)	Heating Demand			Cooling Demand			Heating Emissions			Cooling Emissions		
	2050	2075	2100	2050	2075	2100	2050	2075	2100	2050	2075	2100
Subsidy-20%	3%	7%	8%	3%	4%	5%	2%	3%	2%	3%	4%	4%
Subsidy-40%	7%	15%	19%	8%	10%	12%	4%	7%	5%	8%	10%	11%
Subsidy-60%	13%	26%	32%	14%	17%	22%	7%	12%	11%	14%	17%	20%
Standards	9%	22%	19%	18%	25%	20%	6%	11%	6%	19%	25%	18%
Mitigation	0%	-2%	-15%	1%	33%	56%	40%	68%	86%	91%	100%	100%

The mitigation scenario under SSP2 is (again) the most effective in reducing the emissions and the cooling demand but not so effective regarding the heating demand (an increase is observed). The reductions/percentages for subsidy policies are similar to SSP1, achieving relatively large reductions for the demands, but more mediocre emissions abatement. However, there is a significant improvement on the effect of the standards policy (compared to SSP1), but still this measure scores the last between the three in terms of emission abatement.

Table 13. *The reduction of demand and emissions under SSP3 for the all scenarios. A negative value denotes an increase in the amount.*

SSP3 Reduction (%)	Heating Demand			Cooling Demand			Heating Emissions			Cooling Emissions		
	2050	2075	2100	2050	2075	2100	2050	2075	2100	2050	2075	2100
Subsidy-20%	1%	3%	4%	0%	1%	2%	1%	2%	2%	1%	1%	1%
Subsidy-40%	4%	8%	10%	1%	3%	5%	2%	5%	5%	2%	3%	5%
Subsidy-60%	8%	16%	20%	3%	6%	11%	5%	10%	10%	3%	7%	10%
Standards	12%	30%	39%	17%	33%	39%	9%	20%	21%	19%	34%	36%
Mitigation	-	-	-	-	-	-	-	-	-	-	-	-

Lastly, results under SSP3 (only for SSP1 and SSP2) demonstrate a decrease in the effect of the subsidies but an increase on the effect of the standards scenario. The decline on the subsidies effect is due to the lower GPD projected under SSP3 (poorer households and low cost reduction due to learning, so the investments are still very costly). On the other hand, in a pathway where most of the buildings comprise of level 1 and 2 insulation, excluding these levels through minimum standards policy, improved a lot the buildings stock, with the emissions lowered by almost 40% in 2100.

The comparison until now does not take into account the amount of dollars expensed for the demand and emission reduction on the residential sector. For this purpose, the effectiveness of the mitigation scenario and standards scenario follows. An indicator like the effectiveness cannot be used for the standards scenario since no amount of dollars is directly spent. The increase on expenses (increase on total insulation investments) befall to the actors who have to invest into a better building quality compared to the baselines.

Table 14. *The effectiveness of the subsidy policies and mitigation scenario under SSPs.*

Effectiveness (kg CO2/$)	SSP1				SSP2				SSP3			
	2025	2050	2075	2100	2025	2050	2075	2100	2025	2050	2075	2100
Subsidy-20%	0.03	0.22	0.48	0.68	0.07	0.15	0.22	0.25	0.05	0.34	0.53	0.62
Subsidy-40%	0.03	0.23	0.51	0.74	0.06	0.14	0.22	0.22	0.05	0.30	0.50	0.61
Subsidy-60%	0.04	0.26	0.55	0.81	0.04	0.14	0.24	0.26	0.04	0.29	0.45	0.53
Mitigation	1.15	4.88	9.43	14.21	1.12	4.49	6.07	7.81	-	-	-	-

The reduction of demands and emissions showed that the highest results are achieved through the mitigation scenario. From **Table 14.** it also becomes evident that the mitigation scenario is also the most "effective" as it has the highest CO_2 mitigation per dollar. So, overall it seems to be a better policy measure than subsidies. The low effectiveness of subsidies could be justified by the high free reding effect that occur (see also **Table 7**). The standard policy on the other hand becomes highly effective in SSP3, in a pathway that it cannot be compared with the mitigation scenario due to lack of data.

Another useful observation regarding the subsidies is that although a higher subsidy leads to more CO_2 emissions, for SSP3 the highest subsidy (60%) has the lowest effectiveness. So, if a subsidy is decided as a way to countermeasure CO_2 emissions under SSP3, a subsidy of 40% should be preferred and an additional coupled policy (e.g. a standard policy) should be chosen.

Summing up, the carbon tax is the most effective in mitigating the emissions of the residential building sectors. However, depending on the perspective examined the other policies have their unique uses. For example, if alongside the emissions reduction a second target of reducing the demand is set, then the carbon tax is not sufficient (heating demand is stable or increased). Such a target aimed in demand reduction is not unusual and as there is an active effort to reduce the demand side in the energy system. In that case a combination of carbon tax with a second policy could be used for optimum results. According to the model, this second policy would be a (40% or 60%) subsidy under SSP1 future development, and the standard policy under SSP2 or SSP3 future development (in SSP2 the 60% subsidy policy achieves similar results to the standards policy, but it is also accompanied with high free rider effect).

6. Discussion

This section first elaborates on the limitations of this research. In addition general remarks regarding the results and policy implications are presented.

6.1. General Observations

As an overall result, the mitigation scenario is the most effective in reducing the CO_2 emissions while other scenarios are more successful in reducing the energy demands. Another difference between the scenarios is the responsibility of expenses, as in mitigation scenario the actors have to “pay” the transaction in the form of a tax (carbon tax), while in case of subsidies each responsible authority (e.g. government) has to provide the subsidies. In case of the minimum standard scenario the actors might have to pay for an insulation level higher than they normally chose (indirect costs).

All lot of dynamics appeared in the assessment of the results. In SSP1 scenarios (baseline, subsidies and minimum standards) the projected demands and emissions are always lower due to behavioural aspects in line with the pathway, as smaller houses, richer households, and “greener” attitude, and socio-economic aspects, like lower population growth, higher GDP growth, more technology advancement etc. All these characteristics lead to an easier and faster transaction towards the decarbonisation future, with less total expenses. In contrast SSP3 can be characterized by inertia and inability to fully achieve to GHG targets. The positive outcomes, when achieved, where always late and more expensive compared to the other SSPs. SSP2 represents a middle-road development, were mitigation is possible, but still slower and more expensive than SSP1. So, it becomes apparent that society should focus on more holistic solutions than the targeted policies and as soon as it is possible, as policies themselves are going to be more painful and less efficient in a non-sustainable future development.

6.2. Limitations

The conclusions above and the analysis of the results is done inside the framework of the model. In reality the outcome could be vastly different since no model can successfully simulate all physical and societal systems and their interactions. There are many limitations inserted due to the nature of the modelling, the uncertainty of the assumptions used and additionally physical and societal barriers, the majority of which are briefly discussed in this section. The description starts with general modelling limitations and then discuss extra limitations of the specific model used (sub-model).

- The integrated assessment models (IAMs) do not structurally represent many social and political forces that can influence future developments (economy shocks, resource (e.g. oil) crisis, geopolitical stability etc.) (Clarke et al., 2014). The implications of these forces can be modelled through assumptions about, economic growth, resource supplies etc., but it is impossible to predict to timing and scale of such developments.
- IAMs also typically assume fully functioning markets and competitive behaviour, so parameters as monopoly, information asymmetries, transaction costs, limited capital, fragmented market, risk aversion and influencing market powers are not taken into account (or at least not fully represented) (Clarke et al., 2014; Lucon et al., 2014).
- Furthermore, cultural, regional and preference aspects are underrepresented. For example, the choice of fuels for heating and cooling are not always economy based, but tradition, resource availability and pure preference can influence the decision. Same goes for the insulation options. As seen in introduction, the insulation can be applied internally and externally of the surfaces. The external option, which also typically results into a better insulation can be less desirable for the actors due to aesthetics or to reduction of owned space (m^2 internally or externally of the building will be “lost”). Another aesthetic usual option observed in regions is the extended glass surfaces (especially in high-rises), which suffer from heat losses since the windows are typically less efficient than a wall.

- Regarding the policies applied except for the mitigation scenario, as homogenous and simultaneous adoption is assumed globally. This is not a very realistic approach, especially in less developed areas, where lack of awareness, lack of financing (e.g. in case of subsidies) and poor enforcement of regulations (e.g. in case of minimum standards) can significantly stall any progress (assuming that a global decision can be achieved in the first place). Same goes for the mitigation scenario where a unanimous carbon tax is applied in the regions. It could be argued that poorer regions should have less carbon taxation, but on the other hand this could lead to mass transit of industries to the said regions.
- Another bottleneck could be the technological learning. In the model major development in insulation installation was due to the learning mechanism and the AEEI. The model assumed full and transparent technology transfer between regions, when in reality patent protections and slow adoption due to inertia could highly influence the outcome. This is also linked to the perfect communication mechanisms assumed in the model. As soon a "technology" is available, people get informed and are willing to adopt it if it is beneficial. In reality this information and knowledge transfer takes some time and a lack of interest from the side of the actors is also possible. These obstacles could be overturned with good communication and targeted policies (e.g. subsidies).
- Additionally, the is the landlord-tenant barrier, which is not simulated in the model. This relates to the fact that the one carrying out the investment (in our case the owner of a building) may not be the one benefited by them (in our case the reduction of energy consumption). It could be argued that by improving the buildings shell the residents value increases, but the are many market factors related to the change and it is difficult to reproduce in a model (especially a global one).
- Finally, there are some practical limitations concerning the inputs parameters of the model. In a global model availability of disaggregated data is rare, and in this research many approximations had to be taken for data to represent the regions. These key parameters are:

  - The building types shares. That's the shares of detached, semi-detached, apartments and high-rises in a region. The data is provided is from 3 regions (Europe, USA and Canada) and through them assumptions were concluded for the rest of the word. Typically, an assumption like that hides a lot of uncertainty since the building types depend on many factors as population density, status and culture, and the data used belongs to developed regions (developing regions are underrepresented). This uncertainty could be limited by further research on data.
  - The dimensions of the four reference houses (surface/floorspace ratio). In combination to building types, the dimensions of buildings are estimated based on logically assumptions (**Table 1**). It is difficult to find characteristics of prototype building type representable for all the world since data is only available for some countries (Atanasiu et al. 2003). According to a BPIE report, "to date, there has been no systematic attempt to gather comprehensive data on energy saving renovation costs at European level" (Economidou et al. 2011).
  - The U-Values. The values used in the model emanate from Europe but were used for all regions due to lack of regional data. To improve the realism in the results, 3 climate zones are defined in methodology, diversifying the U-values in them and thus the buildings heating intensities (concept adopted from the Ecofys report (Petersdorff et al. 2015), but still the uncertainty is high.
  - The cost values of insulation. The per-surface costs used in the model are representative for Europe and the US. These values were used for all regions due to lack

of regional data. Assuming that in reality the insulation costs in developing countries/regions are lower due to cheaper materials and labour, the number of insulated buildings is undermined in the model (higher costs result to lower market share for insulated buildings) and the projected energy intensities are higher than it would be. Since U-Values and costs for the respective insulation, are difficult to be found in literature, contact with insulation companies across various regions could be a way to remove this uncertainty.

- Six insulation levels. The insulations levels developed for the representation of general insulation options, is made as equally spread as possible (in terms of efficiency and costs), covering all the available width (from cheaper to more expensive). However, specific combinations of insulated surfaced are examined, while the possibilities/choices are countless. An incorporation of more options could "unlock" more insulation applications, resulting into a different building stock.

To examine the importance of each approximation in the parameters above a sensitive analysis was conducted during the internship and can be found in Appendix V. The sensitivity shows that the assumed dimensions of the buildings is the most crucial parameter, so it inserts the most uncertainty. Other parameters like the experience index, insulation costs and insulation lifetime become more relevant for the model after 2050. It should be noted that the values for heating demand in the analysis differ than the current demand presented in the rest of the report, because since then the model was significantly improved.

6.3. Model Validation

Despite these all limitations and barriers, there is an effort for realism in results through the calibration of the heating and cooling residential demands with historic IEA data. In the section 4 key parameters and results of the model will be compared to literature data to get an estimation of how well the model can simulate the complex energy system.

1. Renovation Rate

The renovation rate is the ratio of renovated buildings to the total building stock and is endogenously calculated in the model. According to **Figure 10** the rate around 2015 is between 0.77% and 1% (depending on the year examined). The real renovation rates are estimated to be around 1% globally (Europe's is usually between 1% and 1.5% depending on the year) (Artola et al., 2016; Atanasiu et al., 2013; Harrison et al., 2017). So, the model estimations for renovation rates around 2015 is very close to the real value.

2. Total investments on insulation

Total investments spent on insulation according to SSP2 storyline is 69.5 bln$ in 2015 and 89 bln$ in 2016. According to IEA the investments in efficiency of the building envelope were 55.3 bln$ in 2015 and 69.3 bln$ in 2016 (Bryant et al., 2016; Thomas et al., 2017). The projected values this time are relatively close but deviate from the literature values. There are many reasons as to why there is a difference, as for example the insulation level costs that are used might be a bit high (especially for developing regions), or some non-included parameters discussed in limitations might downgraded the investments in real life. A table follows with investments from all SSPs and their deviation from the literature value.

Table 15. *The total investments on buildings envelope efficiency improvement in billion $, according to leterature data and the three socio-economic pathways. The percentage for each SSPs shows how increased in this value compared to the literature data (IEA).*

	IEA data	SSP1		SSP2		SSP3	
2015	55.3	62.6	13%	69.5	26%	68.8	24%
2016	69.3	96.6	39%	89	28%	71.4	3%

3. Heating demand of the global residential building sector

After comparing historic/literature data with representative parameters for the buildings shell energy efficiency improvement, the projected demands for the residential sector are compared with respective historic and modelling results from IEA (IEA, 2019) [a].

Table 16. *The heating demand of the residential sector for 2017 (literature/historic data) and the heating demand until 2040 for 2 IEA future scenarios (New Policy Scenario (NPS) and Efficient Word Scenario (EWS)) and the three baselines of the sub-model (SSPs). Data collected from IEA (IEA, 2019) [a].*

EJ	2017	2020	2025	2030	2035	2040
NPS	24	25	25	25	25	25
EWS	24	24	24	23	22	22
SSP1	16.4	16.8	17.1	17.1	16.6	15.5
SSP2	16.8	17.4	18.3	18.8	18.8	18.5
SSP3	16.7	17.4	21	22.9	23.4	23.6

Table 16 presents the projected global heating demands under two IEA scenarios and the baseline scenarios of this model. It should be noted that for 2017 the IEA scenarios demonstrate a historic data, while in the SSPs that respective value is calculated (historic data in the sub-model stop at 2015). In 2017 the projected sub-model demands are (around) 31% less than the IEA/historic value. The difference between model results for heating could arise due to errors in calibration (the sub-model's last calibrated value is for 2015 and depicts 16.3 EJ which is much lower than 24EJ), or inconsistent definition of energy services (i.e. inclusion of water heating). However, progressing towards 2040, the sub-model's values stand closer to IEA projections.

The SSP1 baseline follows a similar path to Efficient Word Scenario, as in both the heating demand slightly declines by 2040 (in SSP1 it is reduced by 5.5% while in EWS by 8%). The SSP2 baseline is closer to New Policy Scenario, as in both there is a slight increase in heating demand followed by a stabilisation until 2040 (in SSP2 the demand has increased by 10% compared to 2017, while is NPS it is increased by 4%). The lower increase of demand in NPS can be justified by the existence of policies, as SSP2 baseline is policy-free. Finally, SSP3 does not relate with any of the IEA scenarios, which is reasonable since SSP3 pathway describes a defragmented future while the IEA scenarios are sustainability-oriented (through policies and efficiency improvements).

4. Cooling demand of the global residential building sector

As a final step into the model's validation, the cooling demands are compared with IEA's baseline cooling demands (Dean et al., 2018).

Table 17. *The cooling demand of the residential sector for 2017 (literature/historic data) and the cooling demand until 2050 for an IEA baseline scenario and the three SSPs. The IEA values are approximated as they were extracted from a graph (Dean et al., 2018).*

EJ	2017	2020	2025	2030	2035	2040	2045	2050
IEA	2.88	4.32	5.4	6.84	7.92	10.8	12.6	14.4
SSP1	3.67	4.3	5.43	6.74	8.31	10.03	11.72	13.42
SSP2	3.63	4.26	5.4	6.63	7.99	9.51	11.11	12.78
SSP3	3.58	4.2	5.43	6.67	7.9	9.19	10.47	11.74

Table 17 demonstrates the similarities and differences between the IEA baseline and the three sub-model baselines. In 2017 the values are quite different (sub-model's values are 26% higher). However, progressing to 2030 the values come closer, and then shift away until 2050 (but still relatively close for all SSPs). SSP1 seems to better fit IEA baseline, with only significant deviations at 2045 and 2050.

In general, modelling the projection of heating and cooling demand is connected to many parameters that insert vast uncertainties as that depend into future developments, such as the increase of the global average temperature (due to climate change), the installation of heating and cooling appliances (especially in developing countries), the growth of GDP in regions etc. So, values projected from different models are expected to have deviations as these models use different mechanisms input parameters and assumption. Furthermore, every projection is simply an attempt to simulate the human system (e.g. energy system) and the interactions between them, so in principle the outcome could be far from the upcoming future values (main reasons are briefly explained in section 6.1.). However, the validation of a model by comparing projected results with other models is an indicator that it functions properly and that the outcome is reasonable.

6.4. Policy Implications

This research revealed the importance of the buildings' shell improvement in reducing the buildings sector's energy demand and emissions. However, the investments on such improvements are not enough under any future development (SSPs), so additional effort much be made to overcome the market barriers. Effective support policies are needed, and the Governments need to set clear long-term commitments and goals toward this transaction.

The sub-model shows that the policies examined cannot individually (fully) complete their task (demand and emissions reduction in the residential sector), so policy packages are needed. As results indicate, the minimum standards policy in combination with a carbon tax could possibly achieve the mitigation goals but enormous costs would befall households (especially of poor classes), so economical barriers would be created alongside with an increase in poverty. That's why it is essential to pair these policies (mandatory performance standards and carbon tax) with policy tools that make the investments more affordable directly (e.g. subsidies, lower discount rates for the actors (preferential loan schemes encourage energy efficient practices by subsidising interest rates or credit risk support)) and indirectly (through economy-of-scale and learning rates). Group policies as such can lead to a decarbonised, low-energy residential (and non-residential) sector with minimum added stress to the market and the population.

The three SSPs examined provided vastly different results regarding the efficiency costs and the mitigation speed of the policies. In SSP1 the projected energy intensity, heating/cooling demands and emissions are always the lowest, accompanied also by the lowest cumulative costs (investments and costs related to policies) and the fastest mitigation. On the other hand in SSP3 the exact opposite phenomenon is noticed, where huge expenses that burden governments (in case of subsidies) but also for people (investments costs and taxation) result into a mediocre outcome in terms of CO_2 reduction (also 2^{o}C target could not be achieved during the mitigation scenario). SSP2 is in-the-middle situation, where the mitigation targets can be achieved, but are connected to high costs. This outcome signifies the importance of the pathway that society will follow and points out that the closer our future development is to SSP1 to easiest the energy and economic transaction is going to be, towards a sustainable decarbonized system. In turn, this means that attention must be paid to several areas like efficiency improvements, technology development and innovation, sustainable energy production, reduction of income inequity etc.

Finally, attention must be paid in awareness (communication mechanisms) to "push" the decision of actors in favour of more insulated/improved buildings, and to knowledge-sharing across countries to enable the full access to state-of-the-art insulation measures (know-how and material quality).

6.5. Further Research

In this section areas where further work may be performed are suggested.

Improvement of the sub-model

First, more suitable/regional U-Values and their costs could greatly improve the projections. As already mentioned in the limitation, the values used are representative for developed countries, while for developing countries the situation could be very different. Material of lower quality and lower prices (for insulation in total) are expected, and this could lead to vastly different results, of more but less-efficient insulation applications. Another important parameter (the most important according to the sensitivity analysis) is the characteristics of the building types and their shares. The shares currently used are representative of developed regions and the characteristics are logically assumed, covering a big range of regions, but not suitable for all. Additionally, as already mentioned in the limitations, more insulation options (that the six used by the model) could encourage a larger number of investments. Finally, an aspect overlooked in the simulation process is that the insulations have more uses in a household than the buildings efficiency improvement. An example are the windows which sometimes need replacement (due to old age or because they brake). In such a case, the reapplication of insulation comes faster than expected (the 30 years assumed as an insulation lifetime). Furthermore, its cost should not be solely allocated to energy efficiency improvement but also to comfort. Another example are earthquakes (or other natural or human-made disasters), where the house or part of it has to be replaced. However, it is difficult to allocate the expenses to energy efficiency and other uses, let alone model it.

Policies

More policies can be examined (different subsidies, carbon tax and minimum standards), and more importantly combinations of subsidies. Results implied that a combination is needed for an easier transaction towards a decarbonized future.

Furthermore, the application of policies was assumed to be applied in the same manner for all regions but in reality, the potential for policy tools (especially for incentives) differs among regions. With research on regional current policies an indicator could be created showing the possibilities and willingness regarding policy measures and their enforcement.

Better integration of the building stock to REMG

The model simulated the insulation in new buildings and renovations based on the developed building stock. However, all other decisions made in the calculations are disconnected to the inflows and outflows of the stock. For example, the appliances installed in households do not take into account the age of the building (a building could be new or very old, and in the last case an investment would have a decreased lifetime). As a next step of development, the buildings levels can be interconnect with the fuel use the application instalments and all other decisions made in REMG. For example, a high-quality building would have different benefits from a heat pump than a lower quality building. All these improvements would greatly increase the realism of the simulation providing that way more robust results.

7. Conclusion

The aim of this research is to examine "How can improvements in residential buildings envelope help towards reducing heating and cooling energy intensity and CO2 emissions across different socio-economic pathways and climate change mitigation scenarios" . The sub-questions developed to guide the research and the conclusions drawn from them are summarized in this section.

1. How can the improved sub-model (Building-Stock and Renovation model) lead to different heating and cooling demand across differing socio-economic pathways?

The first part of this thesis is aimed to provide insight into the different heating and cooling demands that derive from the various possible future developments (i.e. SSP1, SSP2 and SSP3 socio-economic pathways). The outline of the examination is that in SSP1 pathway, the investments on high-levels insulation in combination with the highest renovation rates (**Figure 7**) result into a fast decline of the useful energy intensity of the building stock, thus improving its quality. The energy intensity of SSP2 on the other hand shows a more stable decline (following a similar trend compared to historic values) and despite the similar to SSP1 renovation rate, is followed by a large amount of investments. Finally, in SSP3 the building stock's quality is only slightly improved compared to historic values, since insulation investments are almost non-existing. Furthermore, the fuel mix used under each SSP differs, with SSP1 being the "greener" pathway, followed by SSP2 and lastly by SSP3. As a result, the application of insulation has diverse effects in heating and cooling demands (and emissions) across the several future developments. Compared to the projected values of a scenario with no insulation appliance (only minimum insulation set by the regulations, while the other dynamics of SSPs are active) the SSP1, SSP2 and SSP3 heating and cooling demands are reduced by 33, 16 and 2% in 2050, and by 64, 64 and 3% in 2100. So, it becomes apparent that although the first two SSPs have the same energy reduction in 2100, SSP1 progression is faster and cheaper (also resulting in lower absolute final energy demand).

2. How do the results concerning heating intensity compare with a version of the model lacking an explicit representation of renovation and efficiency improvement?

The sub-model incorporates the insulation application process as a human decision in its simulation. In contrast, in the older version of REMG the energy efficiency improvement of the buildings' envelope was assumed and used as an input to the model. In this older version the useful energy intensities originally decline, then rise again and stabilize from approximately two decades, to decrease again as the model advances towards 2100 and acquire a final value similar to 2010 (**Table 4**). The sub-model on the other hand simulated a continuously decline in useful energy intensity, which in 2100 acquires a value half of the one presented in 2010. The sub-model's results are in line with the literature which describes an continuous improvement of the quality of the building stock (mainly due to new high-efficiency buildings).

3. How do policies aiming at expediting efficiency improvement in buildings affect choices in renovation and efficiency improvements in residential buildings?

In the second phase of the analysis two policy tools are examined. Subsidies of 20, 40 and 60% and a minimum energy efficiency standards policy. As expected, the higher the subsidy the higher the improvements of the building stock. However, the cost-effectiveness (kg CO_2 / $\$_{2010}$) of the subsidies seems to follow a less direct path (more details follow in the end of this section).
<u>All the reductions shown below refer to a comparison with the baselines (the scenarios of sub-question 1 where no policy is present).</u>

By applying subsidies, the useful energy intensity reduces by 1-10% in 2050 and by 1-35% in 2100, depending on the subsidy and the SSP. Subsidies appear to have a limited effect in SSP3 despite the fact that a significant amount of money is expensed. This is due to the high costs of insulation combined with the low GDP projections that characterise this pathway. Contrary under SSP1 and SSP2 the intensity drops significantly (although the absolute drop in value under SSP1 is small, as in this pathway a lot of investments take place even without a subsidy).

The “standards” scenario assumes a reinforcement of efficiency standards regarding insulation. By applying this policy, the useful energy intensity is reduced by 11-20% in 2050 and by 9-48% in 2100 depending on the pathway. This policy measure has the highest effect for SSP3 as in this pathway most of the buildings consist of the lowest (possible) quality, and through the increase in standards, many investments are forced to the actors. On the other end lies SSP1 where the “standards” effect is limited. This is due to the high-quality building stock already present (only a few investments are forced). SSP3’s outcome seems promising but forcing investments into households (especially for poor classes) can increase the inequity and create an economic barrier for investments and development.

4. How could these policies contribute to GHG emission reductions and climate change mitigation?

The above-mentioned improvements on the envelope of the buildings do not result in a similar reduction on GHG emissions (in this thesis only CO_2 is examined). The reason is the many dynamic mechanisms in place, like average temperature change (climate change), adoption of cooling and heating appliances in households and changes into the fuel mix. The results show that during the subsidy policy the heating emissions abatement is 1-7% in 2050 and 1-11% in 2100 and the cooling emission abatement is 1-14% in 2050 and 1-26% in 2100 (depends on the subsidy and SSP). Under the “standards” scenario the emission abatement for heating is 2-9% in 2050 and 1-21% in 2100 and for cooling 11-19% in 2050 and 7-36% in 2100 (depends on the SSP).

The results show a low reduction of CO_2 for both policy measures. “Standards” policy has some peaks for SSP3 but still these percentages cannot be compared to the almost 100% reduction (compared to 2010 emissions) needed to achieve the 2^{o}C Paris Agreement target. However, these policies can be beneficial as they can significantly reduce the heating and cooling demands of the residential sector (as it is discussed in the end of this section).

5. How do renovations contribute to reducing heating and cooling demand and subsequent CO_2 emissions from the residential sector in climate change mitigation scenarios?

In the mitigation scenario a carbon tax is applied. The carbon tax is developed through an optimization technique with the constraint to decarbonize the system. The optimization was successful for SSP1 and SSP2, but it could not be achieved for SSP3 (no carbon tax could lead into the necessary emission reduction). Under these two pathways the abatement of the heating emission is 24-40% in 2050 and 16-86% in 2100 and the abatement of cooling emissions is 66-91% in 2050 and 96-100% in 2100. The corresponding cooling demand is reduced by 1-27% in 2050 and 14-56% in 2100. However, the heating demand is not reduced in 2050 and in 2100 it is increased (compared to the baselines).

It is apparent that the mitigation scenario can highly reduce the residential sector’s emissions, but it is not so successful in reducing the demands. That inconsistency between demands and emissions originates from the decisions made inside the model. Since this policy is aiming at decarbonizing the whole system and not specifically at expediting efficiency improvement in buildings, the simulation focuses on a “greener” fuel and more efficient energy production, rather improve the buildings quality, so in the end the building quality remains the same as the baseline.

Finally, the cost-effectiveness of each subsidy and for the mitigation scenario are investigated. This is an indicator that incorporates the CO_2 emission reductions and the costs expensed for this purpose (kg CO_2 / $\$_{2010}$). Since the “standards” policy does not require any direct payment (the other policies involve subsidies and taxation) this indicator is not suitable for it. Comparing the subsidies with the carbon tax it becomes apparent that the second is more cost-effective (more kg of CO_2 are abated per $). Another interesting observation is that although increasing the subsidy the effect of it increases along, this is not the case for the cost-effectiveness which after a point declines (the point depends on the pathway followed).

Examining the different policy tools and their strengths and weaknesses it seems that overall the carbon tax is the most suitable for the climate change mitigation (it achieves the higher emission reduction while being the most cost-effective). However, there are cases where it might not be sufficient (an example is SSP3, where is could not produce the required outcome). So, for an optimum solution that would additionally achieve a significant reduction on demands a carbon tax should be coupled with one or both other policies, depending on the case.

8. Literature

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Appendix I

IMAGE regions and countries (ISO)

Region	Nr	Countries
Canada	1	Canada (124)
USA	2	St. Pierre and Miquelon (666), United States (840)
Mexico	3	Mexico (484)
Central America	4	Bahamas, The (44), Barbados (52), Bermuda (60), Belize (84), Virgin Isl. (Br.) (92), Cayman Islands (136), Costa Rica (188), Dominica (212), Dominican Republic (214), El Salvador (222), Grenada (308), Guadeloupe (312), Guatemala (320), Haiti (332), Honduras (340), Jamaica (388), Martinique (474), Montserrat (500), Aruba (533), Netherlands Antilles (530), Nicaragua (558), Panama (591), Puerto Rico (630), St. Kitts and Nevis (659), Anguilla (660), St. Lucia (662), St. Vincent and the Grenadines (670), Trinidad and Tobago (780), Turks and Caicos Isl. (796), Virgin Islands (U.S.) (850)
Brazil	5	Brazil (76)
Rest of South America	6	Argentina (32), Bolivia (68), Chile (152), Colombia (170), Ecuador (218), Falklands Isl. (238), French Guyana (254), Guyana (328), Paraguay (600), Peru (604), Suriname (740), Uruguay (858), Venezuela, RB (862)
Northern Africa	7	Algeria (12), Libya (434), Morocco (504), Western Sahara (732), Tunisia (788), Egypt, Arab Rep. (818)
Western Africa	8	Cameroon (120), Cape Verde (132), Central African Republic (140), Chad (148), Congo, Rep. (178), Congo, Dem. Rep. (180), Benin (204), Equatorial Guinea (226), Gabon (266), Gambia, The (270), Ghana (288), Guinea (324), Cote d'Ivoire (384), Liberia (430), Mali (466), Mauritania (478), Niger (562), Nigeria (566), Guinea-Bissau (624), St. Helena (654), Sao Tome and Principe (678), Senegal (686), Sierra Leone (694), Togo (768), Burkina Faso (854)
Eastern Africa	9	Burundi (108), Comoros (174), Ethiopia (231), Eritrea (232), Djibouti (262), Kenya (404), Madagascar (450), Mauritius (480), Reunion (638), Rwanda (646), Seychelles (690), Somalia (706), Sudan (736), Uganda (800)
South Africa	10	South Africa (710)
Western Europe	11	Andorra (20), Austria (40), Belgium (56), Denmark (208), Faeroe Islands (234), Finland (246), France (250), Germany (276), Gibraltar (292), Greece (300), Vatican City State (336), Iceland (352), Ireland (372), Italy (380), Liechtenstein (438), Luxembourg (442), Monaco (492), Netherlands (528), Norway (578), Portugal (620), San Marino (674), Spain (724), Sweden (752), Switzerland (756), United Kingdom (826), Malta (470)
Central Europe	12	Albania (8), Bosnia and Herzegovina (70), Bulgaria (100), Croatia (191), Cyprus (196), Czech Republic (203), Estonia (233), Hungary (348), Latvia (428), Lithuania (440), Macedonia, FYR (807), Poland (616), Romania (642), Serbia and Montenegro (891), Slovak Republic (703), Slovenia (705)
Turkey	13	Turkey (792)
Ukraine region	14	Belarus (112), Moldova (498), Ukraine (804)
Central Asia	15	Kazakhstan (398), Kyrgyz Republic (417), Tajikistan (762), Turkmenistan (795), Uzbekistan (860)
Russia region	16	Azerbaijan (31), Armenia (51), Georgia (268), Russian Federation (643)
Middle East	17	Bahrain (48), Iran, Islamic Rep. (364), Iraq (368), Israel (376), Jordan (400), Kuwait (414), Lebanon (422), Oman (512), Qatar (634), Saudi Arabia (682), Syrian Arab Republic (760), United Arab Emirates (784), Yemen, Rep. (887)
India	18	India (356)
Korea region	19	Korea, Dem. Rep. (408), Korea, Rep. (410)
China region	20	China (156), Taiwan (158), Hong Kong, China (344), Macao, China (446), Mongolia (496)
Southeastern Asia	21	Brunei (96), Myanmar (104), Cambodia (116), Lao PDR (418), Malaysia (458), Philippines (608), Singapore (702), Vietnam (704), Thailand (764)
Indonesia region	22	Indonesia (360), Papua New Guinea (598), East Timor (626)
Japan	23	Japan (392)
Oceania	24	American Samoa (16), Australia (36), Solomon Islands (90), Cook Isl. (184), Fiji (242), French Polynesia (258), Kiribati (296), Nauru (520), New Caledonia (540), Vanuatu (548), New Zealand (554), Niue (570), Northern Mariana Islands (580), Micronesia, Fed. Sts. (583), Marshall Islands (584), Palau (585), Pitcairn (612), Tokelau (772), Tonga (776), Tuvalu (798), Wallis ans Futuna Island (876), Samoa (882)
Rest of South Asia	25	Afghanistan (4), Bangladesh (50), Bhutan (64), Maldives (462), Nepal (524), Pakistan (586), Sri Lanka (144)
Rest of Southern Africa	26	Angola (24), Botswana (72), Lesotho (426), Malawi (454), Mozambique (508), Namibia (516), Zimbabwe (716), Swaziland (748), Tanzania (834), Zambia (894)

Region classification map. Assessed on: http://models.pbl.nl/image/index.php/Region_classification_map

Appendix II

Table AP.1. *Generic description of the storyline elements and their transaction to model assumptions for SSP1, SSP2 and SSP3 in IMAGE (indication high and low are made in comparison to a median development path).*

	SSP1	*SSP2*	*SSP3*
Generic elements			
Economic growth	High, based on Dellink et al. (2017)	Medium, based on Dellink et al. (2017)	Low, based on Dellink et al. (2017)
Population growth	Low, based on KC and Lutz (2017)	Medium, based on KC and Lutz (2017)	High in developing countries; low in developed countries, based on KC and Lutz (2017)
Governance and institutions	Effective both nationally and internationally	Uneven	International institutions weak; security policies
Technology	Rapid, translated into for instance in assumptions for efficiency, renewable technologies and yields	Medium	Slow
Consumption/ production preferences	Promotion of sustainable development (lower consumption – see further)	Medium	Relative resource intensive consumption
Energy demand			
Transport	Lower share of income spent on transport leading to less kms travelled. More travel time (0,5 min/day increase each yr) resulting in less shift to faster modes. Preference for public transport, car sharing, and faster increase in efficiency (10% in 2100).	Medium assumptions	Slower reduction of costs and efficiency increase of new technologies. Higher share of income spend on transport and later saturation of transport demand. No increase in travel-time implying a more rapid shift to high speed modes.
Buildings	Behavioural changes lead to overall lower demand for energy services (heating, cooling, appliances). Adoption of more efficient technologies. Faster rural electrification. Rapid phase out of traditional fuels.	Medium assumptions	Slower improvement rates of efficient technologies.Low improvements towards access to modern energy carriers
Industry	Low intensity for cement and steel demand; clinker-cement ratio to 0.7. Preference for efficient technology and natural gas/bio-energy. Penalty for coal. High steel scrap recovery rate.	Medium assumptions	High intensity for cement and steel demand. No convergence in clinker-cement ratio. Preference for standard technologies and fuel preferences based on price only.
Non-energy	Low intensity, following Daioglou et al. (2014)	Medium, following Daioglou et al. (2014)	High intensity, following Daioglou et al. (2014)
Energy supply and conversion			
Fossil fuels	Global trade of fuels; and median technology development for fossil fuel extraction technologies.	Global trade of fuels; Median technology development	Trade barriers; and slow development of technologies.
Bio-energy	Traditional biofuels mostly phased out around 2030; bio-fuels in transport taxed for possible biodiversity damage; less potential based on nature reserves but increased from abandoned lands; high yields; improved efficiencies and costs of biofuel production technologies; residues based on Daioglou et al. (2016).	Traditional biofuels phased out in line with income growth. Default assumptions for modern bio-energy. residues based on Daioglou et al. (2016).	Traditional biofuels phased out at a slower rate; Lack of nature reserves increases potential land; Lower yields; low efficiencies and high costs of biofuel production technologies; residues based on Daioglou et al. (2016).
Renewables	Rapid technology development (high values for learning rates); low integration costs	Medium technology development	Slow technology development (low values for learning rates)
Agriculture and land use			
Land use change regulation	Strong – Protected areas are extended to achieve the Aichi target of 17%. Additional areas are protected making in total 30% of terrestrial area unavailable for agricultural expansion.	Medium – Protected areas are extended to achieve the Aichi target of 17% of the terrestrial area, gradually implemented from 2010–2050.	Low – protected areas at current level.
Agricultural productivity (crops)	Strong – crop yield increase as a function of GDP, increase in irrigation efficiency 20% higher than SSP2	Medium – following largely the projections by FAOs agricultural outlook	Low- crop yield increase as a function of GDP, increase in irrigation efficiency 20% lower than SSP2
Agricultural productivity (livestock)	Efficiency parameters achieve 50% convergence to the levels of the most efficient regions in SSP2	Medium – following largely the projections by FAOs agricultural outlook	Efficiency stagnates at current regional levels
Environmental Impact of Food consumption	Low – Consumption of animal products 30% lower than endogenous outcome in high income countries, reduction of food waste by 1/3.	Medium- Endogenous dynamics	High – Consumption of animal products 30% higher than endogenous outcome, increase of food waste by 1/3.
Trade			
Trade in agricultural commodities	Abolishment of current import tariffs and export subsidies by 2030, preference for regionally produced products.	Current tariffs and subsidies.	Introduction of a 10% import tax for all agricultural products by 2050, for self- sufficiency concerns
Trade in energy carriers	No trade restrictions	No trade restrictions	Stronger reliance on domestic production.
Air pollution			
Emissions factors	Low; rapidly falling in all regions, see Rao et al. (2017)	Medium; falling in low-income regions with some delay see Rao et al. (2017)	High; considerable delay across the regions see Rao et al. (2017)

Appendix III

RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100).

Figure AP.1. Overview of representative concentration pathways (RCPs). Approximate radiative forcing levels were defined as ±5% of the stated level in W/m2 relative to pre-industrial levels. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents.) *(Van Vuuren et al. 2011).*

Table AP.2. *Share of fuel sources used for heating the residential's sector buildings for specific years.*

	SSP2			SSP1			SSP3		
Shares	**2025**	**2050**	**2100**	**2025**	**2050**	**2100**	**2025**	**2050**	**2100**
Solid fuel	3.7%	1.4%	2.1%	3.3%	1.7%	5.0%	3.9%	1.7%	5.3%
Liquid fuel	13.5%	19.6%	9.8%	14.2%	18.9%	13.2%	14.6%	19.9%	23.7%
Gaseous fuel	49.5%	29.9%	9.9%	46.3%	23.8%	16.4%	45.0%	32.8%	20.1%
Modern BioFuel	1.8%	2.8%	2.0%	1.7%	3.9%	8.1%	1.4%	2.3%	4.0%
Traditional BioFuel	7.1%	3.0%	0.8%	5.5%	1.6%	0.8%	7.6%	3.7%	4.0%
Hydrogen	1.2%	13.1%	12.4%	1.3%	21.4%	29.6%	1.0%	11.0%	15.0%
Secondary Heat	16.0%	14.3%	5.4%	16.0%	16.1%	14.5%	16.0%	17.1%	11.7%
Electricity	12.2%	11.5%	6.3%	11.6%	12.5%	12.5%	10.5%	11.5%	16.2%

Appendix IV

1. Baselines - Regions

In this section the heating/Cooling demand and CO_2 emissions for selected regions are presented.

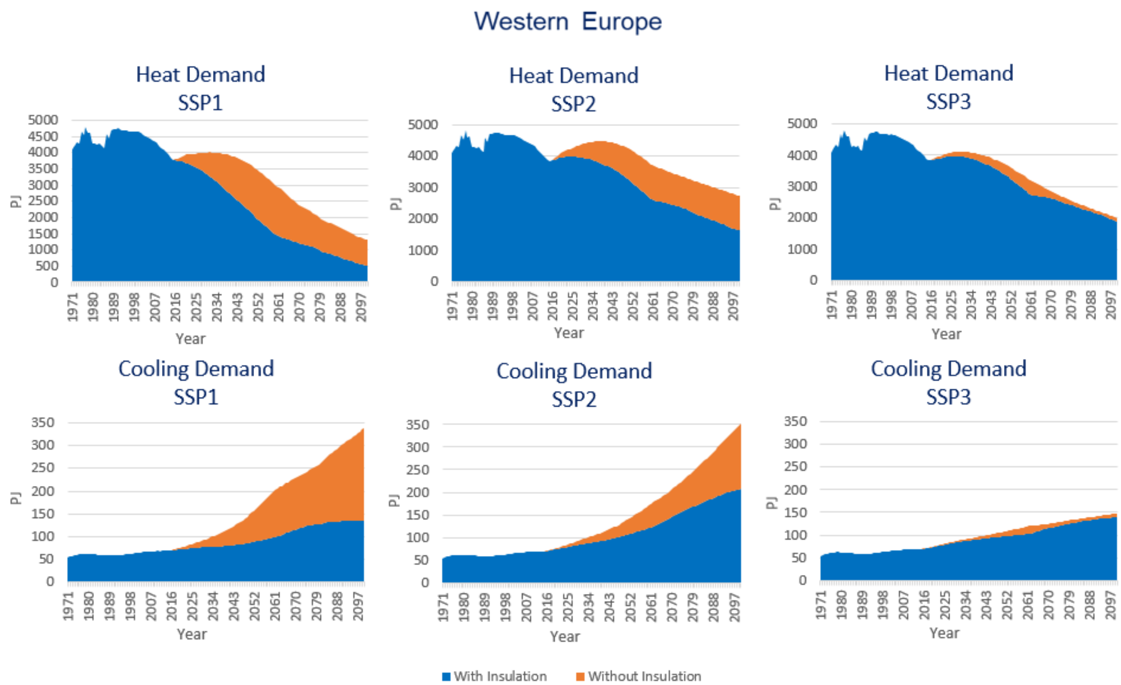

Figure AP.2. *Western Europe's heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand with and without the appliance of extra insulation on buildings (higher than level 1 insulation). Bottom Row: Cooling demand with and without the appliance of extra insulation on buildings.*

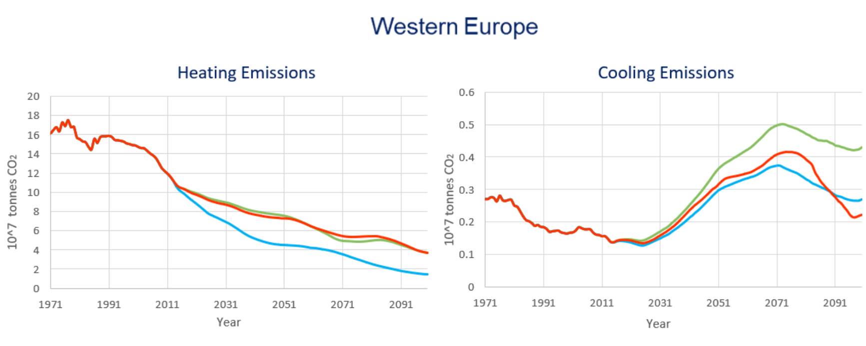

Figure AP.3. *Western Europe's emissions originated from heating and cooling of the residential building sector under SSP1, SP2 and SSP3.*

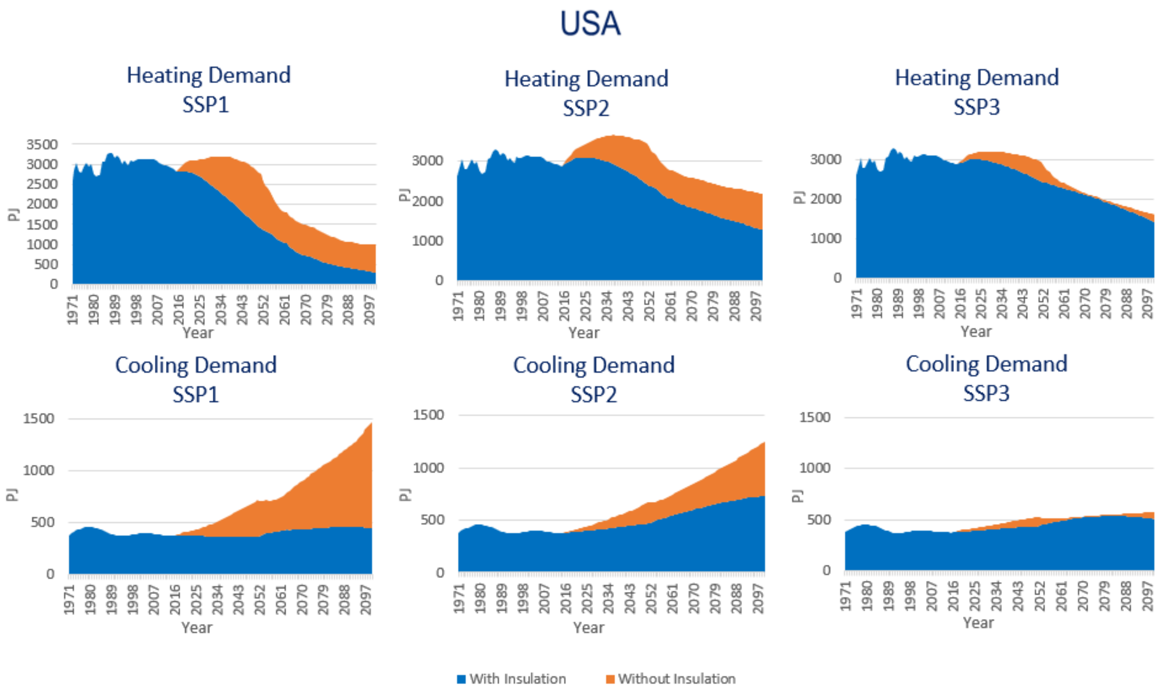

Figure AP.4. *USA's heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand with and without the appliance of extra insulation on buildings (higher than level 1 insulation). Bottom Row: Cooling demand with and without the appliance of extra insulation on buildings.*

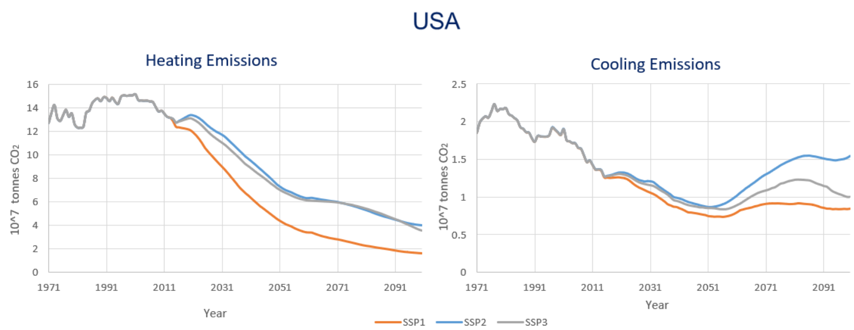

Figure AP.5. *USA's emissions originated from heating and cooling of the residential building sector under SSP1, SP2 and SSP3.*

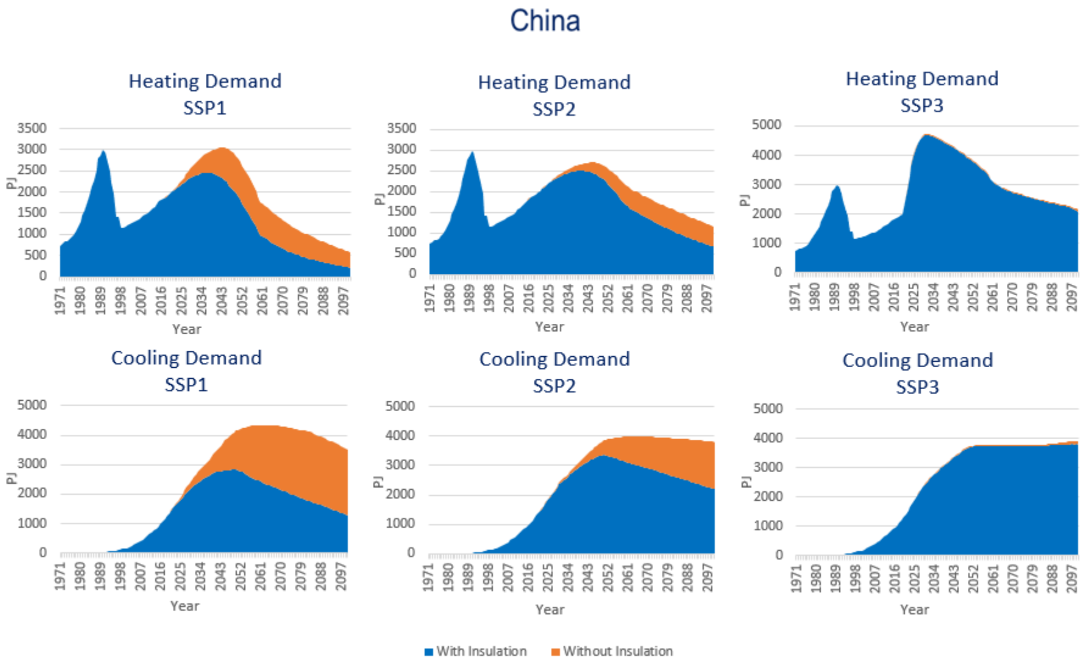

Figure AP.6. *China's heating and cooling demand under SSP1, SP2 and SSP3. Top Row: Heating demand with and without the appliance of extra insulation on buildings (higher than level 1 insulation). Bottom Row: Cooling demand with and without the appliance of extra insulation on buildings.*

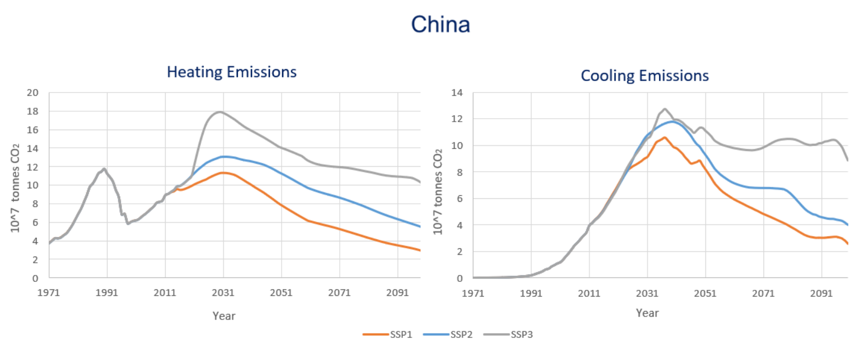

Figure AP.7. *China's emissions originated from heating and cooling of the residential building sector under SSP1, SP2 and SSP3.*

2. Subsidies – Regions

Now the effect of subsidies on the energy demands and CO_2 emissions for the selected regions is examined.

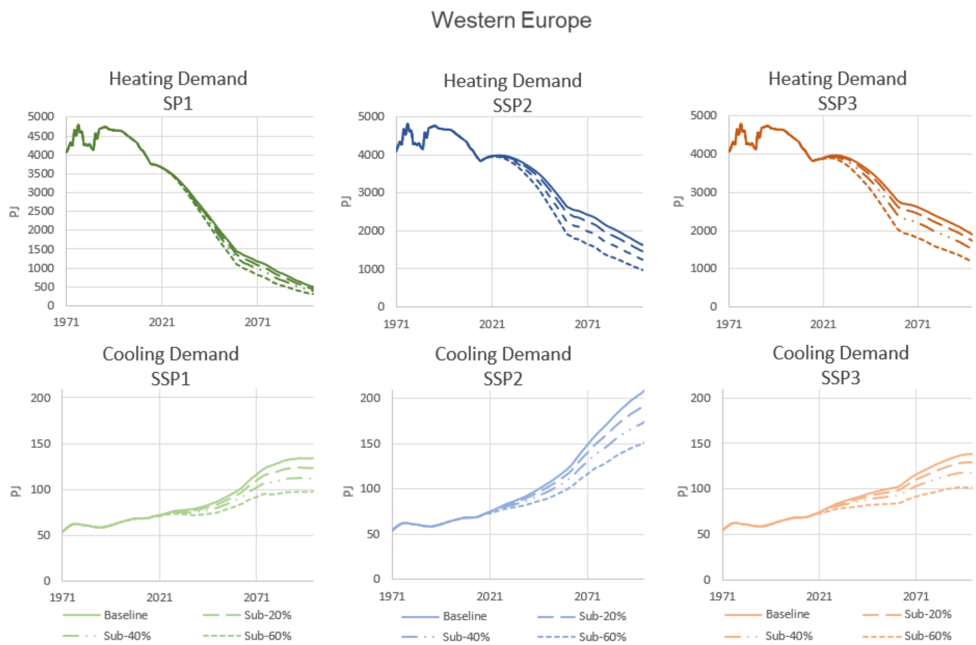

Figure AP.8. *The effect of subsidies on Western Europe's heating and cooling demand under the SSPs. The subsidies examined are of 20%, 40% and 60% of the initial investment cost. Top Row: Heating demand before and after the implementation subsidies. Bottom Row: Cooling demand before and after the implementation of the subsidies.*

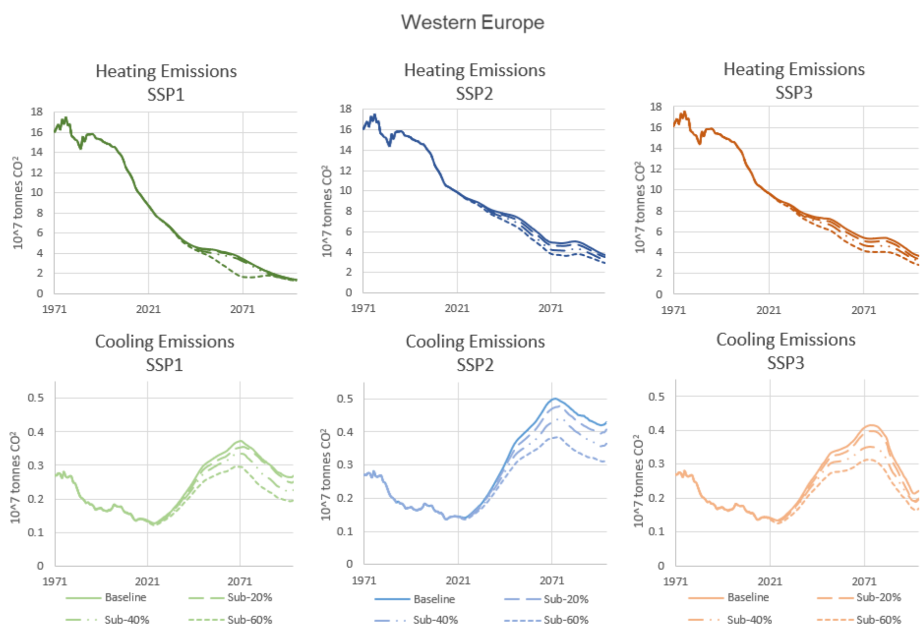

Figure AP.9. *The effect of subsidies on Western Europe's emissions originated from heating and cooling of the residential building sector under SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the implementation subsidies. Bottom Row: Cooling emissions before and after the implementation of the subsidies.*

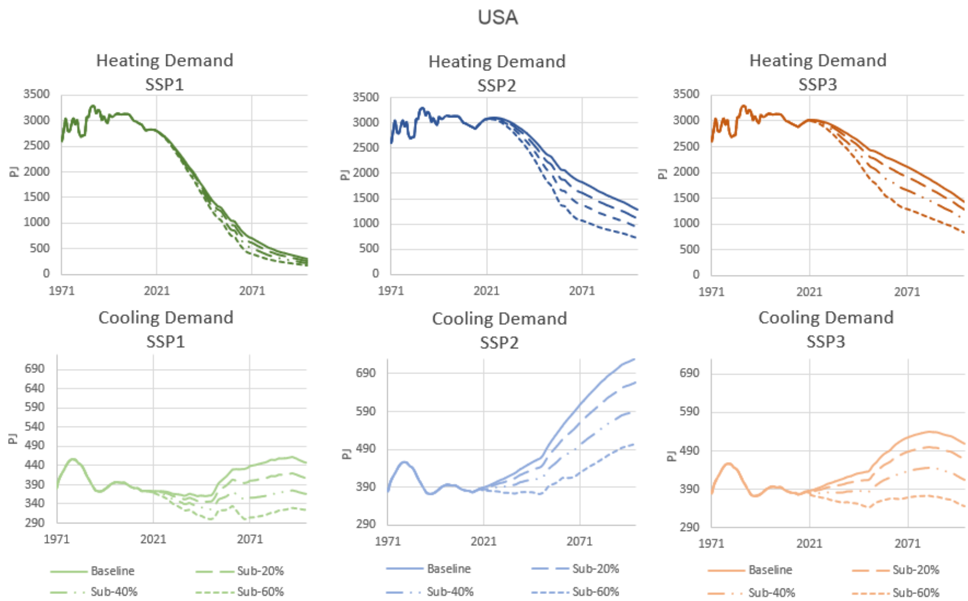

Figure AP.10. *The effect of subsidies on Western Europe's heating and cooling demand under the SSPs. The subsidies examined are of 20%, 40% and 60% of the initial investment cost. Top Row: Heating demand before and after the implementation subsidies. Bottom Row: Cooling demand before and after the implementation of the subsidies.*

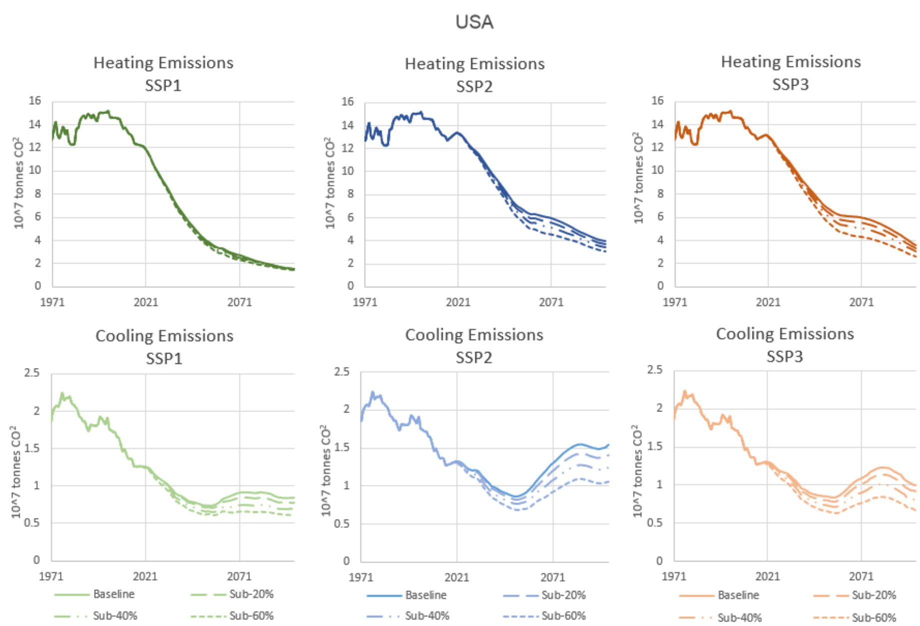

Figure AP.11. *The effect of subsidies on Western Europe's emissions originated from heating and cooling of the residential building sector under SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the implementation subsidies. Bottom Row: Cooling emissions before and after the implementation of the subsidies.*

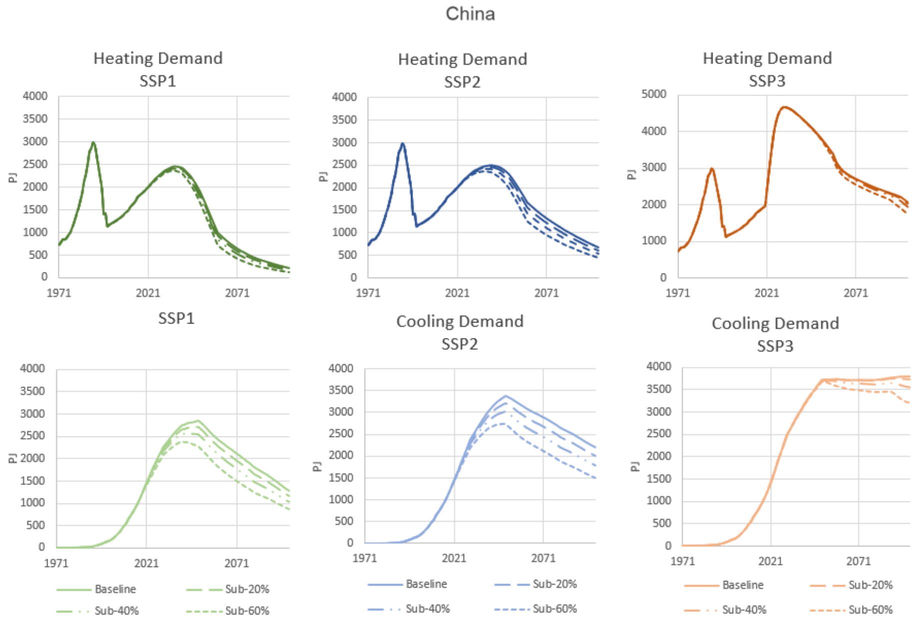

Figure AP.12. *The effect of subsidies on Western Europe's heating and cooling demand under the SSPs. The subsidies examined are of 20%, 40% and 60% of the initial investment cost. Top Row: Heating demand before and after the implementation subsidies. Bottom Row: Cooling demand before and after the implementation of the subsidies.*

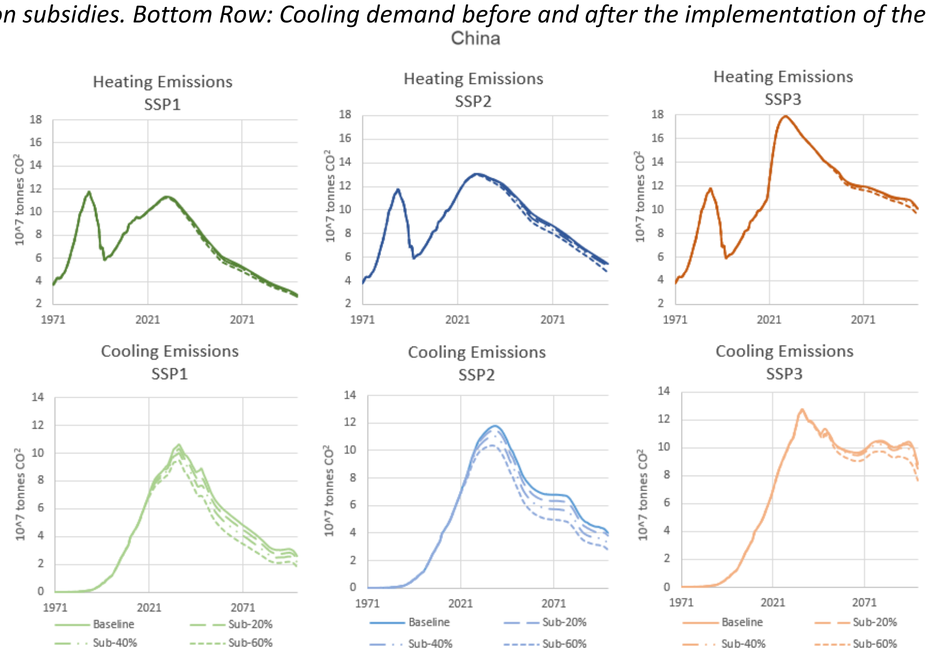

Figure AP.13. *The effect of subsidies on Western Europe's emissions originated from heating and cooling of the residential building sector under SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the implementation subsidies. Bottom Row: Cooling emissions before and after the implementation of the subsidies.*

3. Standards - Regions

The effect of standards policy on the energy demands and CO_2 emissions for the selected regions is examined.

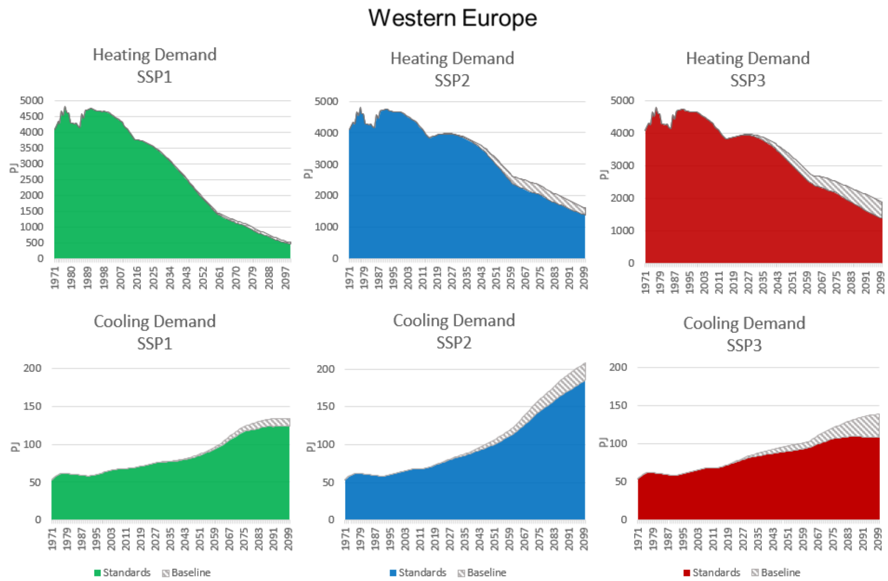

Figure AP.14. *Western Europe's heating and cooling demand under the effect of standards policy and across the SSPs. The standards policy excludes the level 1 insulation option from 2020 inwards and the level 2 insulation option from 2030 onwards. Top Row: Heating demand before and after the increased minimum-required standards. Bottom Row: Cooling demand before and after the increased minimum-required standards.*

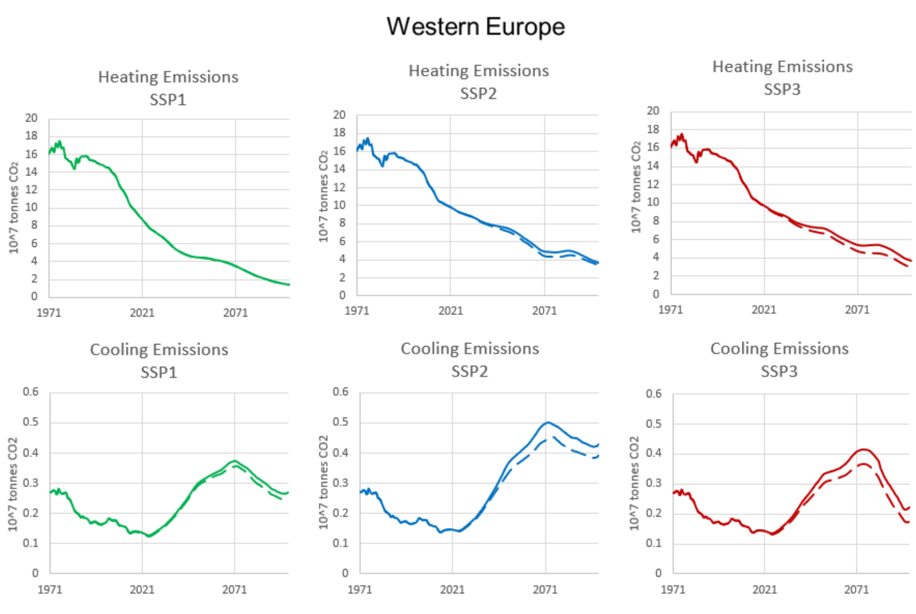

Figure AP.15. *Western Europe's residential heating and cooling emissions under the effect of standards policy and across the SSPs. Top Row: Heating emissions before and after the increased minimum-required standards. Bottom Row: Cooling emissions before and after the increased minimum-required standards.*

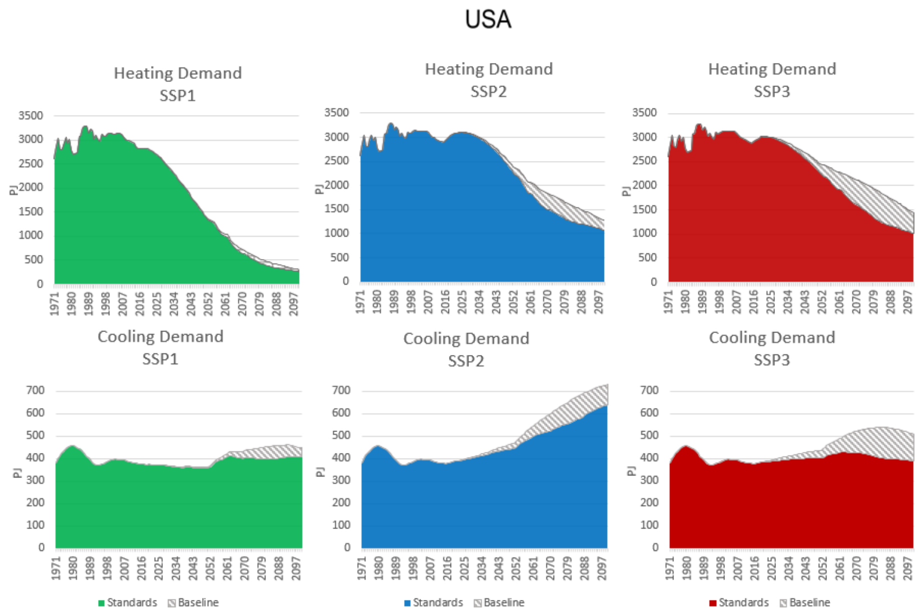

Figure AP.16. *USA's heating and cooling demand under the effect of standards policy and across the SSPs. standards policy excludes the level 1 insulation option from 2020 inwards and the level 2 insulation option from 2030 onwards. Top Row: Heating demand before and after the increased minimum-required standards. Bottom Row: Cooling demand before and after the increased minimum-required standards.*

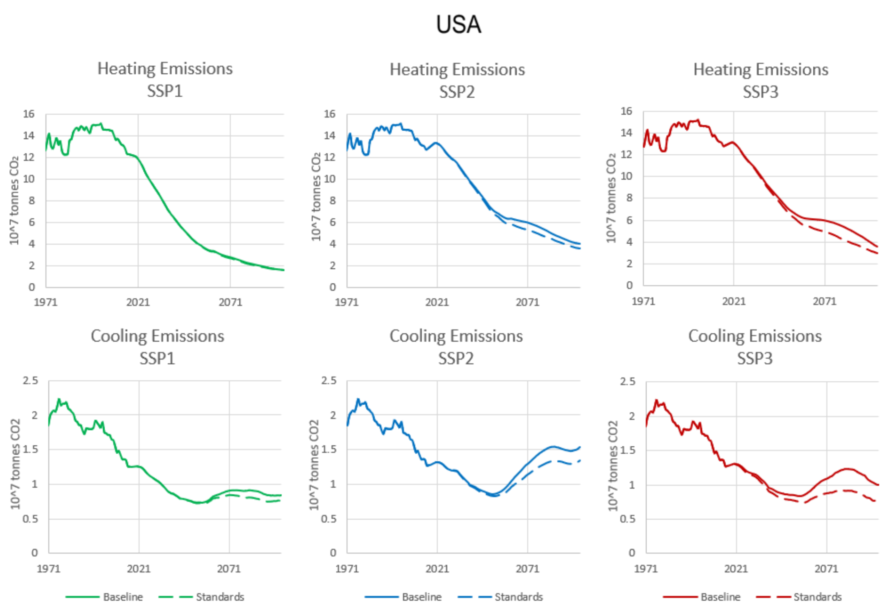

Figure AP.17. *USA's residential heating and cooling demand under the effect of standards policy and across the SSPs. Top Row: Heating emissions before and after the increased minimum-required standards. Bottom Row: Cooling emissions before and after the increased minimum-required standards.*

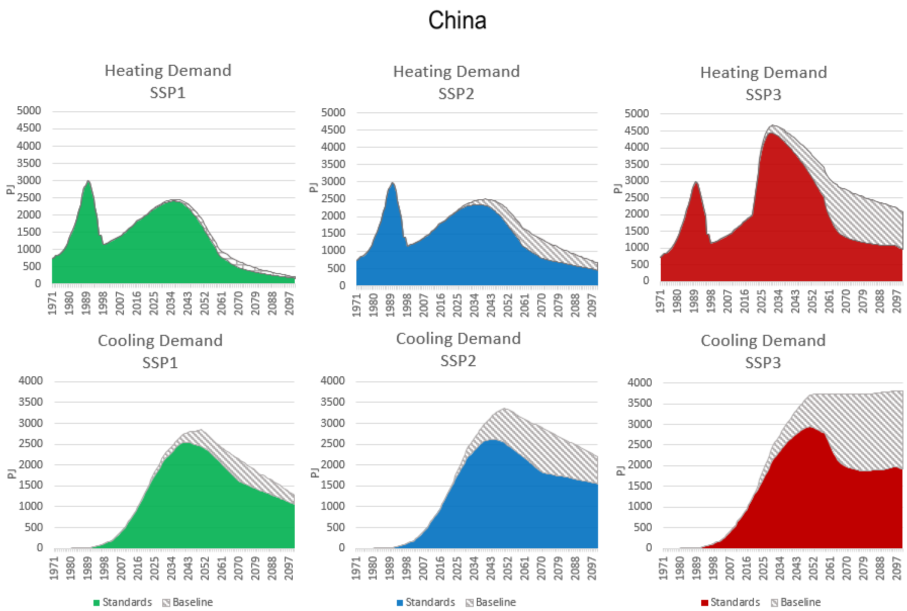

Figure AP.18. *China's heating and cooling demand under the effect of the standards policy and across the SSPs. The standards policy excludes the level 1 insulation option from 2020 inwards and the level 2 insulation option from 2030 onwards. Top Row: Heating demand before and after the increased minimum-required standards. Bottom Row: Cooling demand before and after the increased minimum-required standards.*

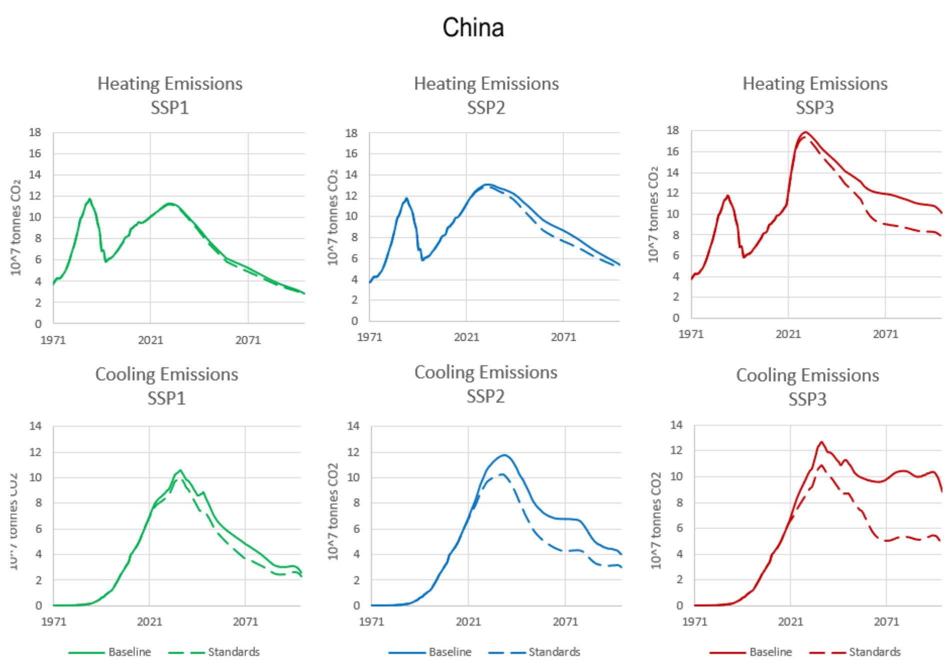

Figure AP.19. *China's residential heating and cooling demand under the effect of the standards policy and across the SSPs. Top Row: Heating emissions before and after the increased minimum-required standards. Bottom Row: Cooling emissions before and after the increased minimum-required standards..*

4. Mitigation - Regions

The effect of mitigation policy on the energy demands and CO_2 emissions for the selected regions is examined.

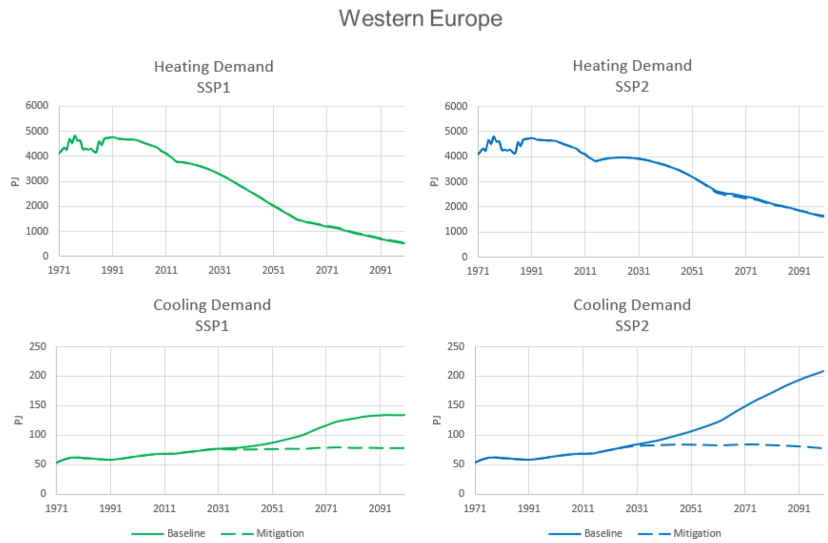

Figure AP.20. *Western Europe's heating and cooling demand under the mitigation scenario and across SSP1, SP2 and SSP3. Top Row: Heating demand before and after the appliance of a dynamic carbon tax (mitigation scenario). Bottom Row: Cooling demand before and after the appliance of a dynamic carbon tax.*

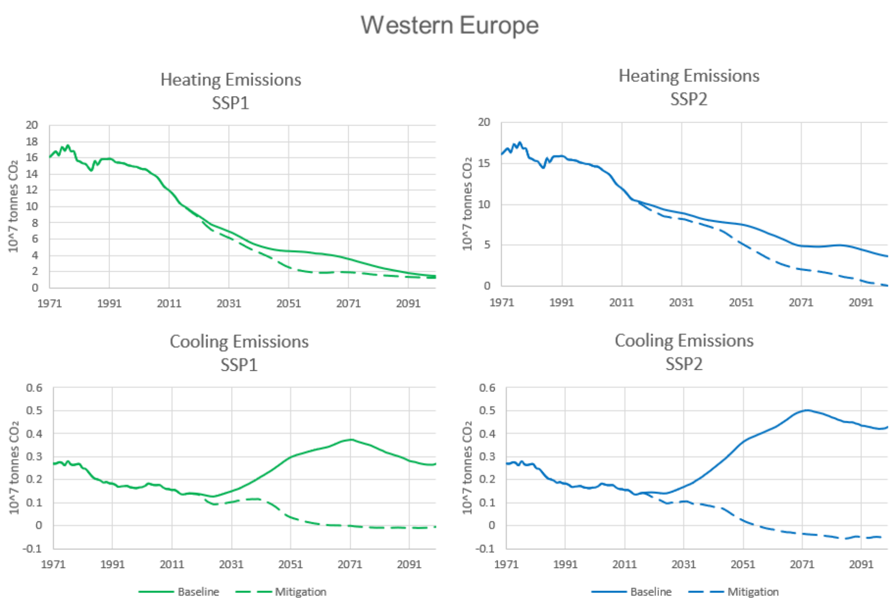

Figure AP.21. *Western Europe's residential heating and cooling emissions under the mitigation scenario and across SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the appliance of a dynamic carbon tax (mitigation scenario). Bottom Row: Cooling emissions before and after the appliance of a dynamic carbon tax.*

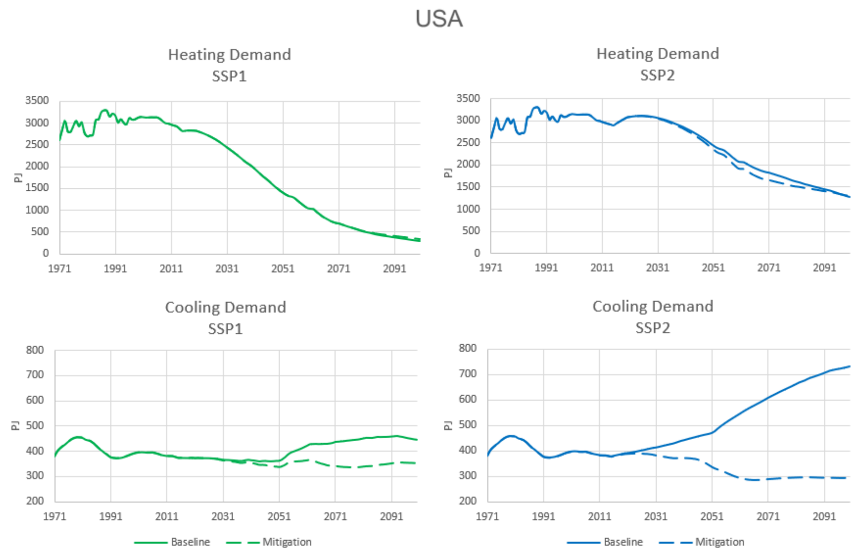

Figure AP.22. *USA's heating and cooling demand under the mitigation scenario and across SSP1, SP2 and SSP3. Top Row: Heating demand before and after the appliance of a dynamic carbon tax (mitigation scenario). Bottom Row: Cooling demand before and after the appliance of a dynamic carbon tax.*

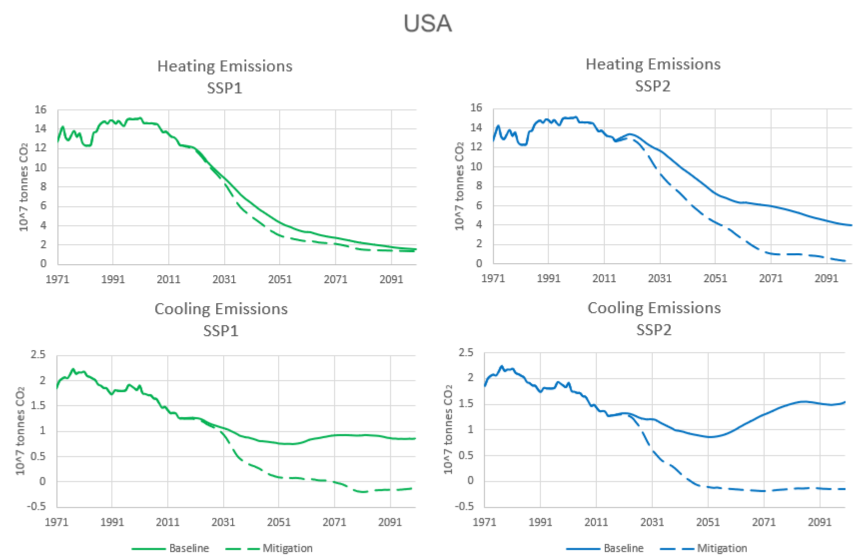

Figure AP.23. *USA's residential heating and cooling emissions under the mitigation scenario and across SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the appliance of a dynamic carbon tax (mitigation scenario). Bottom Row: Cooling emissions before and after the appliance of a dynamic carbon tax.*

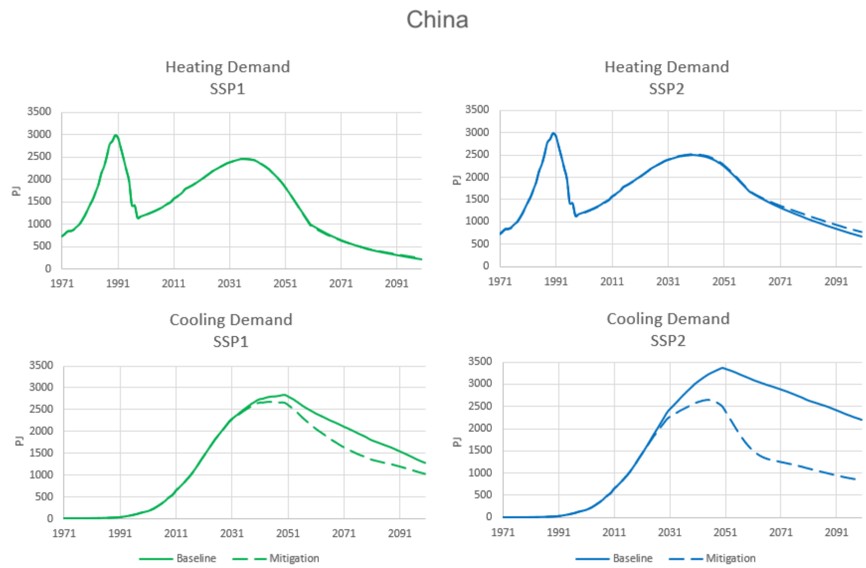

Figure AP.24. *China's heating and cooling demand under the mitigation scenario and across SSP1, SP2 and SSP3. Top Row: Heating demand before and after the appliance of a dynamic carbon tax (mitigation scenario). Bottom Row: Cooling demand before and after the appliance of a dynamic carbon tax.*

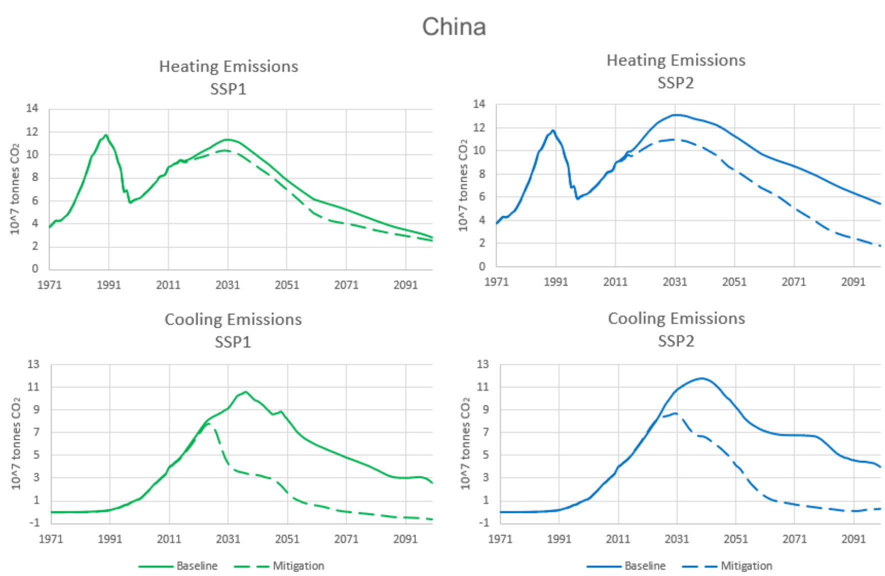

Figure AP.25. *China's residential heating and cooling emissions under the mitigation scenario and across SSP1, SP2 and SSP3. Top Row: Heating emissions before and after the appliance of a dynamic carbon tax (mitigation scenario). Bottom Row: Cooling emissions before and after the appliance of a dynamic carbon tax.*

Appendix V

Sensitivity Analysis on residential sector's demand

The results of the sensitivity belong to a previous version of the sub-model, so some inconsistencies are expected. Key parameters are tested in order to achieve a minimum and maximum possible outcome on residential sector heating demand. Minimum and maximum parameters used are based on theoretical and logical assumptions.

1. The buildings stock characteristics – Buildings average lifetime (change ± 20%).
2. Insulation/Investment lifetime (change ± 20%).
3. The prototype building characteristics - $surface_j$/floorspace ratio (change ± 50 %).
4. Investment/insulation costs per surface ($\$/m_{2surface}$) (change ± 20 %).
5. AEEI increased and decreased by 0.4%.
6. Experience index (b), where theoretical minimum (-0. 515) and maximum (-0. 074) are used.

Note: For the buildings type characteristics the prototype house used in the internship report is used and it differs from the prototype houses used in this thesis.

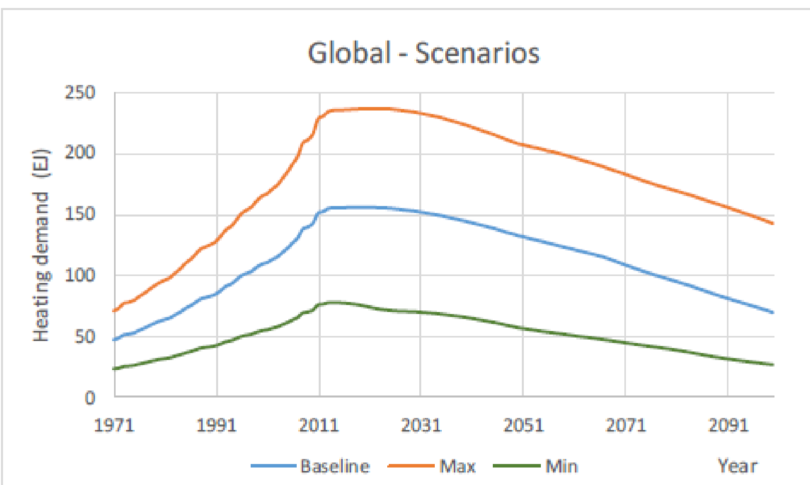

Figure AP.26. *Global heating demand for the residential sector for the baseline minimum and maximum scenarios.*

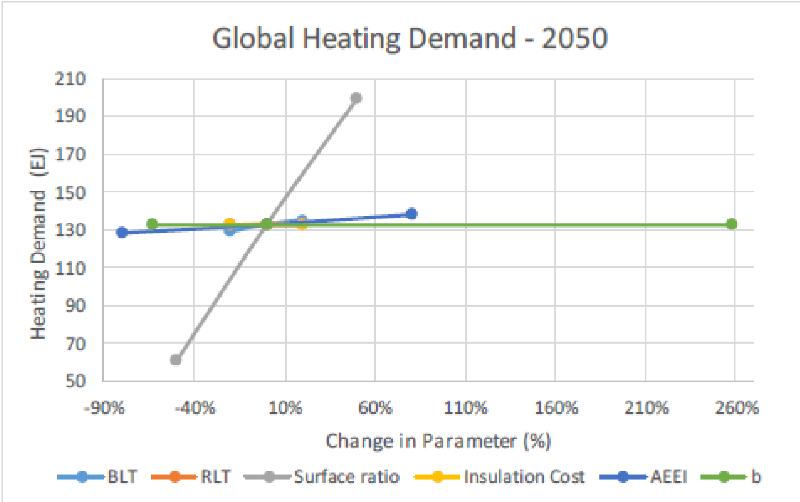

Figure AP.27. *Sensitivity analysis on the heating demand of the residential sector for 2050.*

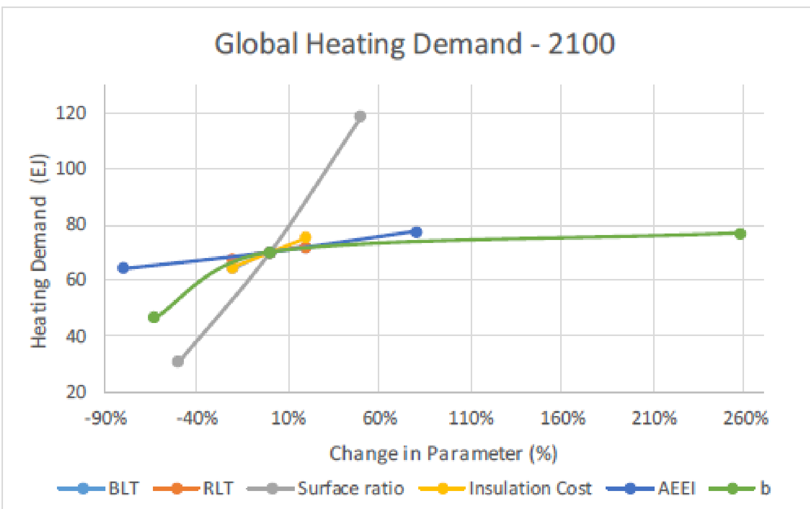

Figure AP.28. *Sensitivity analysis on the heating demand of the residential sector for 2100.*

The analysis of 2050 shows that changes on the insulation costs, the insulation lifetime and the experience index (learning effect) do not affect the heating demand. This is due to the low number of insulation appliance that are simulated from the model. Diversity on the buildings' lifetime and the AEEI affect the heating demand, but not by much. On the other hand, the system is very sensitive (biggest slope) to alterations on the surface/floorspace ratio, which also results to the biggest diversion of the final outcome (largest ranges for values of heating demand).

The sensitivity analysis of 2100 gives similar results regarding the changes on the surface/floorspace ratio, which remains the most decisive factor. But, now, experience index, Insulation costs and insulation lifetime are relevant for the outcome, since their slopes have increased. Especially experience index, as it approaches its minimum value, acquires a slope similar to the slope of the surface/floorspace ratio, and thus becomes similarly important.