Energy Modeling of Danish Housing Stock Using System Dynamics

Reza Fazeli[1], Brynhildur Davidsdottir[2]

[1] School of Engineering and Natural Sciences, University of Iceland, Email: rfazeli@hi.is
[2] School of Engineering and Natural Sciences, University of Iceland, Email: bdavids@hi.is

Abstract

Implementation of energy efficiency measures will play a crucial role in future energy consumption in buildings. In this study, we developed a dynamic building stock model, which captures the effects of building aging on total energy consumption for space heating demand. We also studied the behavioral dynamics by focusing on the key processes affecting the implementation of retrofitting measures. Calibrating the model to Danish housing stock, five policy scenarios are evaluated in terms of total energy consumption and total costs. Implementation of cost-effective measures resulted in 11.0% reduction in energy consumption for space heating by the end of century. It was also found that implementation of mandatory measures that are cost-ineffective can increase the energy saving by 3.3%, while incentives can only affect the timing of retrofitting and not the amount of saved energy. Restricting the rebound effect was found to be an effective policy (23.4% reduction in 2100). Total energy saving has significantly increased to 48% in 2100, when tight building regulation was introduced in 2020. We also compared five policy scenarios based on their total costs. Significant increase of costs in incentive-based policy is driven by "free rider" effect. Therefore, the estimated costs should be interpreted cautiously.

1. Introduction

The motivation for a shift in our current energy path and reduction of emissions of greenhouse gases is substantial. Due to slow building stock turnover the majority of opportunities to improve energy efficiency over the next several decades is in the existing building stock, that is constrained by old equipment and aging infrastructure. Energy efficient and low-carbon technologies will play a crucial role in the energy revolution needed to make this change happen. According to the IEA (IEA, 2013a), the buildings sector is the largest energy-consuming sector, accounting for over one-third of final energy consumption globally and an equally important source of carbon dioxide (CO_2) emissions.

In the Nordic countries, the buildings sector used 1527 petajoules (PJ) of energy in 2010, or about 33% of total energy use, which is similar to the worldwide share of energy use despite cold climates. The Nordic countries have progressively reduced the role of fossil fuels in the buildings sector as well as increased the energy efficiency of buildings, by implementing various polices including financial incentives, awareness campaigns, energy certificate systems, a system for certifying qualified experts in addition to implementing strict building codes (IEA, 2013b). Because building stock turnover in the Nordic countries is slow (on the order of 1% per year), the majority of opportunities to improve efficiency over the next several decades will be in existing building stock, most of which is constrained by old equipment, aging infrastructure, and inadequate operations resources. However the potential is significant, and the challenge is to “unlock” that vast potential and realize the benefits of a built environment that is comfortable, efficient, and cost-effective.

Some of the key obstacles to studying the above mentioned inertia in detail are the analytical difficulties considering the interrelated processes of dwelling age, new construction, demolition and retrofitting. Particularly, the retrofitting process is directly related to the social dynamics in the system, which is rarely studied at a system level (Santin et al., 2009). This study presents a dynamic simulation model that captures the impacts of physical processes such as aging, as well as social processes such as familiarity of households with retrofitting. The paper is structured as follows. In the following section, we describe the scope and structure of the simulation model as well as the calibration with Danish data. Then we assess the impacts of five policy scenarios on energy consumption and greenhouse gas emissions. The contribution of this study is the creation of a simulation model that enables the assessment of long-term impacts of different retrofitting policies in terms of energy savings and emissions accounting in the context of building stock turnover in Denmark. The generic model could though be applied to any housing stock in the Nordic countries.

2. Model

To investigate the dynamics of the dwelling stock we have used the system dynamics (SD) approach. SD is extensively applied in the study of dynamic systems by representing them as a set of interrelated stocks, flows and feedback mechanisms and simulating their temporal evolution (Forrester, 1969; Groesser and Ulli-Beer, 2007; Sterman, 2000). This study improved the model developed by Yücel, (2013). Using the developed system dynamics model, we aim to explore the effectiveness of certain policy options that can alleviate the inertia of an existing dwelling stock. In this study, the system scope is set to Danish housing stock and its energy-related renovation, i.e. refurbishment that improves building energy performance (in contrast to renovation without impacting on energy use, or simple maintenance). The buildings are classified according to three construction periods (pre-1960, 1960-1980, and post-1980). The temporal scope of the model is set to the period 1990-2100.

2.1. Feedback Loops

The final energy consumption of a household depends on five factors: building energy requirement, household income, heating-degree-days, energy expenses and technological progress. The causal loop diagram that depicts the relation between key factors and household energy consumption is given in Figure 1.

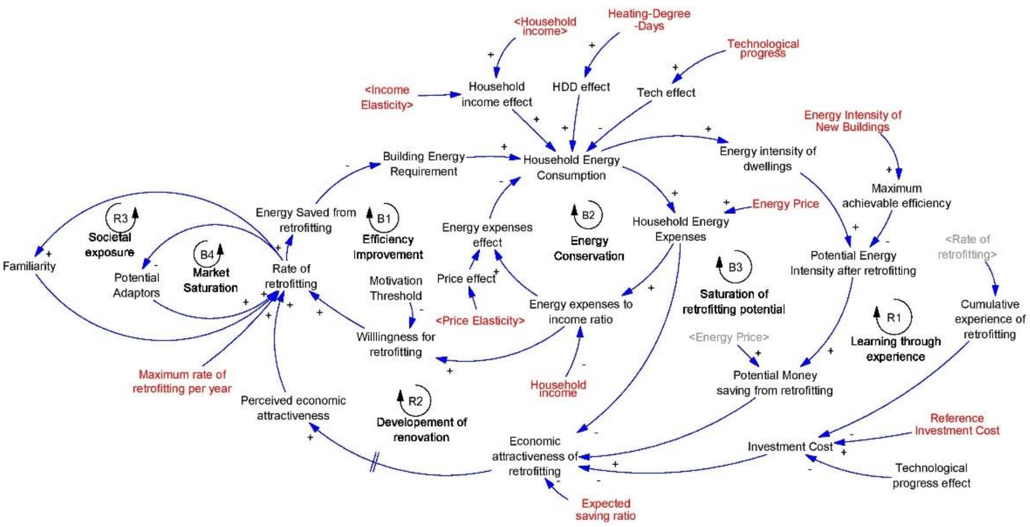

Figure 1: Causal loop diagram of energy consumption in dwellings

The developed model incorporates two fundamental household behaviors driven by the improvement of building energy performance and changes in energy expenses. These behaviors are shown as balancing loop for efficiency improvement (B1) and balancing loop for energy conservation (B2) in Figure 1. In this analysis, four balancing loops have been identified as key challenges that limit the gain from retrofitting options. They influence the energy performance of dwellings as well as the attractiveness of retrofitting measures:

- Efficiency improvement (B1)

  With the increase in household energy consumption, and consequently household energy expenses, households' willingness for retrofitting increases. After implementing retrofitting measures, the energy consumption is expected to decrease, as well as the ratio of energy expenses to income per household. According to this balancing loop, the willingness for retrofitting diminishes as the energy efficiency level of a dwelling increases.

- Energy Conservation (B2)

  With the increase in household energy expenses, the ratio of energy expenses to income for households rises. The tendency of the households to renovate is related to two factors:

the perceived level of energy expenses to household income, and economic profitability of retrofitting. After implementing retrofitting measures, the ratio of energy expenses to income for households decreases. Therefore, the household will increase the intensity of energy consuming activities as a result of increasing income (or decreasing cost of consumption), which directly corresponds to the rebound effect broadly discussed in the energy consumption literature.

- Saturation of retrofitting potential (B3)

Another factor that drives the retrofitting is the perceived economic profitability of retrofitting. As more renovation is done in buildings, the building energy efficiency improves which reduces the potential for further improvement, which consequently reduces the potential money saving from retrofitting. Therefore the potential for efficiency improvement saturates and the tendency/ability of households for renovation incrementally declines.

- Saturation of market (B4)

The rate of retrofitting depends directly on the potential adaptors. So it will saturate as retrofitting measures are implemented in the dwellings.

These balancing loops counteract the interest for retrofitting by reducing the willingness of households to renovate as well as profitability of energy saving measures as the energy efficiency level of a dwelling increases. However, there are three reinforcing loops in favor of more renovation in buildings:

- Learning through experience (R1)

It’s expected that with the implementation of retrofitting options in dwellings, the cumulative experience increases, which subsequently decreases the investment cost of options. The reduction in investment cost will increase the economic profitability of retrofitting options.

- Development of retrofitting (R2)

In this model, to identify the expected economic gain from retrofitting, the expected saved money from retrofitting was normalized by being divided by household energy expenses. Therefore, with the reduction in energy expenses due to the renovation, the relative economic gain from retrofitting increases, which increases the rate of retrofitting.

- Social Exposure (R3)

As more buildings are being renovated, households are getting more familiar with the experience and due to the effect of word of mouth, they get familiar with the main purpose and achievable benefits of building renovation. With the increase in familiarity of households, the rate of retrofitting increases.

2.2. Coflow Structure

Sterman (2000) pointed out that system dynamic modelers often need to capture not only the total quantity of material in a network of stock and flows, but also the attributes or characteristics of the stocks. While the stock and flow network reflects the amount of material in the fundamental stock, it does not reveal anything about the characteristics of that stock. Coflows however can be used to keep track of the attributes of the items that are flowing through the stock and flow structure. As a result, coflows are parallel structures that can be "used to account for the attributes of items flowing through a stock and flow network".

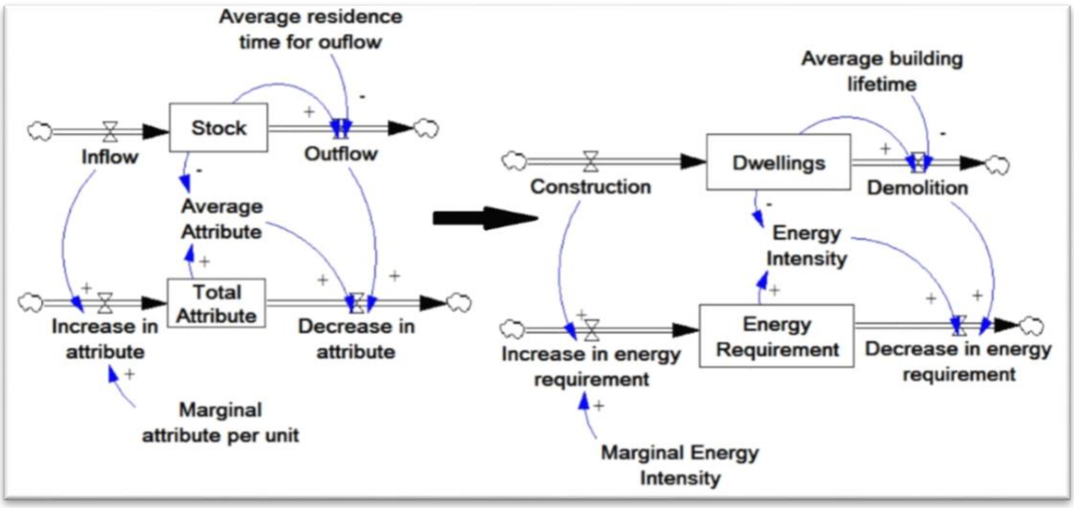

Figure 2: Generic coflow structure

Figure 2 (Left, Sterman, 2000) illustrates the generic coflow structure. As each unit of the fundamental "Stock" increases the quantity of that stock, a unit of the associated attribute is added to "Total Attribute" stock. The "Marginal Attribute per Unit" is simply the number of units of the attribute added to the "Total Attribute" stock, for each unit the fundamental "Stock" is increased. As the number of units of the fundamental "Stock" is reduced through the outflow, there is a corresponding decrease in the number of units of the "Total Attribute". The number of units by which the attribute is decreased is the product of the "Average Attribute" quantity and the "Outflow" rate, where the "Average Attribute" quantity is the "Total Attribute" quantity divided by the quantity of fundamental "Stock".

The right side of Figure 2 presents an example of how we use this standard coflow structure to model the energy use in dwelling stock. The fundamental stock is the number of “Dwellings” in Denmark. The underlying attribute is the amount of “Energy Requirement” for space heating and cooling where the “Increase in Energy Consumption” is the product of the “Construction” of new buildings and “Marginal Energy Intensity”. The “Decrease in Energy Consumption” is estimated by multiplying the rate of building “Demolition” by the average “Energy Intensity”.

2.3. Aging Structure

As was mentioned earlier, in this study, the dwelling stock is divided into three age groups:

- Old Buildings: buildings more than 30 years old
- Mature Buildings: buildings between 10- 30 years old
- New Buildings: building less than 10 years old

Figure 3 shows a stock-and-flow diagram of the key components of our dwelling stock model. Stock-and-flow-diagrams are used to represent the structures of a system in close relation to the equations that are actually simulated. With the three stocks and the aging rates, an aging chain for dwelling stock was formed (the middle chain in Figure 3). The original energy requirement and energy requirement (accounting for retrofitting impact) are the main coflows (the first and third chains in Figure 3).

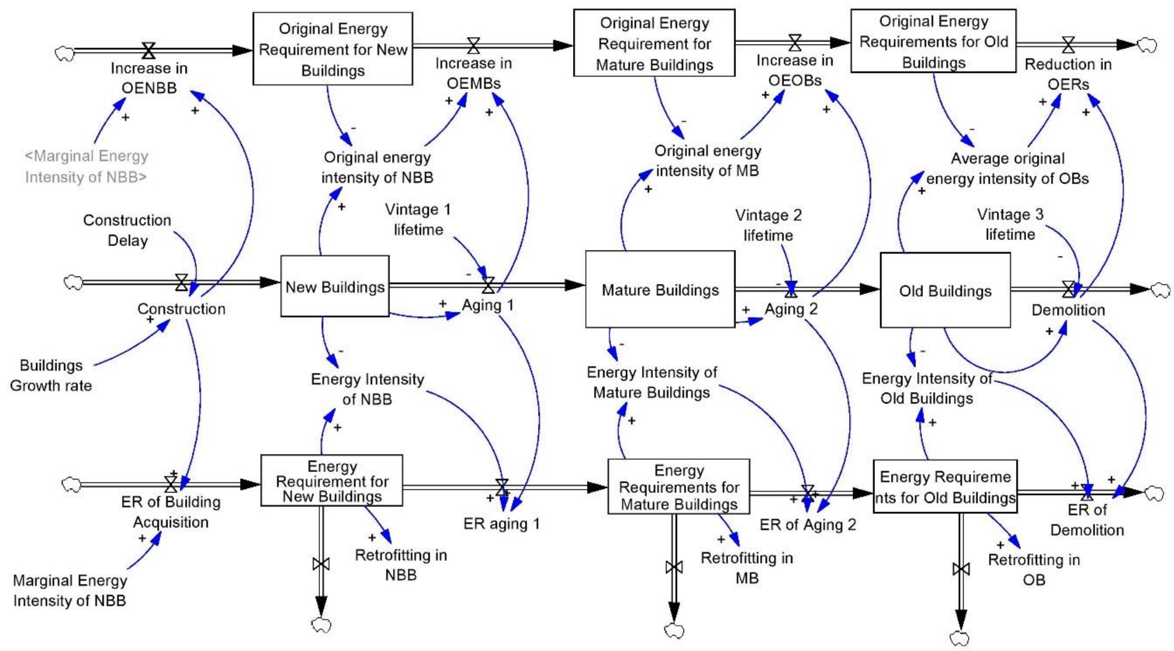

Figure 3: Stock-and-flow-diagram of the building sector

2.4. Retrofitting

Retrofitting with the aim of energy savings is typically made as an integrated part of other renovations, and considering the wear and tear of e.g. roofs or windows. However, the rate of retrofitting has so far been slow in Denmark, as the majority of the houses still lack sufficient energy efficiency, e.g. insulation. This is partly because aspirational types of renovations (in the kitchen and bathroom) are prioritized over energy saving renovations (Gram-Hanssen, 2014). In this study, the impact of four factors that contribute to decisions concerning energy retrofitting of existing dwellings have been studied:

- Perceived economic attractiveness of retrofitting: Retrofitting is considered to be economically attractive when the normalized saving index (the ratio between the lifetime energy avoided cost of a retrofitting option and energy expenses) exceeds a certain expected level, which could vary by households.
- Familiarity with retrofitting: Familiarity is a key factor that directly affects the retrofit decision-making process. Word-of-mouth effect played an important role in the implementation of retrofitting options. The larger the stock of retrofitted buildings, the greater the exposure to and knowledge of that experience among potential adopters, increasing the chances that households will consider and renovate their houses. The familiarity can also be improved by informative policies and marketing.
- Willingness to renovate: Willingness to renovate represents more than simple familiarity. Many people are aware of the achievable gain through retrofitting, but do not take them seriously in their decision. In this study, it was assumed that the willingness to renovate increases when the ratio of saving from energy improvement to income level goes above the motivation threshold.
- Potential adaptors: Rate of retrofitting depends directly on the potential adaptors. The larger the stock of retrofitted buildings, the fewer the potential adapters, reducing the rate of retrofitting.

3. Case Study: Danish dwelling stock

To study the energy performance of Danish dwelling stock, the developed system dynamics model needs to be calibrated with the historical data. In this study, 1990 was selected as the base year and the data collected from Danish Energy Authorities (2014) between 1990 and 2012 was used to calibrate the system dynamics model. Three types of dwellings are studied: Single Family Detached House (SFDH), Single Family Terraced Houses (SFTH) and Multi-dwelling Houses (MDH). The distribution of dwelling stock based on construction year 1990 and by type of the dwelling is shown in Figure 4. Dwellings built before 1960 account for 70.0% of total stock and considering their low energy performance, the focus of energy improvement plans should be on retrofitting these old buildings.

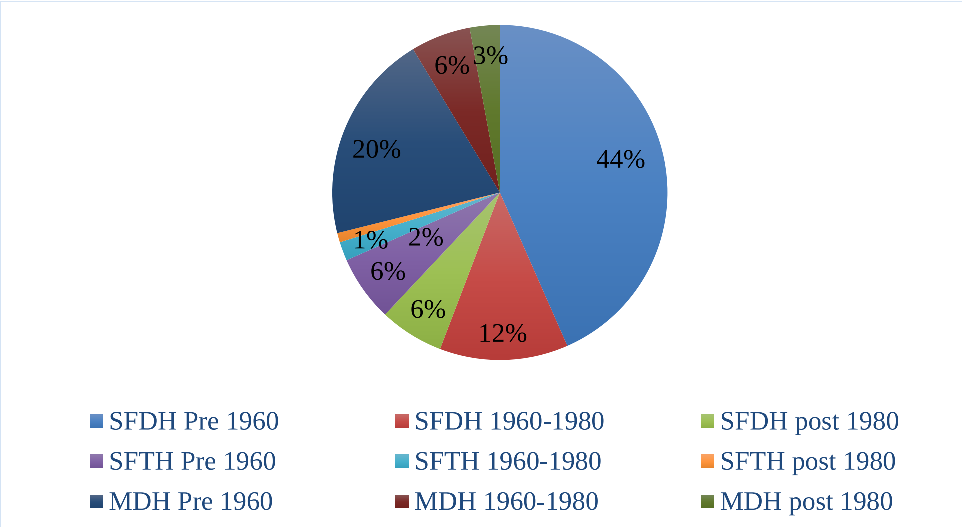

Figure 4: Distribution of Danish dwelling stock by type and construction year 1990 – source: statistics Denmark

As explained in the previous section, the dwelling stock is divided into three groups according to their age. The evolution of Danish dwelling stock by type of buildings is shown in Figure 5.

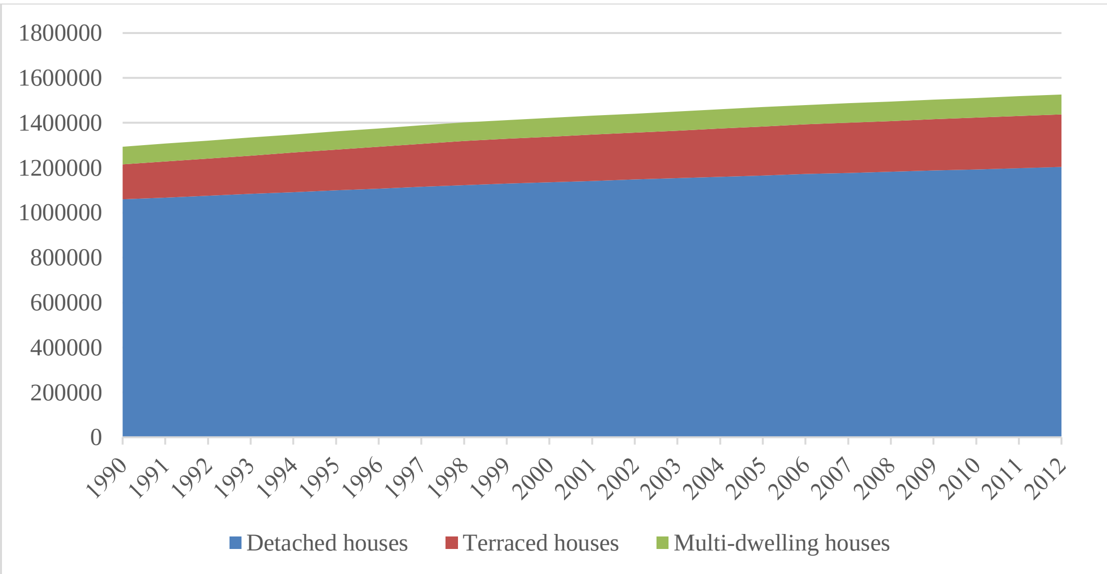

Figure 5: Total number of Danish stock by type – Source: Statistics Denmark

3.1. Evolution of Building Regulations in Denmark

Denmark is one of the first EU countries to set up their national Zero Energy Building (nZEB) definition and roadmap to 2020. Based on the Building Regulations 2010 (BR10) (The Danish Ministry of Economic and Business Affairs, 2010), the total demand of residential buildings for energy supply for heating, ventilation, cooling and domestic hot water per m² of heated floor area must not exceed 52.5 kWh/m²/year plus 1650 kWh/year divided by the heated floor area. The minimum energy performance requirements from set building regulations will gradually become stricter, starting from the actual standard, BR10, with an interim milestone in 2015 and a final target in 2020 (table 1).

Table 1: Evolution of the primary energy performance requirements towards nZEB levels in Denmark (COHERENO, 2013)

		BR10	2015	2020
Minimum requirement	Residential buildings (housing sector and hotels)	52.5 + 1650/A* $kWh/m^2/yr$	30 + 1000/A $kWh/m^2/yr$	20 $kWh/m^2/yr$
	Non-residential buildings (offices, schools, hospitals, others)	71.3 + 1650/A $kWh/m^2/yr$	41 + 1000/A $kWh/m^2/yr$	25 $kWh/m^2/yr$

3.2. Calibration of the model

The developed model is used as a dynamic tool that can be used to explore different scenarios to improve our understanding regarding the interactions of various processes. While doing so, the model's correspondence with the Danish dwelling sector with regard to the size of the dwelling stock and socio-economic characteristics is maintained. Before the scenario analysis phase, the model is tested for the validity of its structure. The historical data on the evolution of building stock and energy consumption in dwellings from 1990-2012 was used to calibrate the developed system dynamics model.

The model is initialized based on actual data corresponding to year 1990, and the 1990–2012 period (a period about which reliable data was accessible from Kragh and Wittchen, (2014) is used for behavioral comparison purposes. Model-generated behavior for the stock of dwellings per type compared with the actual data can be found in figures 6-8. As can be seen from the plots, the model is able to capture the general trends.

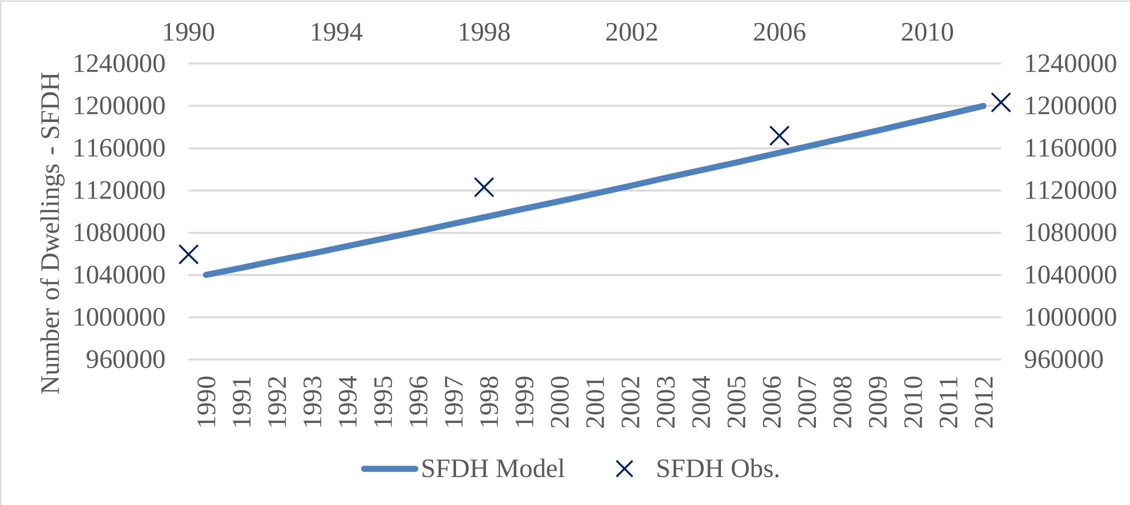

Figure 6: Number of dwellings - Single-Family detached houses (model vs. observation)

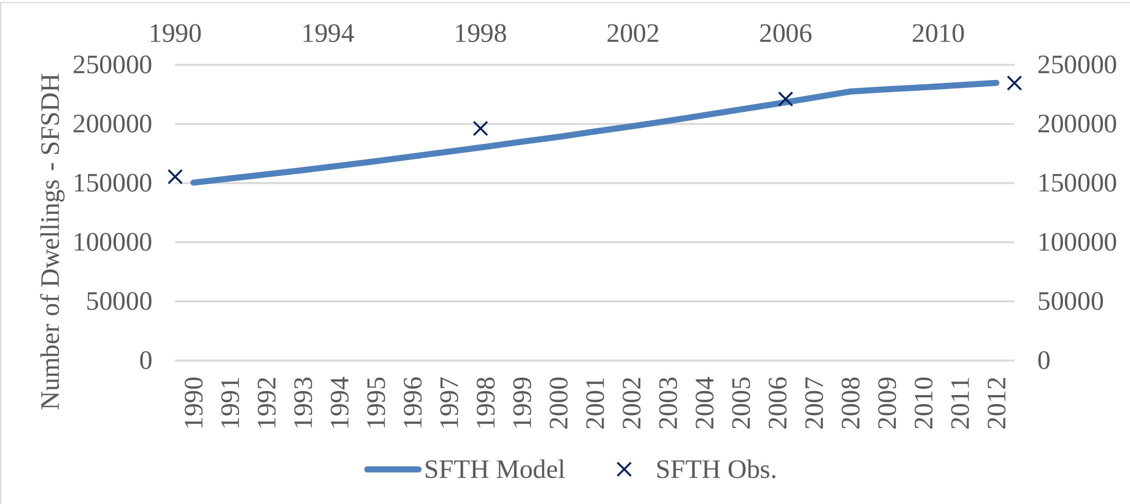

Figure 7: Number of dwellings - Single-Family Terraced houses (model vs. observation)

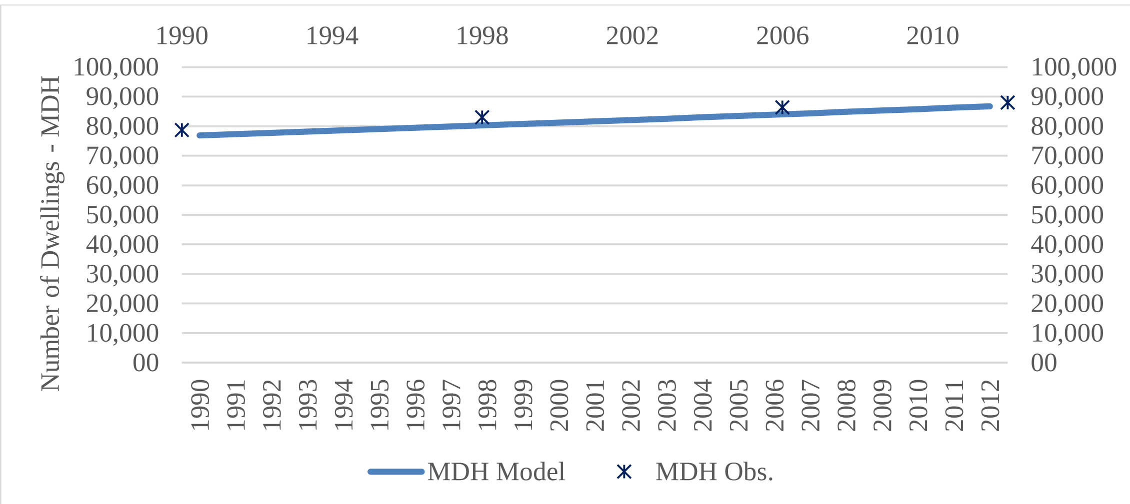

Figure 8: Number of dwellings – Multi-Dwelling houses (model vs. observation)

The outcome of the developed model on energy consumption by type of dwellings is also compared to the collected data in the validation period. Based on figures 9-11, the outcome of the model is acceptable.

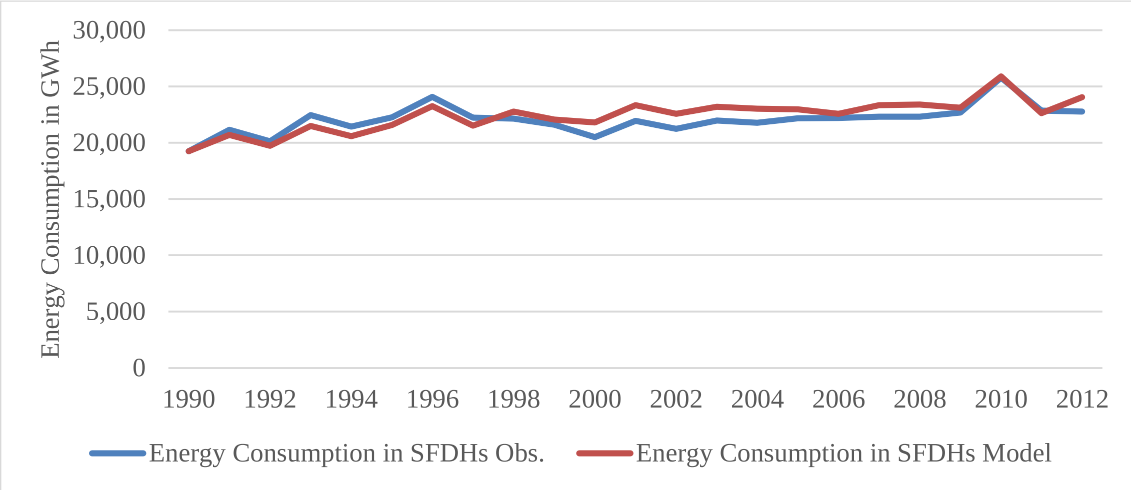

Figure 9: Energy consumption for space heating in Single-family detached houses in GWh- model vs observation

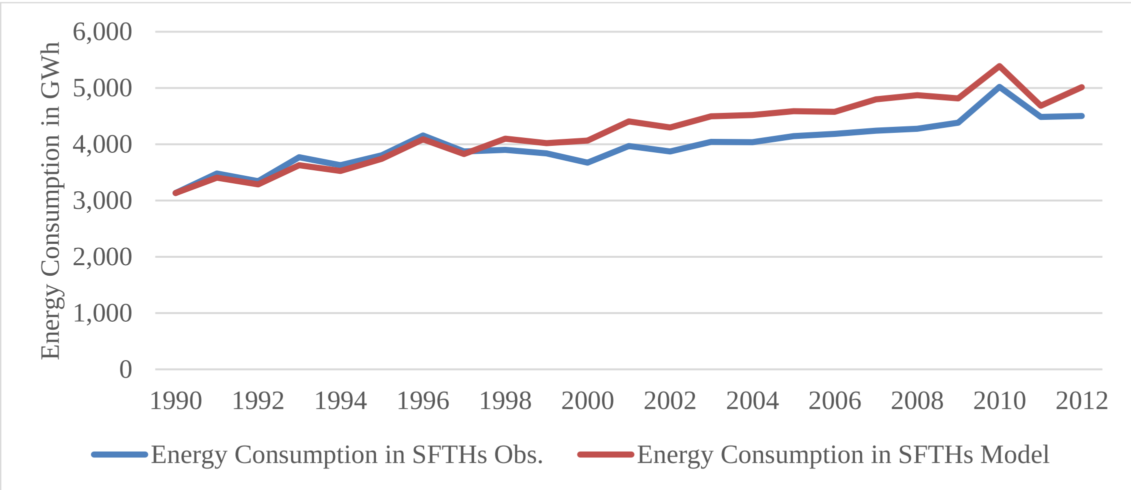

Figure 10: Energy consumption for space heating in Single-family Terraced houses in GWh- model vs observation

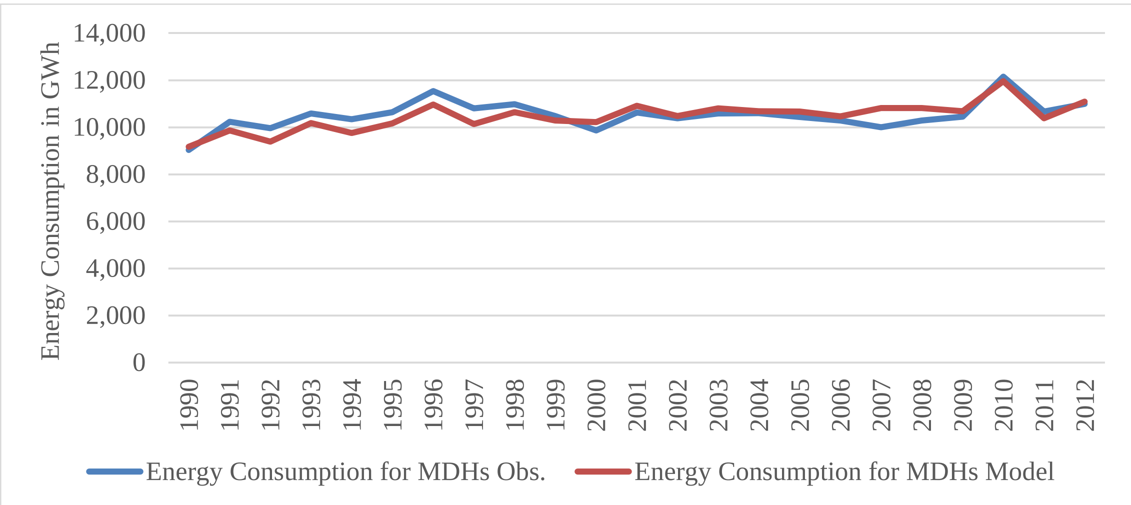

Figure 11: Energy consumption for space heating in Multi-dwelling houses in GWh- model vs observation

3.3. Retrofitting Scenario

During the last decade, several standards and regulations regarding energy consumption of buildings have emerged with the focus on new buildings, specifying increasing levels for energy efficiency requirements. However, these standards provide less guidance on the renovation of existing buildings that will have to face similar challenges in the near future.

Appendix 6 in the Danish Building Regulations 2010 (BR10) contains a summary of measures that are often cost-effective to implement in relation to existing buildings undergoing renovation. Based on that guideline, the primary energy demand exclusive of renewables in kWh/m2 annually is reported in the SBI 2013 report for different building types, year of construction and heat supply fulfilling the energy requirements in BR10 for existing buildings undergoing major renovation. We have estimated the required energy saving in single-family houses and multi-dwelling houses to fulfill the energy requirements in the Danish Building Regulations (table 2).

Table 2: Retrofitting potential according to building regulation 2010 – own calculations

Building type and age category	Energy saving potential
Single-family house – Old Building	51.3%
Single-family house – Mature Building	36.4%
Multifamily house – Old Building	53.7%
Multifamily house – Mature Building	35.5%

The contribution of the present work is to study the long-term impacts of effectiveness of various policies in terms of energy savings from buildings in Denmark, considering the estimated energy saving potential in table 2.

4. Results & Discussions

After calibrating the model with the historical data, the model was used to simulate the Base scenario. In the Base scenario, it is assumed that households do not invest in energy-related renovations, and they do not conserve energy. Figure 7 demonstrates the change in the energy intensity of the three dwelling type-groups, as well as the average of the whole stock (the yellow line) in the Base scenario. Because of the construction of more efficient dwellings, and the demolition of inefficient old ones, the energy intensity levels are on the decline.

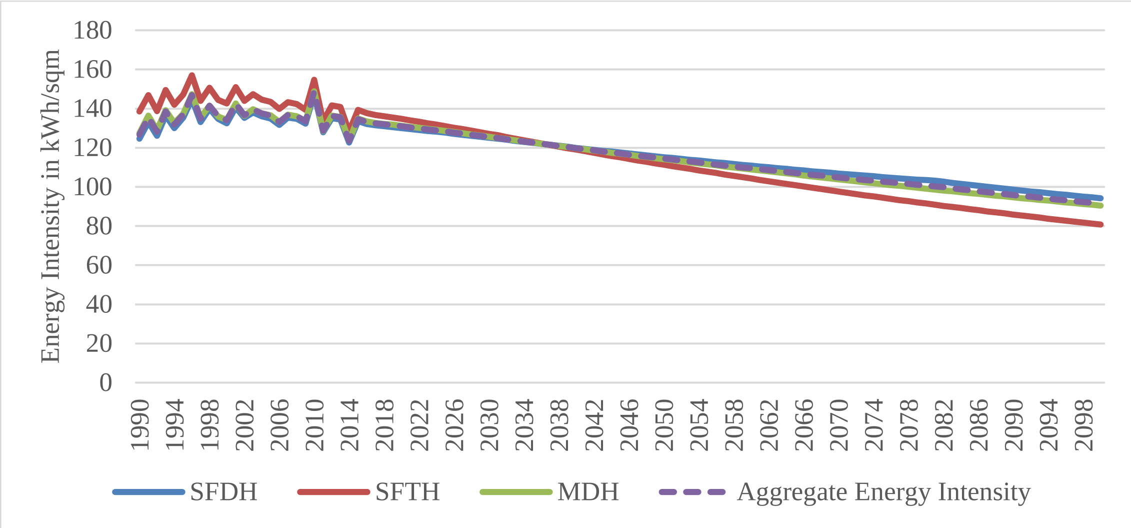

Figure 12: Projected energy intensity for three dwelling type-groups, as well as the average of the whole stock

Then, we were interested in analyzing the impact of policy scenarios in terms of energy saving and required investment.

First of all, we studied the scenario in which the proposed energy requirement for buildings becomes effective in 2020. Total energy consumption for space heating in base and BR20 scenarios are compared in Figure 13.

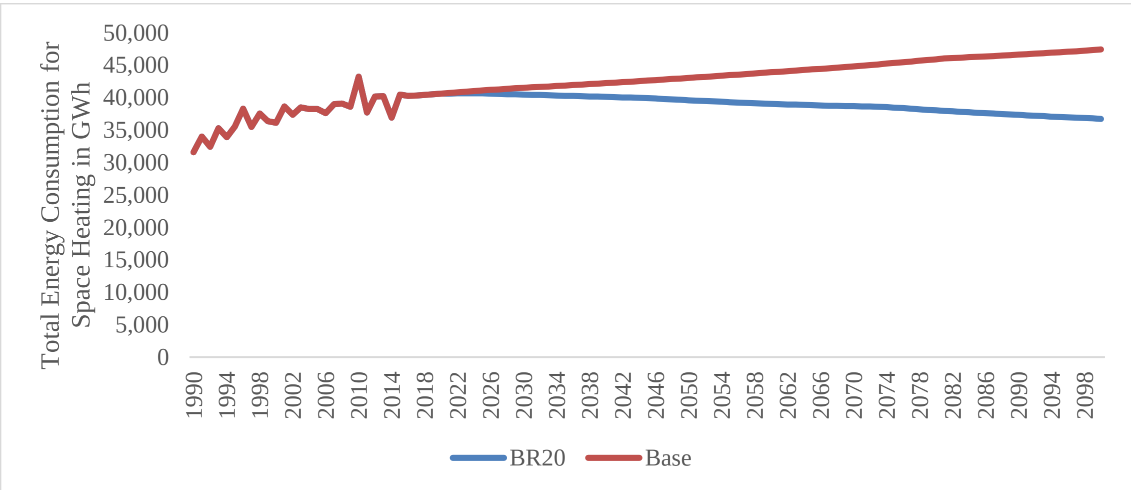

Figure 13: Total energy consumption for space heating in GWh

According to figure 13, the energy consumption for space heating in residential buildings is expected to decrease by 2.5% in 2030 and by 22.5% at the end of century. This insignificant reduction (0.3% per year) clearly indicates the importance of the extent of inertia caused by the existing building stock against an energy transition in the residential sector in Denmark.

To affect the stock turnover, there are two possible policies that should be assessed in terms of energy reduction potential; one is the scenario with a high construction rate (EU average level) and the other one is the demolition policy with a high demolition rate (+40% more than the historical trend). In order to see the potential effectiveness of such policies, the construction rates and the demolishing rates of all dwelling types are varied after 2015. The impacts of these two policies on space heating demand and energy intensity compared with the base scenario is shown in Figure 14.

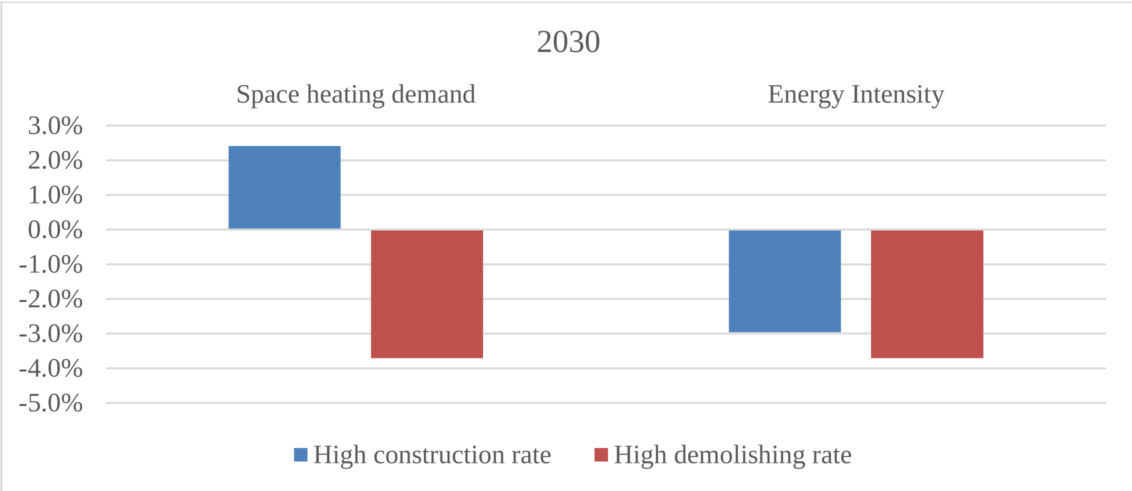

Figure 14: Impact of high construction and demolition rate on energy consumption for space heating and average energy intensity of building stock in 2030

Figure 14 shows that the changes in total space heating demand in 2030 are +2.4% and -3.7% in high construction and high demolition scenarios, respectively. However, both policies are effective in reducing the average energy intensity of building stock by more than 3% until 2030. This figure clearly shows that demolishing old buildings is significantly more effective in reducing the space heating demand compared to the investment on construction of new efficient buildings.

Next we run a set of scenarios to assess the potential of retrofitting. In the "R1" scenario the implementation of retrofitting measures was possible from 2015. According to BR10, if the annual saving from a retrofitting option multiplied by the lifetime, and divided by the investment, is greater than 1.33, that measure is deemed to be cost-effective and will be implemented. It basically means that applying that measure will pay for itself within 75% of its expected lifetime. In the "R2" scenario, we let the model choose from non-cost effective measure to reach the higher energy saving level (80%). Then, in the "R3" scenario, we included the financial incentives of 100 $/sqm for households. Figure 15 demonstrates interesting dynamics in these three retrofitting scenarios.

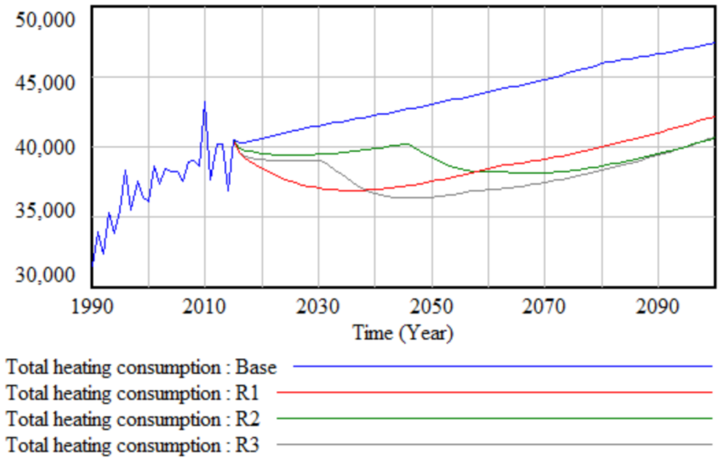

Figure 15: Comparison of total energy consumption for space heating in three retrofitting scenarios and base scenario

Compared to the base scenario, implementation of cost-effective measures will reduce the energy consumption for space heating by 10.7% by the end of the century, which is unexpectedly low. This trend is due to the impacts of the balancing loops that were discussed previously. Although the energy reduction was significant in the “R1” scenario at the beginning, the reduction trend vanishes after 2030. This behavior can be justified by the increase in energy consuming activities as a result of an improvement in the efficiency of buildings (the “rebound effect”). In the “R3” scenario, the more aggressive retrofitting plan resulted in reducing the total energy demand for space heating by 3.3% compared to the “R2” scenario. Providing the incentives to households increases the rate of retrofitting after 2030, but the differences in savings with “R2” disappears by the end of century. To analyze the overall impacts of rebound effect, in a hypothetical scenario of “R4”, we disconnected the link for the second balancing loop (B2). Figure 16 depicts the differences in total energy consumption in retrofitting scenarios.

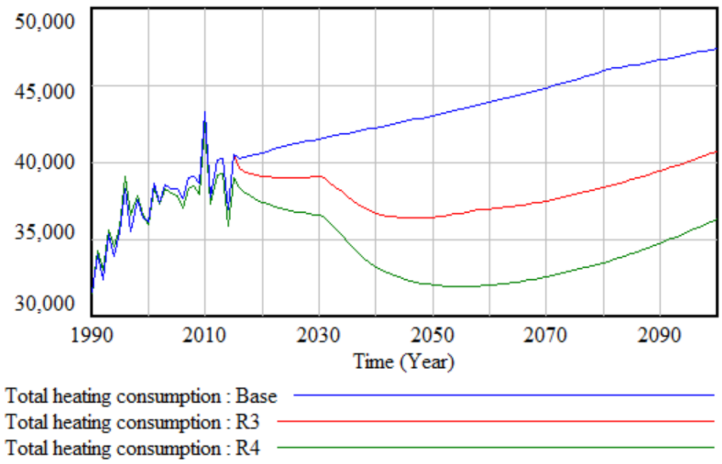

Figure 16: Total energy consumption for space heating in three retrofitting scenarios

The differences in total energy consumption between the "R3" and "R4" scenarios represent the increase in energy consuming activities motivated by rebound effect. Compared with the scenario with rebound effect, the reduction in energy consumption for space heating has increased to 6.1% and 9.2% in 2030 and 2100, respectively. In the integrated scenario "I1", we assumed that the proposed building regulation will be in place in 2020 and this condition was added to the "R4" scenario.

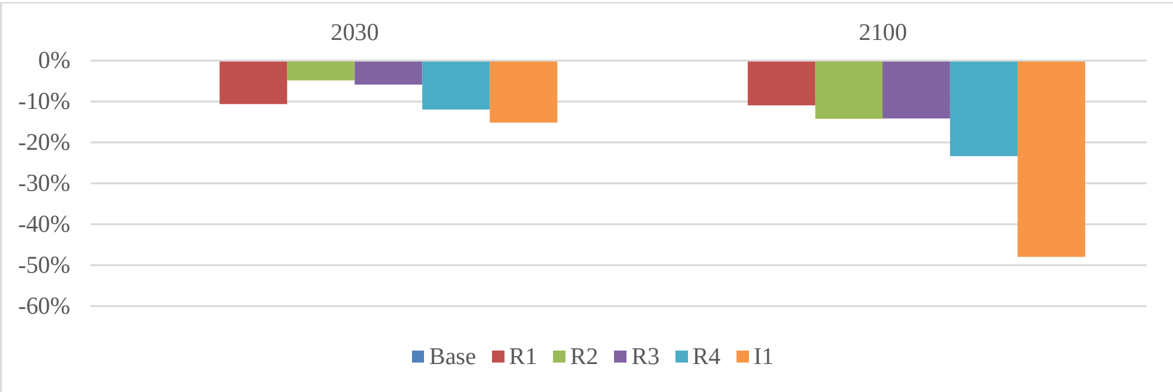

Figure 17: Energy consumption reduction by percentage in various scenarios

The significance of having tight building regulation in 2020 on reducing the energy consumption is clear in figure 17. Although the differences in 2030 are not significant, we can observe that the saving potential becomes much more evident by the end of the century.

At this point, a comparison of the total costs for retrofitting in different scenarios is critical to have a better understanding of the effectiveness of policy scenarios. In this study, total costs covers the investment cost for retrofitting to the households and the costs of incentive policies to the policy makers.

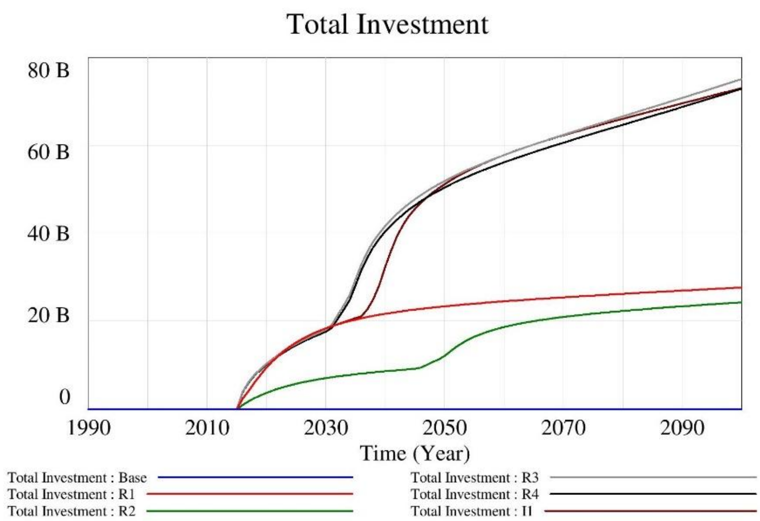

Figure 18: Comparison of total cost for five policy scenarios in USD

According to Figure 18, the total investment costs for cost-effective measures in “R1” scenario can reach 18.38 and 27.66 billion USD in 2030 and 2100, respectively. As expected with having an incentive policy in the “R3” scenario, the total cost dramatically increases compared to “R2”. But, considering the fact that the proposed retrofitting measures by building regulation are cost effective, we believe that this huge investment of 75.05 billion USD until 2100 is driven by the “free rider" effect. Free riders are people who would invest in retrofitting anyway, so they shouldn’t receive the incentives. Therefore, it’s critical to keep in mind that the estimated total costs should be interpreted cautiously. Besides, Figure 18 shows the reduction in total cost by having the building regulation in place in 2020 by 2.7% in 2100.

5. Conclusions

As the building stock turnover is slow in the Nordic countries (on the order of 1% per year), the majority of opportunities to improve efficiency over the next several decades will be in existing building stock, most of which is constrained by old equipment, aging infrastructure, and inadequate operations resources. One of the key obstacles to study the inertia in detail is the analytical difficulty considering the interrelated processes of dwelling age, new construction, demolition and retrofitting.

In this study, we develop a dynamic building stock model, which captures the impacts of physical processes such as aging. We also illustrate the importance of behavioral dynamics by focusing on the key processes affecting the implementation of retrofitting measures: word of mouth, social exposure and the willingness of the consumer. Initially, we compared the impact of a high construction rate with a high demolition rate.

It was found that although the total energy consumption has slightly increased in the case of higher construction, they are both effective in reducing the average energy intensity of building stock by 3% until 2030. In this analysis, four balancing loops have been identified as major challenges that restrict the implementation of retrofitting measures, and also the benefit from these efforts. Calibrating the model to Danish conditions, five policy scenarios are compared to a base case focusing on energy consumption and total cost.

Primarily, we estimated that the implementation of cost-effective measures can reduce the energy consumption for space heating by 11.0% by the end of century, which is surprisingly low. Although the energy reduction was significant in the “R1” scenario at the beginning, the reduction trend vanishes after 2030. Due to the insignificant saving, the “R2” scenario with aggressive retrofitting measures, and a scenario with financial incentive “R3” were analyzed. Total energy consumption for space heating is expected to fall by 3.3% and 3.2% in “R2” and “R3” compared to “R1”. Then, a scenario “R4” was studied where the impacts of rebound effect are limited. Compared with “R3”, the reduction in energy consumption for space heating in “R4” has increased to 6.1% and 9.2% in 2030 and 2100, respectively. The significance of having tight building regulation in 2020 on reducing the energy consumption was assessed in “I1” scenario and the estimated energy saving in 2100 is 48.0%.

We have also compared the scenarios in terms of total costs. According to Figure 18, the total investment costs for cost-effective measures in the “R1” scenario can reach 18.38 and 27.66 billion USD in 2030 and 2100, respectively. As expected with having incentives for households in the “R3” scenario, the total cost dramatically increases compared to “R2”. But, considering the fact that the proposed retrofitting measures by building regulation are cost effective (in the “R1” scenario), we believe that the significant share of the 75.05 billion USD investment until 2100 is driven by “free rider" effect. Therefore, it’s critical to keep in mind that the estimated total costs should be interpreted cautiously.

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