Energy transitions in Built Environment of Netherlands: A System Dynamics approach to diffusion of Solar boilers and Insulation

Tariq Abdul Muhaimin **Mavroeidis Nikolaos**

Faculty of Technology, Policy and Management
Delft University of Technology
Jaffalaan 5, 2628 BX, Delft
Telephone: + 31 15 27 89801
tariq.abdul.m@gmail.com ; mavroeidis.n@gmail.com

Abstract

In context of rising demand for energy amidst limited resources, energy efficiency is one of the major concerns of a modernized world. Gas consumption in the built environment constitutes for more than 30% of the overall energy consumption in the world. Hence, energy transitions and their preferences in the built environment demand urgent attention by policy makers in order to implement cost-effective and long-term sustainable policies. However, the highly dynamic nature of decision making adopted by households involves complex interaction between various factors. Therefore, in this study, a modified Bass diffusion structure was used in a System Dynamics model to examine energy transitions and subsequent reductions in overall gas consumption in the built environment of Netherlands. Specifically, the gas consumption by different types of owner-occupied houses was studied by considering the probability of adoption of solar boilers and/or insulation by these households. Also, the effect of different policy measures such as subsidies, demolition, innovation driving, and increased advertisement/awareness, under different scenarios, was evaluated. These experiments confirmed that there is great potential for energy saving in the building sector. Moreover, policies that focus on changing people's behavior were found to be more effective in the energy transitions process.

Keywords: System Dynamics, energy transition, gas consumption, solar boilers, insulation, Built Environment, Netherlands

1. Introduction

In the last two decades, issues such as global climate change, security of fossil fuel supply, and potential risk of future fossil fuel scarcity have led to discussions and policies aiming for transitions to energy sustainability at both national and international levels. In March 2007, the Brussels European Council acknowledged the importance of energy conservation and called on European Union (EU) member states to pursue actions to develop a sustainable integrated European climate and energy policy (Council of EU, 2007). In their statement, EU leaders made a firm independent commitment to achieve at least 20% reduction in greenhouse gas emissions by 2020 compared to 1990. They also endorsed the EU aim of having a binding target of a 20% share of renewable energies in overall EU energy consumption by 2020.

In northern European countries such as The Netherlands, built environment contributes to about 30% of the total energy consumption (Ministry of the Interior and Kingdom Relations, 2011; ING, 2013). Moreover, a major part of the total Energy consumption by households takes place in the form of *natural gas consumption* for the purposes of water and space heating. Acknowledging this great potential for energy saving, the Dutch Ministry of Interior and Kingdom Relations published the *Plan of Action: Energy Saving in Built Environment* in 2011. In this plan, the Ministry concluded that "by changing heating behavior, or installing insulation or improving insulation, users or owners can ensure less energy is consumed" (Ministry of the Interior and Kingdom Relations, 2011).

Till date, several researchers have tried to analyse the impacts of policies related to energy transitions in the built environment. While some researchers focussed on the prevailing inertia in the built environment sector due to old-age dwellings (Yucel, 2013), others have studied the impact of energy-efficient innovations like building designs on the overall energy consumption (Grosser et al., 2006). A few others have also evaluated the impact of energy performance indicators like energy labels adopted under the *Energy Performance of Building Directive (EPBD)* (BPIE, 2010; Beerepoot, 2007). But, direct evaluation of policies that aim at impacting household behavior through the adoption of energy efficient measures like solar boilers and/or insulation of buildings is missing.

In this paper, the effectiveness of four policies that aim to promote the adoption of solar boilers and/or insulation measures by Dutch households is studied. The policies selected for this study are: demolition of old-age dwellings and construction of new insulated dwellings, provision of income-based subsidies for solar boilers and insulation, investment in solar boiler and insulation related R&D, and advertisement/awareness creation. Since the system involves complex interrelations between different factors like dwelling age, new constructions, demolitions, renovations and occupant behavior, a System Dynamics model was used for this study in order to capture important feedback effects.

The paper is structured as follows: the following section introduces the scope and structure of the simulation model. Then, Section 3 elaborates the simulation experiments that were performed on the SD model. This includes an impact study of the four policies. Section 4 is dedicated to general conclusions and indications for possible future research.

2. Model description

The objective of the model is to simulate the aggregate natural gas consumption in owner-occupied residential buildings of The Netherlands. Till date, about 56% of the Dutch housing stock is owned by occupant-owners, and it is predicted that this percentage will increase to 70% in the near future (Bogerd et al., 2009). Hence, a commitment towards energy-saving among owner-occupied households is highly important to achieve the targeted reduction in CO_2 emissions. The model focuses on the energy consumed for domestic water and space heating in dwellings, since this constitutes a major portion (i.e., 70–80%) of the total residential energy consumption (Yucel, 2013). The natural gas consumption by households depends mainly on the dwelling type, dwelling age, and occupant's response to various socio-economic factors. Accordingly, the factors that are used to formalize the decision making process by households (in regards to adoption of energy efficient measures) are shown in Figure 1.

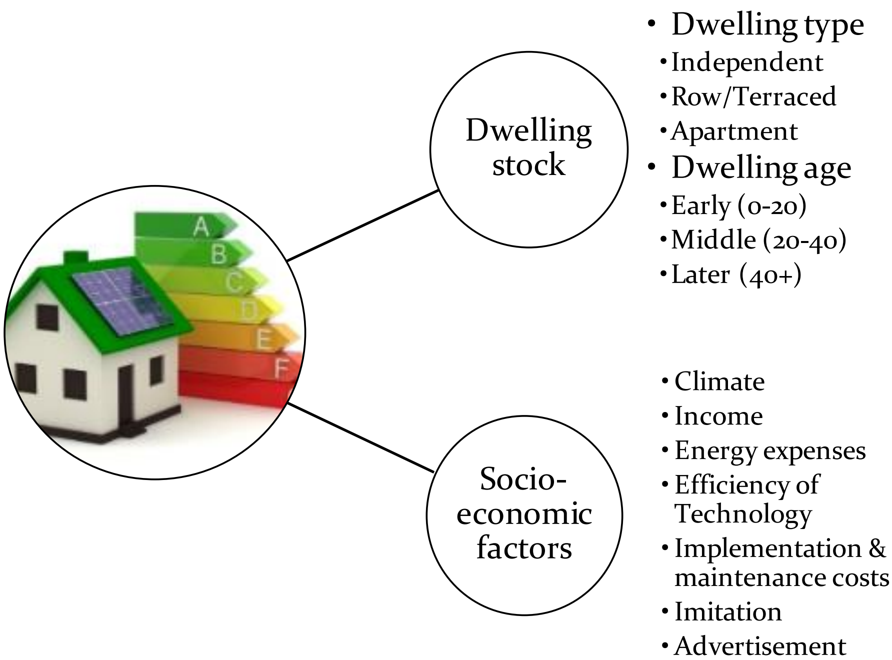


Figure 1: Factors involved in energy transition decision making by households

In brief, socio-economic factors (e.g. income, energy expenses, etc.) as well as climatic conditions influence the natural gas demand of a household in the model. This demand coupled with the quality of the dwelling (determined by its age and type) determines the final natural gas consumption by that dwelling. Hence, the System Dynamics model that simulates the total natural gas consumption of the Dutch housing sector covers the following aspects in order to simulate aggregate consumption at the national level.

2.1. Dwelling stock

As shown in Figure 1, the quantity aspect of the housing stock (the number of dwellings), and the quality aspect of the housing stock (energy efficiency of the dwelling) were modelled by considering the subdivision of this stock into different groups. Because of the vast diversity in the type of dwellings, homogenising the Dutch housing stock may result in the overlooking of important dynamics. On the other hand, trying to capture diversity in its full scale may result in a model that is of little use due to its level of detail. Considering this trade-off, the Dutch housing stock can be grouped under three main categories: Independent dwellings, row/terraced dwellings, and apartments (see Figure 2). The total Dutch dwelling stock and the

Independent dwelling | *Row/Terraced dwelling* | *Apartment/Gallery flat*

Figure 2: Representative dwelling types

distribution of different types of dwellings are shown in Figures 3 and 4.

According to Yucel (2013), Gallery flats are predominantly social housing units, which accommodate low-income families and detached dwellings are commonly occupied by high-income households. This fact was used in the modelling process in order to consider the differential decision making aspect of different income groups.

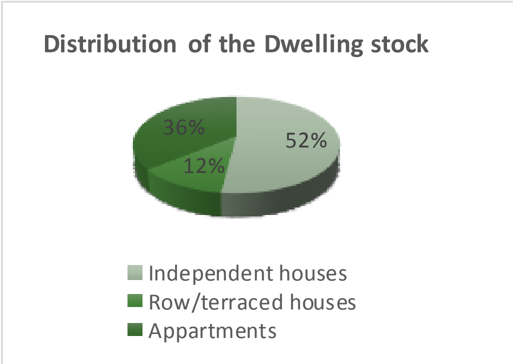


Figure 3: Distribution of dwelling stock (2000) (Yucel, 2013)

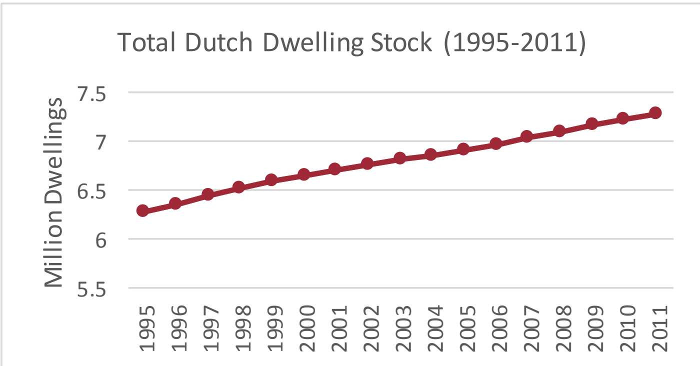
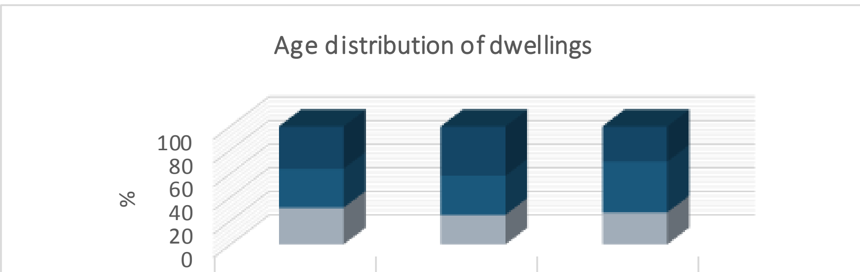


Figure 4: Total Dutch Dwelling Stock (Yucel, 2013)

While describing the housing stock, another very important aspect, with respect to energy efficiency, is the Dwelling age. Capturing the age distribution of the dwelling stock is important because important characteristics such as construction materials used, technology employed etc., during construction of dwellings change based on the time period in which it is built. Also, the age distribution of dwelling stock is not uniform. This is primarily because of changes in demand for housing over the years. The distribution of dwelling age in The Netherlands as of year 2000 is shown in Figure 5.



	Independent	Row/terraced	Appartments
40+	36	42	30
20-40	33	33	43
0-20	31	25	27

Figure 5: Age distribution of Dutch dwelling stock (2000) (Yucel, 2013)

To capture these incumbent fluctuations in the number of dwellings with different service times, the age distribution of dwellings is classified into three stages (or age categories). The first two age groups are of a 20-year duration, while the later stage category consists of buildings that are more than 40 years old. The decision of dividing the stock into these durations was taken due to data availability. But before doing this, the total Dutch dwelling stock is divided into four parts – Households with no insulation or solar boilers, Households with only insulation and no solar boilers, Households with no insulation and only solar boilers, and Households with both insulation and solar boilers. Each of these parts are modelled as a separate stock. And within each stock, the three age categories were introduced at the micro-dynamics level (Fallah-Fini et al., 2013) using the subscripting function of Vensim.

Figure 6 shows the dwelling stock structure that was made for No-insulation and No-solar households. Within this structure, an aging chain is modelled. The 'years in each age group' variable was initialized to 20 and used only for the early and medium stages. The age duration of the later stage category is determined by the demolition rate for that particular type of household. Although theoretically the useful service time of a dwelling ranges between 75 and 100 years, historical figures in The Netherlands show that the fraction of dwellings that are being demolished annually ranges between 0.15 and 0.35% (Yucel, 2013). Hence, when a rough estimation is done, these figures suggest an average service time greater than 200 years. Based on this data, the demolition rates of independent houses, Row houses, and apartments were initialized to be 0.005, 0.008 and 0.01 respectively, indicating an average service time of 200 years, 125 years and 100 years.

Figure 7 shows the conceptual model representing the movement of households from one stock to another. The four blocks present at the four corners of this figure represent the dwelling stock that was divided into households without Insulation or Solar boilers (NI-NS), Households with Insulation but no Solar boilers (WI-NS), Households without Insulation but with Solar boilers (NI-WS), and Households with both Insulation and Solar boilers (WI-WS). Each block also shows the subdivision of these households into the early stage, middle stage and later stage. Within each of these stages, again the households were classified into four income groups – First Quartile, Second Quartile, Third Quartile, and Fourth Quartile.

2.2. Income Groups

Based on the World Development Indicators' database of The World Bank, the gross national income (GNI) at purchasing power parity (PPP) per capita of Netherlands in 2010 was classified into the following five quintiles: €11994 for the first 20%, €20864 for the second 20%, €27209 for the third 20%, €36709 for the fourth 20%, and €61045 for the fifth 20% (calculated using the average exchange rate of 2010: 1 $ = 0.755 €) (World Bank, 2014). However, in order to reduce complexity and considering the fact that the results will probably overestimate income in poorer quintiles and underestimate income in richer quintiles because the shares were calculated by ranking households, and not persons, the representative incomes for the four income quartiles in this model were set as: First quartile – €10000, Second quartile – €20000, Third quartile – €40000, and Fourth quartile – €70000.

These income groups, along with the dwelling type, dwelling age and other socio-economic factors were then used to model household behavior and decision making process. This has been explained in detail in the next subsection.

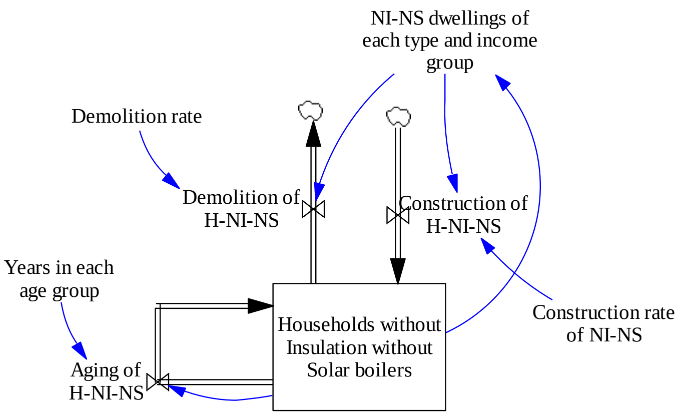


Figure 6: Dwelling stock used for modelling No insulation-No Solar households

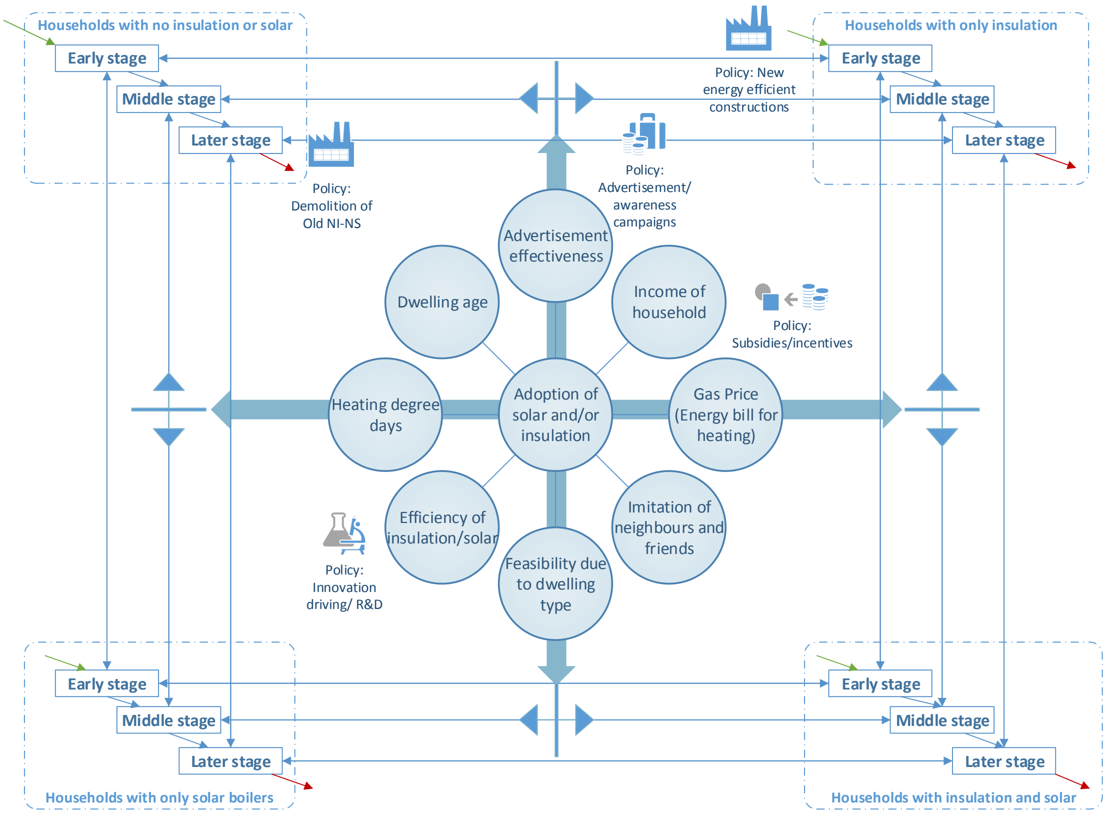


Figure 7: Conceptual Model

2.3. Household behavior and Decision making

The central structure of the conceptual model in Figure 7 shows all the factors that were used to model the decision making process. As pointed out by other researchers (Ben Maalla & Kunsch, 2008; Yucel, 2013), the behavior of households with respect to their reaction to energy expenditures is extremely important. This factor was modelled as the willingness of households to adopt insulation and/or solar boilers based on the amount that they are willing to spend on energy related expenses; and this differs for each income group. Apart from this, the technical factors related to the feasibility of households to adopt either of the two technologies are also important (Van Raaij & Verhallen, 1986). This feasibility, which is mainly based on the household type and technical efficiency of each technology, was modelled as *Attractiveness of Insulation/Solar*. Also, social influences play a very important role in determining the adoption rate of a particular technology. Hence, the effect of advertisements and influences through physical contact like mouth-to-mouth discussions were modelled as *Adoption from advertising* and *Adoption from word of mouth*. In the SD model, a modified Bass diffusion structure as shown by Sterman (2000) was used to incorporate this adoption process. The equations used for the adoption rate are given below:

$$AR = W \cdot AoT \cdot \left(Ad + WoM \right)$$

where

AR:Adoption Rate

W:Willingness to adopt

AoT: Attractiveness of Technology

Ad: Adoption from advertising

WoM: Adoption from Word of Mouth

$$Ad = Ef \cdot F \cdot P$$

where

Ad:Adoption from advertising

F:Feasibility of technology per type and age of dwelling

P:Potential adopters

$$WoM = c \cdot af \cdot F \cdot P \cdot \frac{A}{D}$$

where

WoM: Adoption from Word of Mouth

c: contact rate

af: adoption fraction

F: Feasibility of technology per type and age of dwelling

P: Potential adopters

A: Adopters

D: Total Dwellings

The two primary feedback structures that drive adoption of a technology are shown in the Causal loop diagram of Figure 8. The first loop depicts adoption by households based on the percentage of income that they are currently spending on energy expenses. The current spending is compared with the percentage of income that they are willing to spend. This is a negative feedback loop because an increase in the number of insulated/solar-adopted houses will decrease the overall aggregate gas consumption and in turn decrease the average willingness to adopt. The second important loop is the effect of implementation cost, maintenance cost and efficiency on the adoption. These 3 factors together determine the attractiveness of technology. With more houses adopting insulation and/or solar, the learning curve effect causes a positive feedback loop to function here (Kersten et al., 2011; Mályusz & Pém, 2013). Thus, the overall adoption rate of a particular technology is a function of all these factors. However, the values of several exogenous variables were determined based on an approximation of available information/data. These have been indicated in the following subsection.

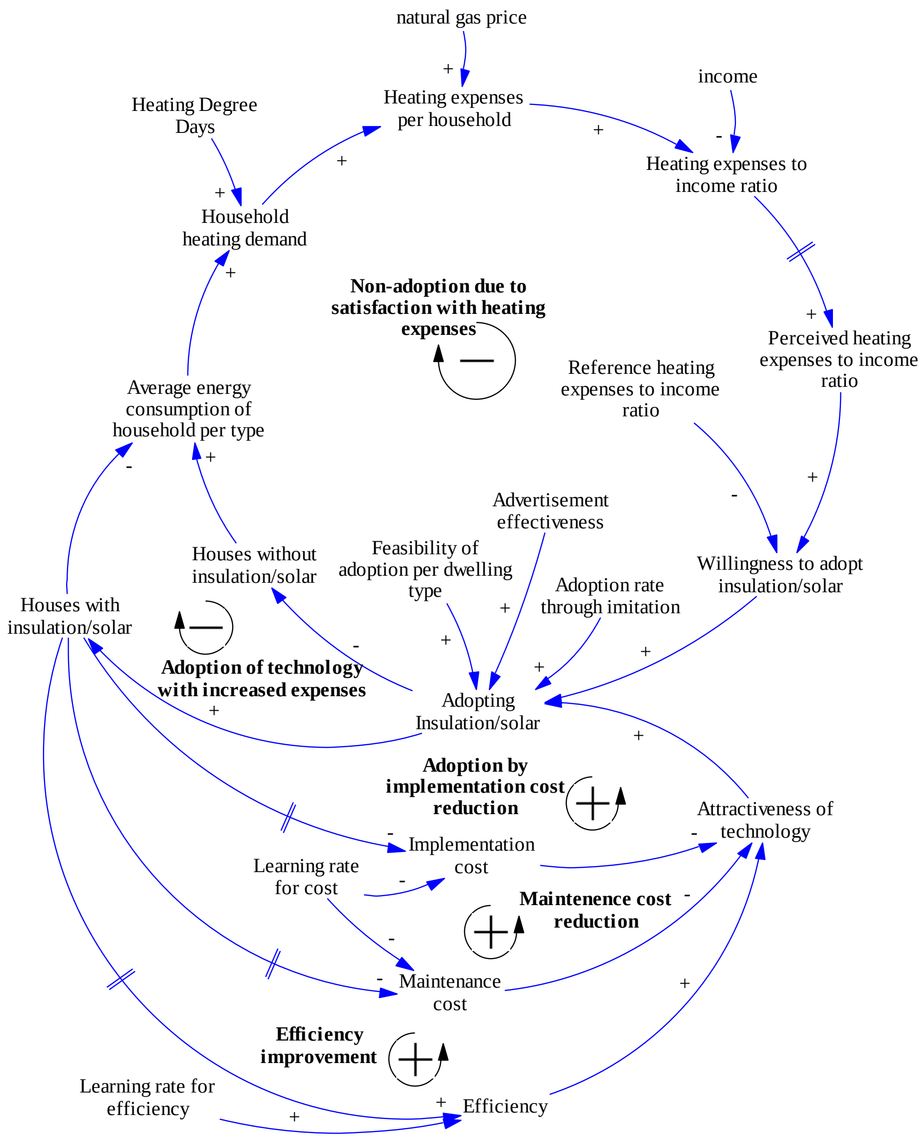


Figure 8: Causal Loop Diagram for decision-making by households

2.4. Primary assumptions in the model

A few important constants that were assumed are: advertisement effectiveness factors, implementation costs, natural gas price, learning rates of cost and efficiency, contact rates, reference heating expenses to income ratio, feasibility of adoption based on dwelling type, convincing degree, construction rates and demolition rates of different types of houses. However, to prevent any bias, the model was subjected to sensitivity testing for a wide range of values in these variables. The Key Performance Indicators (KPIs) were not found to be behaviorally sensitive to +/- 10% changes in these constants. Hence, the assumed values could be effectively used for studying the long-term behavior of this system, if not for exact estimation of outcomes. But, as mentioned before, the purpose of this model is only to observe the possible behavior of the system as a whole under different policy measures.

2.5. Model boundaries

Before moving on to the simulation experiments, it is important to point out that the model used for this study has certain well defined boundaries. Most importantly, it considers only owner-occupied residential buildings because of their ability to take decisions related to the adoption of either of these two technologies. The Bulls eye diagram of Figure 9 shows the variables/parameters that are included and the ones that are excluded for this study. Some technical aspects related to houses are kept outside the model boundaries because of the non-relevance of such micro aspects while studying the aggregate/overall behavior.

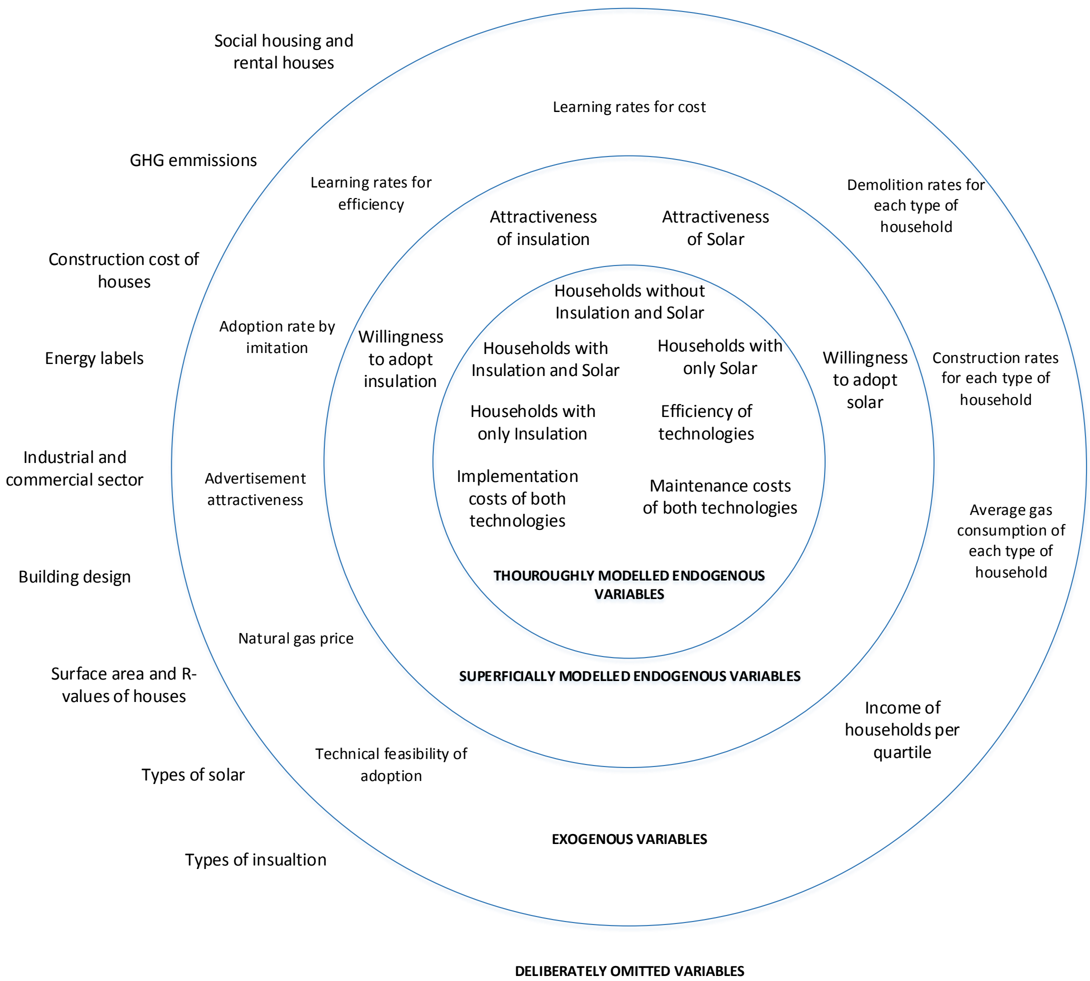


Figure 9: Bulls eye diagram of model boundaries

3. Simulation experiments

As mentioned in Section 1, the primary objective of this study is to gain a generic insight into the adoption trend of two energy efficient technologies – Insulation and Solar boilers – under four different policy measures. Accordingly, only relevant results of different experiments performed on the model are produced here. The variables that served as Key Performance Indicators (KPIs) in this model are: 1. Total gas consumption (in m^3), 2. Total households with/without insulation and/or solar boilers, 3. Willingness to adopt insulation/solar boilers, and 4. Attractiveness of insulation/solar boilers.

Prior to entering the experimentation phase, the model was also tested for validity of both its structure and expected behavior in order to see if it serves the purpose at hand. For this, the established verification and validation procedures proposed in the field (Sterman, 2000) were used. It is concluded that the model serves fit for the purpose at hand.

In this section, the baseline case is first established in order to demonstrate the aggregate gas consumption trend without any policy interventions. Then, the impact of four policies – demolition of old-age dwellings, provision of income-based subsidies for solar boilers and insulation, investment in solar boiler and insulation related R&D, and advertisement/awareness creation – is studied in comparison with this baseline behavior.

3.1. Baseline case

The baseline/reference case is a completely hypothetical case that can help in drawing a baseline for the gas consumption trend in the owner-occupied residential sector of Netherlands. In order to arrive at this, it is assumed that households continue to adopt either/both Insulation and/or Solar boilers at the rate at which they do at present depending on the values presumed for different constants and parameters in the model. Also, the dwellings continue to exist as they were built i.e., the rate of building new Insulated houses or houses with Solar boilers remains the same throughout the timeline of 2013 – 2050.

As shown in Figures 10 and 11, in the reference case the total owner occupied dwellings increase while the overall gas consumption decreases. This is caused by the fact that households that have implemented at least one of the two technologies will eventually implement the other one too; and most new constructions are already assumed to be insulated. Also, as shown in Figure 12, the first quartile households are willing to adopt energy efficient technologies more than the other quartiles because their heating expenses devour a large share of their total income. However, they do not proceed to implementation because the *attractiveness of a technology* (as shown in Figures 13 and 14) considers the cost aspects of implementation; and implementation cost is a big obstacle for the first quartile households. But, the attractiveness of solar boilers is higher than that of insulation and more equally spread because of relatively lower implementation costs.

The fluctuations observed in the *willingness to adopt a technology* (as shown in Figure 12) are caused due to the influence of climatic conditions on the perceived need to adopt insulation/solar boilers by households. In the model, these fluctuations in climatic conditions are introduced through the use of Heating Degree Days (HDD). The willingness to adopt a second technology, if they already have one, is found to be less than half of the willingness to implement it for the first time. However, through imitation and advertisement there is a constant increase in this rate.

A sensitivity analysis on parameters like “contact rate”, “feasibility of technology”, “learning rates” showed mainly numeric sensitivity. Scenario-testing on *HDD* and *natural gas price* showed that the willingness to adopt, and therefore the energy transitions, are comparatively lesser in the “low” value scenarios.

Therefore, without implementation of any policy the total gas consumption is found to be diminishing. However, since a higher rate of transition is desired, four different policies are explored. The following subsections discuss the impact of these policies.

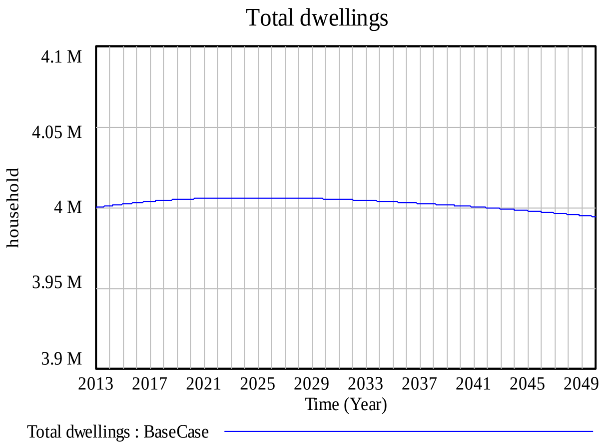


Figure 10: Total Dutch dwelling stock (reference case)

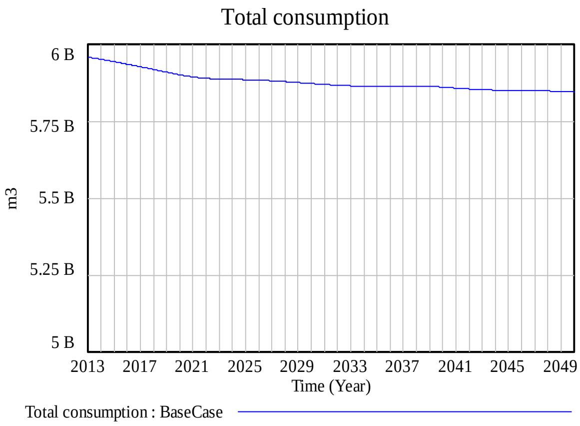


Figure 11: Total gas consumption (reference case)

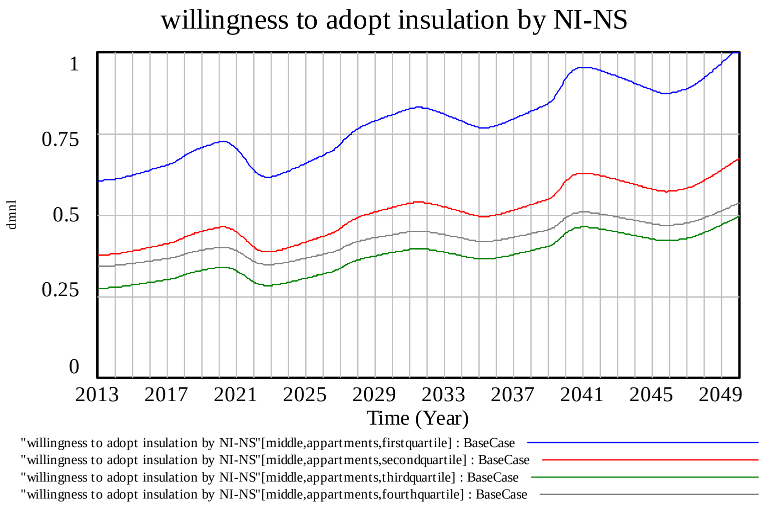


Figure 12: Willingness to adopt insulation by households without Insulation or Solar (based on income quartiles)

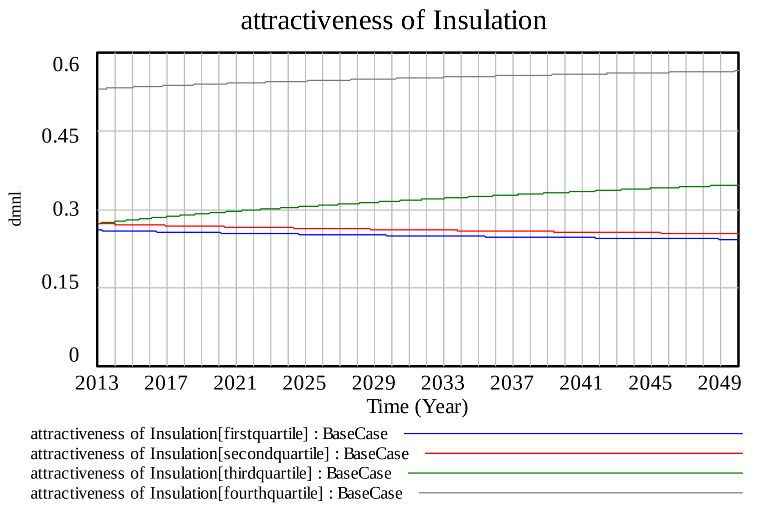


Figure 13: Attractiveness of insulation by households (based on income quartiles)

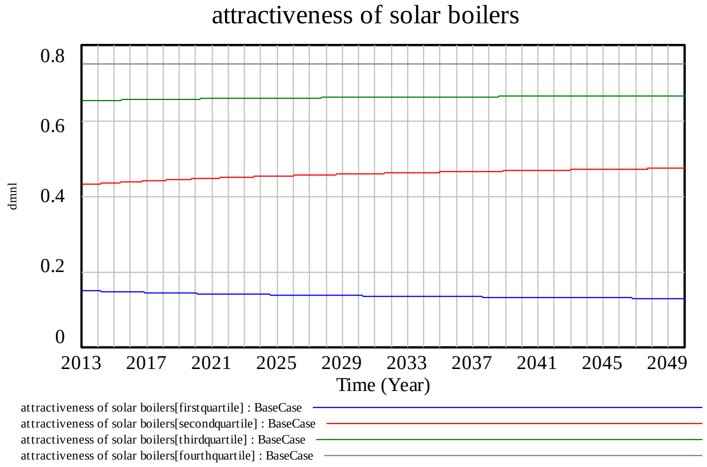


Figure 14: Attractiveness of Solar boilers by households (based on income quartiles)

3.2. Demolition policy

The reference case experiment is extended by introducing a policy that aims at promoting the demolition of later stage dwellings that do not have insulation or solar boilers. Also, the construction of dwellings with insulation is promoted. This policy could be implemented by setting a minimum level of insulation for new constructions.

In the experiment carried out using the model, this policy sets a target of doubling the demolition rate of dwellings that have no insulation or solar boilers between the years 2015 and 2035. The policy results in an increase of the demolition and construction rates as shown in Figures 15 and 16. Only the demolition and construction trends of apartments are shown in these two figures. After the implementation of this policy, the aggregate gas consumption is found to decrease immensely (see Figure 17). This is due to the change in composition of the dwelling stock. If this policy is implemented, the total number of dwellings with no insulation or solar boilers will decrease by a large extent and the number of dwellings with a certain degree of insulation increase. When this happens, households become more energy efficient as the preferred ambient temperature is maintained without the use of natural gas for space heating.

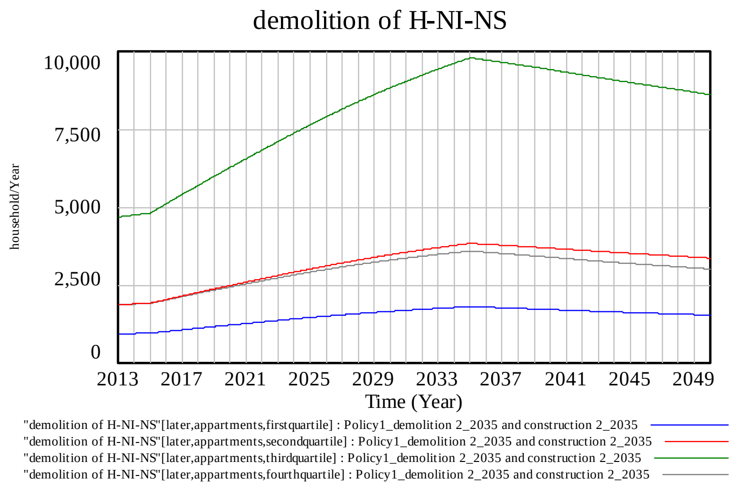


Figure 15: Policy - Doubling demolition rate of non-insulated and non-solar houses over 20 years

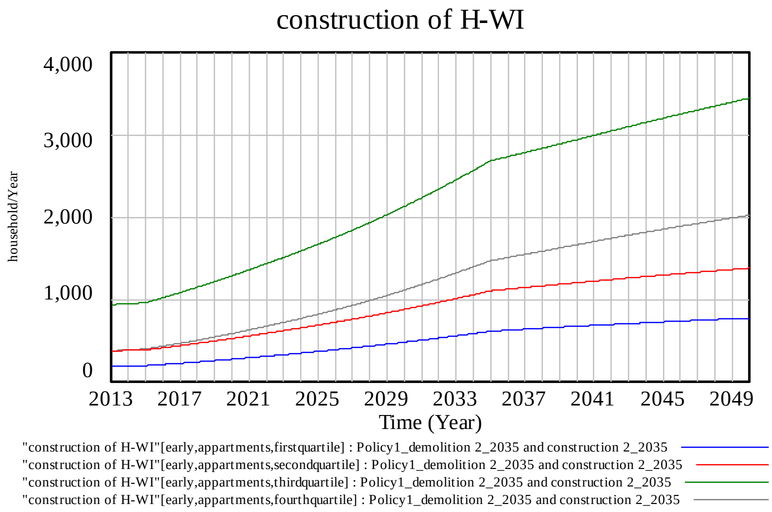


Figure 16: Policy - Doubling construction rate of insulated houses over 20 years

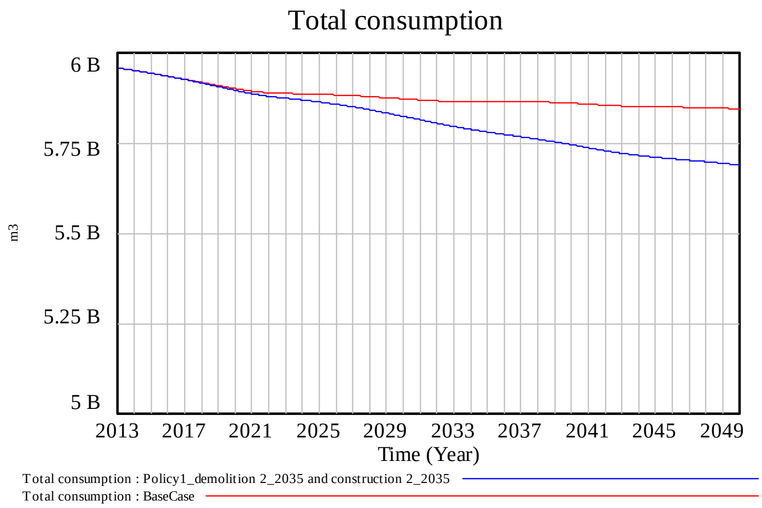


Figure 17: Total gas consumption after implementation of demolition policy

Also, as shown in Figure 17, this policy helps in setting the trend for a long-term impact on the aggregate gas consumption. Although the implementation of this policy is politically debatable, setting certain minimum allowable insulation standards will certainly facilitate the energy transitions process in the Built environment.

3.3. Subsidies policy

Another policy that is usually employed by government agencies while promoting certain technology or policy, is the provision of subsidies. In recent years, a budget of €121 million was made available under the Ministry of Housing, Spatial Planning & the Environment in order to support the agreements that were made under the Clean & Energy Efficient programme in The Netherlands (Ministry of the Interior and Kingdom Relations, 2011). This was used to create a diverse package of temporary stimulant schemes that would help in kick-starting the desired market development of energy efficient technologies.

In this experiment, the impact of this policy is measured under three possible scenarios: 1. Subsidies only for insulation, 2. Subsidies only for solar boilers, and 3. Subsidies for both insulation and solar boilers. Subsidies are provided as a percentage of the total cost of implementing either of the two technologies. Also, the subsidy percentages are higher for the low income groups and lower for the high income groups: first quartile – 60%, second quartile – 40%, third quartile – 20%, and fourth quartile – 10%. These subsidies are provided only for a 5-year period (2015-2020) in order to see if this policy can indeed help in kick-starting market development on its own.

As shown in Figure 18, the impact of providing subsidies on solar boilers is higher than the impact of providing subsidies for insulation. This is due to the relatively higher cost of insulation. Even after the provision of subsidies, very few households can actually adopt insulation measures since this involves renovating their existing house or completely demolishing and constructing a new one. Also, even if the subsidies given to insulation are set higher than those given to solar boiler installations, the diffusion towards solar boilers is found to be higher; this is because the overall implementation cost for insulation still remains higher. Additionally, when subsidies are provided for both insulation and solar boilers, there is not much change in the aggregate consumption trend when compared to the change caused by solar boiler subsidy.

Thus, the results show that the subsidies policy is highly effective in kick-starting the desired market development for solar boilers, but not for insulation. Moreover, these policies mainly affect the 1st and 2nd income quartiles. For them, the perceived attractiveness of solar boilers dramatically changes.

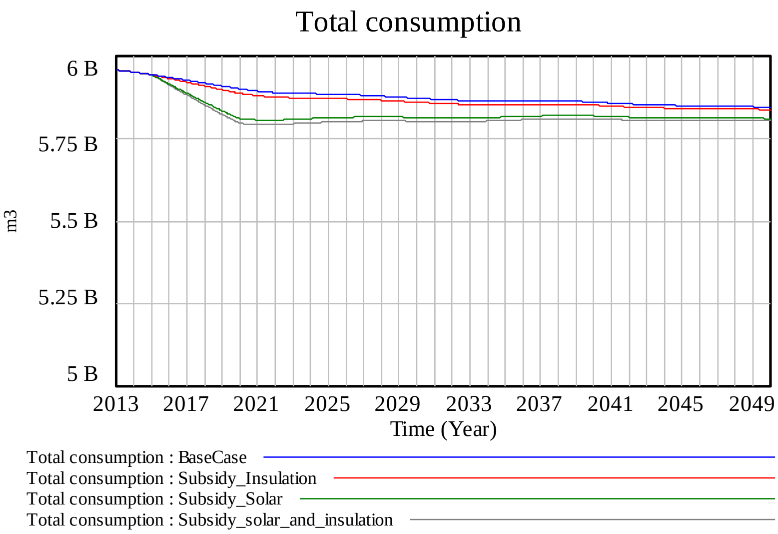


Figure 18: Aggregate gas consumption trend after implementing subsidies policy

3.4. Driving innovation and R&D

In their Plan of Action for Energy Saving in the Built Environment (Ministry of the Interior and Kingdom Relations, 2011), the Ministry acknowledges the importance of driving innovation and R&D in order to realize more energy savings in the long-run. The innovation program Energiesprong [Energy Leap] was taken up to stimulate these innovations. This aims for a reduction of 50% energy consumption in the built environment by 2030 (in comparison to 1990).

In this experiment, we examine the impact of a change in learning rates for both cost and efficiency of solar boilers and insulation caused through innovations and R&D.

First, the learning rates of both the implementation costs are subjected to sensitivity testing around the baseline value:

1. For learning rate of Insulation cost – Baseline: 0.6, Sensitivity: 0.3 - 0.9.
2. For learning rate of solar boiler cost – Baseline: 0.8, Sensitivity: 0.6 - 0.9.

The results of these sensitivity runs are shown in Figures 19 and 20. As can be seen, only a decrease in the cost of insulation will lead to a small decrease in energy consumption through higher adoption of insulation measures. However, there is no impact on the adoption of solar boilers even if the cost of solar boiler falls. This is because the cost of solar boilers is already very low.

The learning rates for efficiency of solar boilers and insulation are also subjected to sensitivity testing around the baseline value:

1. For learning rate of Insulation efficiency – Baseline: 0.6, Sensitivity: 0.3 - 0.9.
2. For learning rate of solar boiler efficiency – Baseline: 0.8, Sensitivity: 0.6 - 0.9.

The results of these sensitivity runs are shown in Figures 21 and 22. As can be seen, there is great potential for energy saving by causing an increase in efficiency of either or both technologies. Hence, while driving innovation, research that results in higher technical efficiency should be given preference to research that focusses on optimizing the cost of either technology in order to make it more accessible.

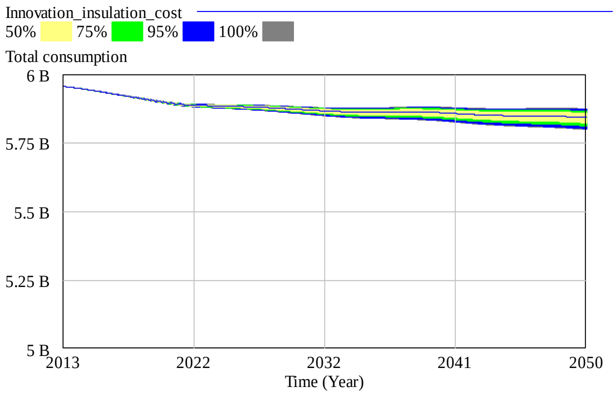


Figure 19: Sensitivity run for learning rate of insulation cost

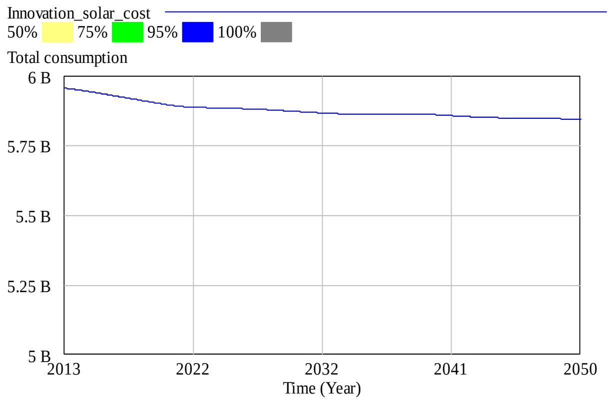


Figure 20: Sensitivity run for learning rate of solar cost

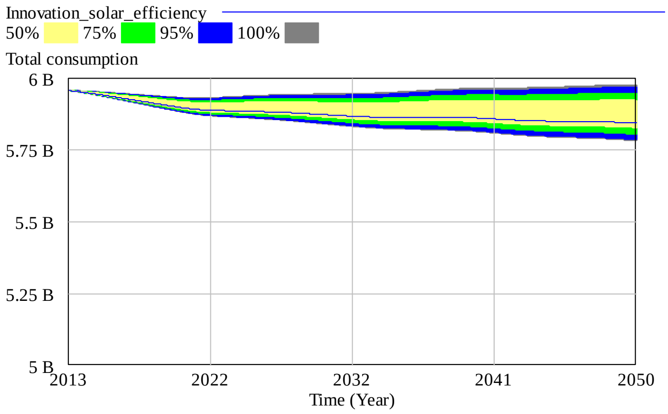


Figure 21: Sensitivity run for learning rate of solar efficiency

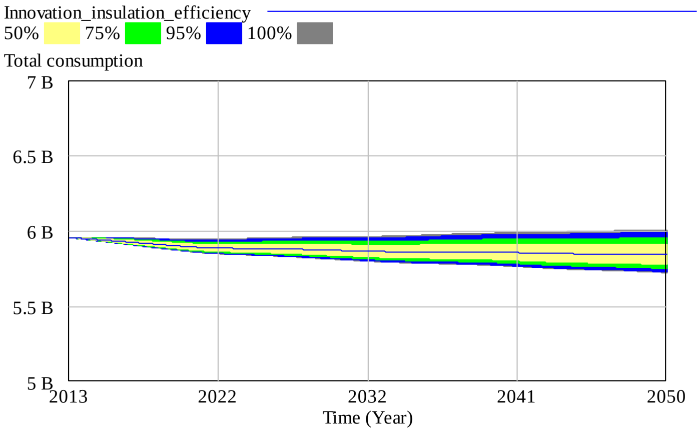


Figure 22: Sensitivity run for learning rate of insulation efficiency

3.5. Advertisement policy

The last policy that was tested for effectiveness was advertisement promotion/awareness creation. An advertisement/awareness policy can aim at increasing the effectiveness of advertisements or awareness programs that already exist. This can be done by increasing the number or the range of campaigns related to the adoption of solar boilers and insulation, or by focusing advertisement on smaller target groups (municipality level instead of national level).

For examining the possible effects of such an investment on advertisement, a sensitivity analysis was done for a wide range of advertisement effectiveness factor for both technologies. The factor was varied between 0 and 0.1 (baseline being assumed as 0.05 for both solar and insulation). Figures 23 and 24 depict the impact of increased advertisement effectiveness on the overall gas consumption. As can be seen, at higher advertisement rates there is considerable decrease in the aggregate gas consumption. This happens because of an increase in mouth-to-mouth adoption. As more households get exposed to these technologies, they not only adopt them (given that the other financial and technical aspects remain congenial) but they also communicate this to the households that have still not adopted. Also, as more households adopt either of the two technologies, the learning curves for both cost and efficiency grow at a faster rate and hence facilitate the growth again through a positive feedback loop (Kersten et al., 2011; Mályusz & Pém, 2013).

Interestingly, on implementation of this policy, the higher income quartiles have a higher rate of adoption than the lower income quartiles. This is conceivable due to the fact that lower income households are restricted by financial constraints even after being exposed to the use/impact of these two technologies. This variation in the rate of adoption by different income groups can be seen in Figures 25 and 26. Figure 25 shows the change in composition of the number of households with only solar boilers when the advertisement effectiveness of solar boilers is increased from 0.05 to 0.1. Figure 26 shows the change in composition of the number of households with only insulation when the advertisement effectiveness of insulation is increased from 0.05 to 0.1.

Hence, investing in advertisements or at least facilitating the awareness process will have a huge impact on the overall energy trend in built environment. However, this may not be a socially inclusive policy unless the lower income groups are being supported with subsidies also.

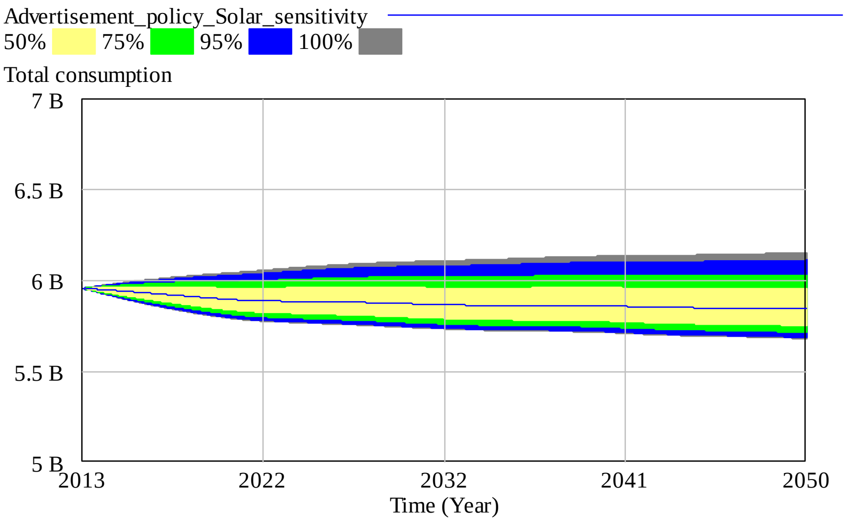


Figure 23: Sensitivity on advertisement effectiveness of solar

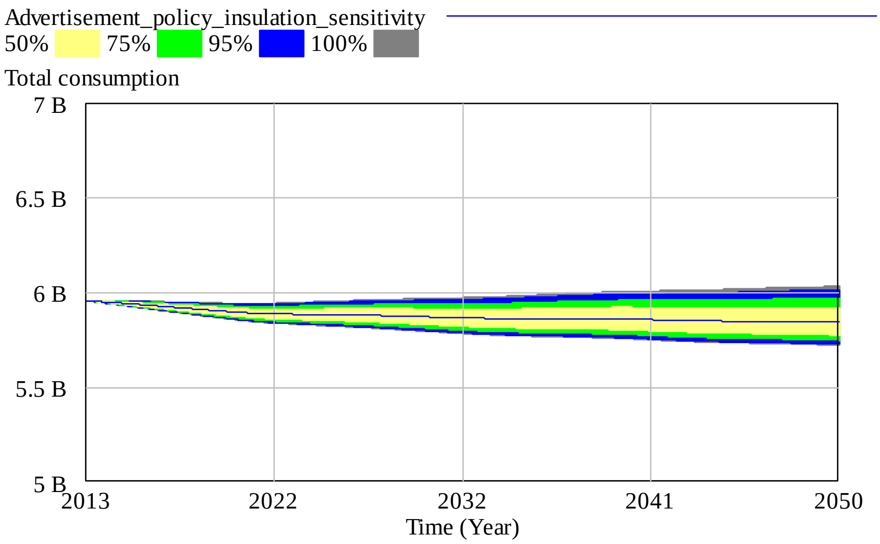


Figure 24: Sensitivity on advertisement effectiveness of insulation

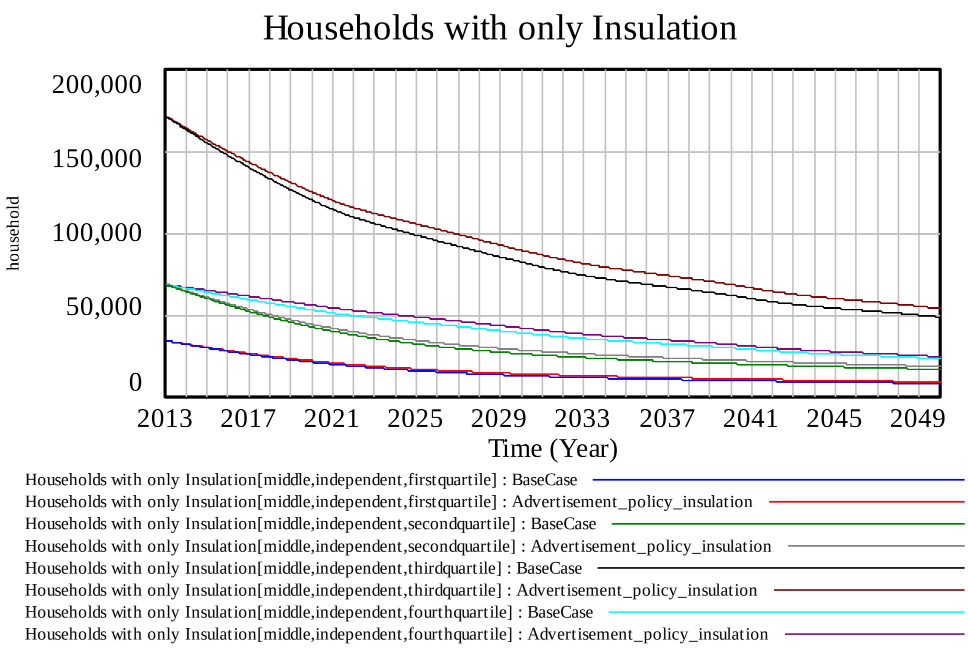


Figure 25: Impact of advertisement policy for only insulation (based on income groups)

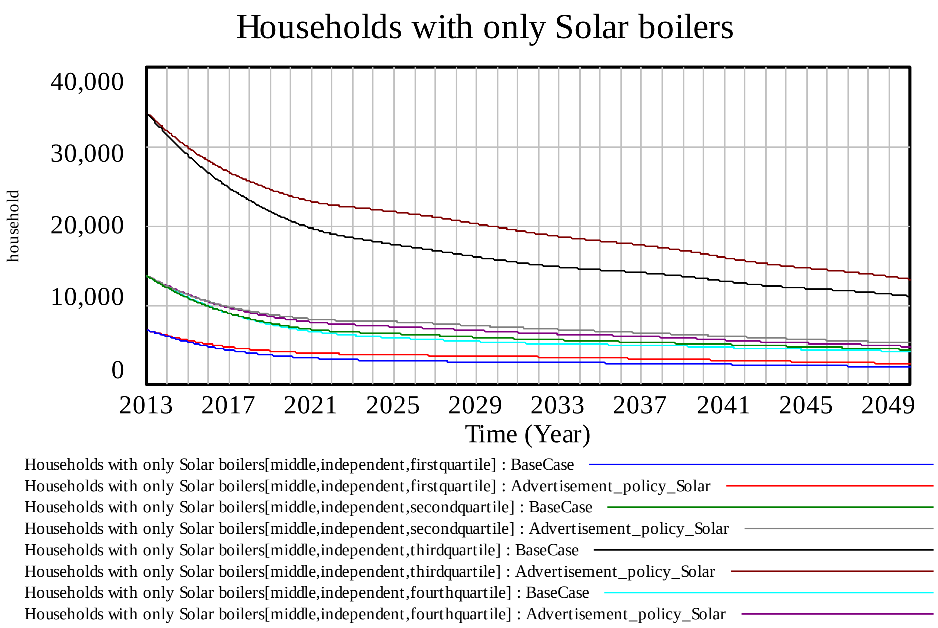


Figure 26: Impact of advertisement policy for only solar boilers (based on income groups)

4. Discussion and Conclusions

While several researchers have already studied the impact of regulations adopted under the *European guideline for energy performance of buildings (EPBD)*, a systemic study of the impact of policies related to the provision of financial stimulants, driving of innovation, demolition of inefficient buildings, and creation of awareness about energy efficient technologies, is lacking. Specifically, with respect to two of the most important technologies that have great potential to drive energy saving – namely, Insulation and Solar boilers. So, for this purpose a System Dynamics model was developed in this study in order to explore the impact of these four policies on the adoption of either/both of these technologies, and the result of this adoption on the aggregate gas consumption of the Built environment in Netherlands.

The model includes four different types of households – ones without insulation/solar, ones with insulation but no solar, ones with solar but no insulation, and the ones with both insulation and solar. Within each type, the houses are classified based on their technical characteristics – independent houses, row/terraced houses, and apartments. Also, in order to capture the social complexity involved in decision making, the households are divided into four income quartiles under each of the above classifications.

In the first experiment, a hypothetical situation about the future was simulated by presuming that everything will go on as it is. This experiment revealed that the aggregate gas consumption in the residential sector is diminishing without the intervention of any policy. However, the rate of decrease is not too high and hence subsequent experiments were conducted to see if this rate could be facilitated through the four policies mentioned above.

In the second experiment, the construction of dwellings with insulation is promoted by doubling the demolition rate of non-insulated buildings over a period of 20 years starting from 2015. It was seen that this policy helps in setting the trend for a long-term impact on the reduction of aggregate gas consumption. Hence, setting certain minimum allowable insulation standards will certainly facilitate the energy transitions process in the Built environment.

In the third experiment, subsidies were provided for the implementation of insulation and/or solar boilers. It was seen that the diffusion towards solar boiler adoption is significantly higher when compared to insulation adoption. Hence, provision of subsidies for solar boilers will prove more effective to cause a greater decrease in the aggregate gas consumption.

In the fourth experiment, the impact of investing in innovation and R&D was studied by observing the system's response to less costly and more efficient solar boilers and insulation measures. It was found that researches that result in higher technical efficiency are more effective than researches that focus on optimizing the cost.

In the last experiment, the effectiveness of investments in advertising or the facilitation of awareness process is studied. It was found that increased advertisements indeed have a huge impact on the overall energy transitions process. However, the transitions are greater among the higher income quartiles when compared to the lower income quartiles. Hence, this policy could be made socially inclusive in combination with the subsidies policy.

The model used for this study has certain limitations and drawbacks as any other model. Although several micro-level aspects related to the social behavior of households were modelled, it would be appropriate to say that the chosen level of aggregation is rather high. The Dutch dwelling stock was grouped into three homogenous types, thus overlooking the heterogeneity that exists in reality. However, this structural simplicity was needed in order to capture the long-term dynamics at a higher aggregation level. The uncertainty around different parameters that were assumed during the modelling process is also an important issue. To account for this uncertainty, and to ensure robustness in behavior, sensitivity analyses were performed on all the important and uncertain parameters. Although the results are found to vary numerically, the general behavior of all key performance indicators are found to stay intact over a wide range of values in these uncertain parameters.

Lastly, the scope of this study could be expanded in many ways. The inclusion of rebound effect while modelling consumer behavior, the inclusion of gas consumption by households for cooking and other purposes, incorporation of non-energy related expenses of households, and the provision of energy tax based on energy labels or EPC values could be some aspects that would make the system boundaries more realistic. Furthermore, different technical characteristics of dwellings, such as building design and surface area, can be used to impact the diffusion process. Market limitations posed by the lack of ability to cope with a sudden increase in demand for either of the two technologies could also be incorporated. Also, other energy efficient measures related to the consumption of natural gas could be included in the study. Finally, with relevant alterations the model can be extended to include the industrial and commercial sector.

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