Correlation between Rebound Effect and Household Income

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. However, there is inadequate understanding about the effectiveness of energy efficiency policies, particularly due to the rebound effect. This study presents a dynamic simulation model that comprises the impacts of physical processes such as aging, as well as social aspects such as households' energy conservation efforts. The focus of this study is to develop a framework to enhance our understanding of consumer behavior by studying the correlation between the rebound effect and the household income for five household categories. Based on this analysis, as expected, the lower-class households were found to be the most sensitive household categories to high energy expenses. It was also observed that the rebound effect is higher for middle-class households compared to lower-class and upper-class households. The following step of this research is to estimate the long-term benefits of energy efficiency polices based on the outcomes of this study regarding the rebound effect for different household categories.

Keywords: Energy efficiency, rebound effect, consumer behavior, dwelling market, system dynamics.

1. Introduction

In 2015, building sector used 1356 petajoules (PJ) of energy in the Nordic countries, or about 33% of total energy use, which is similar to the worldwide share of energy use despite cold climates. 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, 2013). As a result, energy consumption shown an annual reduction of around 0.8% since 2000 and the average energy intensity of space heating across the Nordic building stock reached to 126 kWh per square meter, which is still 12% higher than the European Union (EU) average. 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. Thus, more rapid renovation of existing Nordic building stock is needed to lower energy demand (IEA, 2016). However, the challenge is how to "unlock" that vast potential and realize the benefits of a built environment that is comfortable, efficient, and cost-effective. Energy efficient and low-carbon technologies are expected to play a crucial role in the energy revolution needed to make this change happen. At the same time, improvements in energy efficiency make energy services cheaper, and therefore encourage increased consumption of those services. This so-called direct rebound effect offsets the energy savings that may otherwise be achieved (Khazzoom, 1980; Berkhout et al,. 2000).

Sorrell et al., (2009) provides a broad overview of the methodological approaches to estimate direct rebound effects. In the quasi-experimental approach, the direct rebound effect is estimated through measuring the changes in demand for the energy service before and after an energy efficiency improvement. Yet, there are other factors that may also have affected the demand for the energy service which need to be accounted for (Frondel and Schmidt, 2005; Meyer, 1995). Besides, other limitations include small sample sizes, a failure to measure the error associated with estimates, and monitoring periods that are short to capture long-term effects (Sorrell et al., 2009).

Econometric analysis is a more common approach to calculate direct rebound effects. The required data can take different forms (e.g. cross-sectional, time-series, panel) and use at different levels of aggregation (e.g. household, region, country), while it should contain information on energy demand, the relevant energy service and/or the energy efficiency of that service. Depending upon data availability, the direct rebound effect may be estimated from one of three energy-efficiency elasticities (Sorrell et al., 2009):

- $\eta_{\varepsilon}(E)$: the elasticity of demand for energy (E) with respect to energy efficiency (ε)
- $\eta_{\varepsilon}(S)$: the elasticity of demand for energy services (S) with respect to energy efficiency (where $S=\varepsilon E$)
- $\eta_{P_S}(S)$: the elasticity of demand for energy services with respect to the energy cost of energy services (P_S),

Usually, data on energy consumption (E) and energy prices (P_E) is both more available and more accurate than data on energy services (S) and energy efficiency (ε). Also, even if data on energy efficiency is available, the estimates of either $\eta_{\varepsilon}(E)$ or $\eta_{\varepsilon}(S)$ can have a large variance, while estimates of $\eta_{P_S}(S)$ may have less variance owing to significantly greater variation in the explanatory variable (P_S). Table 1 summarizes the results of estimates of the direct rebound effect. Despite the methodological diversity, the results for individual energy services are broadly comparable.

Table 1: Econometric estimates of the long-run direct rebound effect for household energy services in the OECD (Sorrell et al., 2009)

End-use	Range of values in evidence base (%)	'Best guess' (%)	No. of studies	Degree of confidence
Space heating	0.6–60	10–30	9	Medium
Space cooling	1–26	1–26	2	Low
Other consumer energy services	0–41	<20	3	Low

There are several concerns regarding the estimates of the direct rebound effect. First of all, conventional models assume similar responses by households for the change in demand due to the change in energy prices and the change in energy efficiency, but opposite in sign. Besides, they presume the energy efficiency as an exogenous factor, while, in practice, both of these assumptions may not be true. Thus, the estimates of the direct rebound effect based on the historical and/or cross-sectional variations in energy prices could overestimate the direct rebound effect, mainly because the additional capital costs required to improve energy efficiency is not included (Henly et al., 1988). On the other hand, the expected high demand for energy services may increase the demand for energy efficiency. In such cases, the demand for energy services depends on the energy cost of energy services, which depends upon energy efficiency, which depends upon the demand for energy services (Small and Van Dender, 2005). Therefore, the direct rebound effect would not be the only reason for any measured correlation between energy efficiency and the demand for energy services. This so-called 'endogeneity' can be analyzed through the use of simultaneous equation models, but these are relatively rare due to their larger data requirements.

Regarding the estimates of direct rebound effect for household heating, an overlooked issue is the impact of building stock inertia on energy demand, mainly because of lack of accurate information and analytical difficulties. This study presents a dynamic simulation model that captures the impacts of physical processes such as aging, as well as social aspects such as households' energy conservation efforts on residential energy demand. System dynamics (SD) approach has been 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). The focus of this study is to improve our understanding about household's energy conservation behaviors by studying the correlation between the rebound effect and the household income for five household categories. The scope of the model is set to Danish dwelling stock and the use of district heating.

The paper is structured as follows. Section 2 describes the scope and structure of the system dynamics model, while section 3 presents the case study and the calibration of building stock with Danish data. Section 4 summarizes the results and discusses the implication of results for policy makers. Section 5 concludes the findings and identifies future steps for this research.

2. Model

System dynamics approach was applied to investigate the dynamics of the Danish dwelling stock, and also to study household's energy conservation behaviors with the focus on the correlation between the rebound effect and the household income. This study improved the model developed by Yücel, (2013). 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 1990-2014.

2.1. 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".

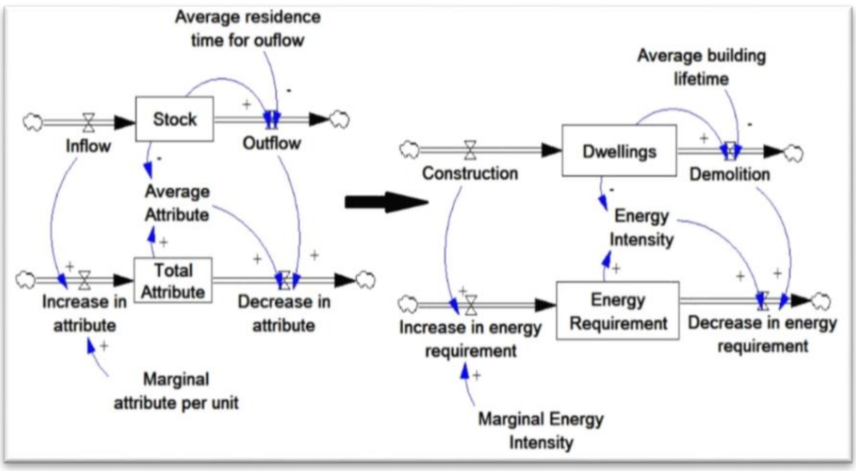

Figure 1: Generic coflow structure

Figure 1 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 1 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".

2.2. Aging Structure

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

- Old Buildings: Dwellings built before 1960
- Mature Buildings: Dwellings built between 1960-1980
- New Buildings: Dwellings built after 1980

Figure 2 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 2).

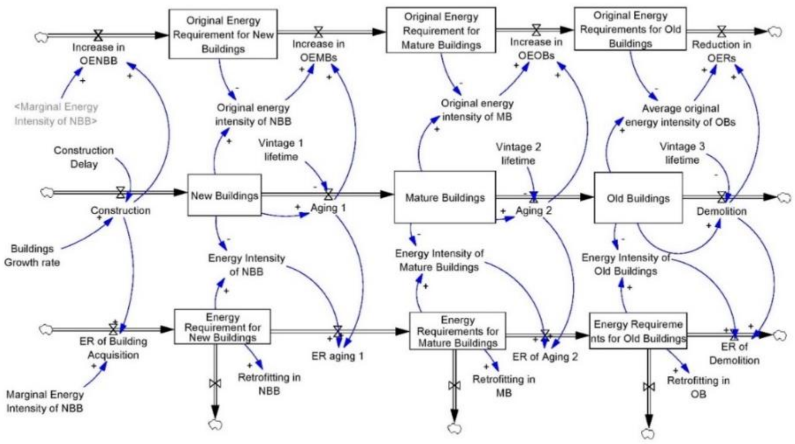

Figure 2: Stock-and-flow-diagram of the building sector

2.3. Feedback Loops

The final energy consumption of a household depends on five factors: energy efficiency of building shell, household income, heating-degree-days, energy expenses and efficiency of appliances (tech effect). The causal loop diagram that depicts the relation between key factors and household heating demand is given in Figure 3.

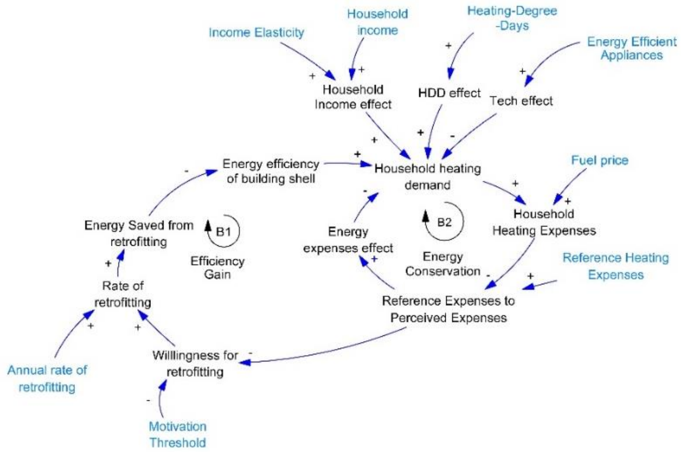

Figure 3: Causal loop diagram of energy consumption in dwellings

The 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 3. They influence the energy performance of dwellings as well as the attractiveness of retrofitting measures:

- Efficiency gain (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. Thus, household heating demand (HHD) can be estimated by:

$$HHD_{hc} = E_{energy\ efficiency\ of\ building\ shell} \times E_{household\ income,hc} \times E_{HDD} \times E_{Tech} \times E_{EE,hc} \quad (1)$$

where, $E_{\text{Energy efficiency of building shell}}$ represents the average energy efficiency of building stock, $E_{\text{householdincome,hc}}$ is the effect of household income for each Household Category[1] (HC), E_{HDD} represents the effect of heating-degree-days, E_{Tech} is the effect of improvement in the energy efficiency of heating appliances, $E_{EE,hc}$ represents the effect of energy expenses category on household heating demand for each household.

$E_{\text{energy efficiency of building shell}}$ is estimated in this study using the three-stage aging chain with a coflow structure (figure 2) and accounts for not only the impact of construction of new efficient

[1] Household categories are defined in section 3 based on income level

buildings, but also the impacts from aging of building stock and demolition of old inefficient buildings.

$E_{household\ income,hc}$ increases with household income, however, since the marginal increase of income effect decreases at higher income level, in this study the logarithmic formulation was used to capture the impact of household income on household heating demand for each household category (figure 4).

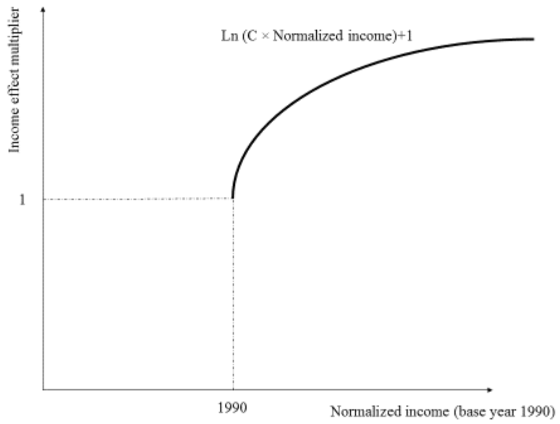

Figure 4: Income effect multiplier as a function of normalized income

The normalized income is used to estimate the income effect, so the income effect is 1 in the base year 1990. The coefficient "C" will be estimated in the calibration phase for each household category to capture the sensitivity of the heating demand to increase in the household income.

E_{HDD} depends with the total number of heating-degree-days in each year. The multiplier factor was defined as the ratio of HDD based to the HDD in 1990.

E_{Tech} is estimated based on the stock model of heating appliances to capture the impact of technological progress in the period of 1990-2014.

The effect of energy expenses on heating demand ($E_{EE,hc}$) consists of two components. Higher fuel price will result in the reduction of demand (price elasticity), while the excess income from using more efficient appliance can increase the heating demand (Rebound effect). To be able to extract the pure rebound effect, the following approach is suggested.

In case "A", it was assumed that the energy expenses effect corresponds only to the changes in fuel price. Therefore, it's reasonable to use the price elasticity to capture the changes in heating demand as a result of changes in fuel price. Since, there is no data on the price elasticity for each household category, similar price elasticity for households was used for all household categories. Based on Econ Pöyry 2007, the price elasticity of district heating is -0.25.

In case "B", the energy expenses effects capture the changes in heating demand due to fuel price changes and also efficiency improvement. This effect is estimated using a linear function (figure 5) which represents the inverse linear correlation between the energy expenses and heating demand.

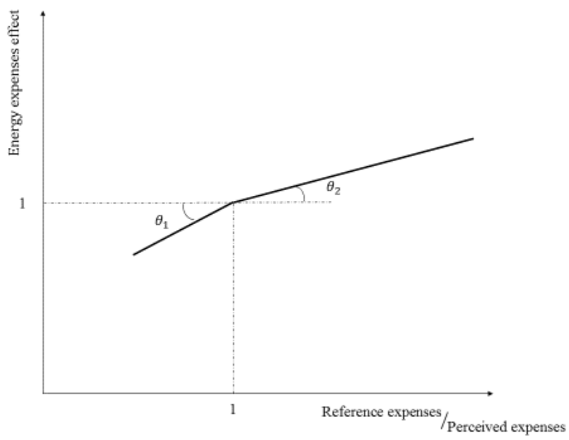

Figure 5: Energy expenses effect as a function of perceived expenses

As shown in figure 5, when the perceived expenses is similar to the reference expenses for households, there is no rebound effect and E_{EE} =1. However, in the case that the perceived expenses decreases (due to an improvement in the efficiency or fuel price reduction), the energy expenses effect will be more than 1 (right hand side of the figure 5). On the other hand, when the fuel price goes up the heating demand will be reduced. θ_1, θ_2 are estimated for each household category in the calibration phase.
The differences between the two cases can show the significance of the rebound effect.

3. Case Study: Danish dwelling stock

To study the heating demand by Danish households, the 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 2014 was used to calibrate the system dynamics model. The distribution of dwelling stock based on construction year 1990 is shown in Figure 4. Since the type of dwellings for each household category was not available, the impact of dwelling type was not included in this study. In a previous work, the characteristics of different Danish dwelling types have been fully studied (Fazeli and Davidsdottir, 2015).

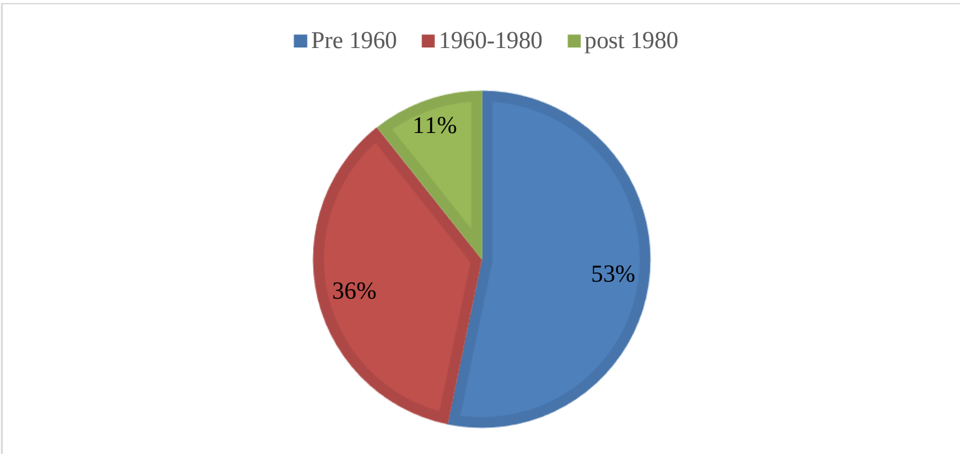

Figure 6: Distribution of Danish dwelling stock by construction year – source: statistics Denmark

According to figure 6, dwellings built before 1960 account for 53% of total stock and considering their low energy performance, the focus of energy improvement plans should be on retrofitting these old buildings. Therefore, it's critical to have a comprehensive understanding on household's behavior to energy efficiency policies and specially the rebound

effect. It’s expected that the household annual income directly affects the rebound effect, therefore based on StatBank database, Danish household have been classified into five categories based on annual income level: under 150,000 DKK, 150,000-299,999 DKK, 300,000-499,999 DKK, 500,000-799,999 DKK, 800,000 DKK or over.
The developed model is used as a dynamic tool that can be used to explore different scenarios to improve our understanding on household’s energy conservation behaviors. 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 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 1990–2014 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 compared with the actual data can be found in figures 7. As can be seen from the plots, the model is able to capture the general trends.

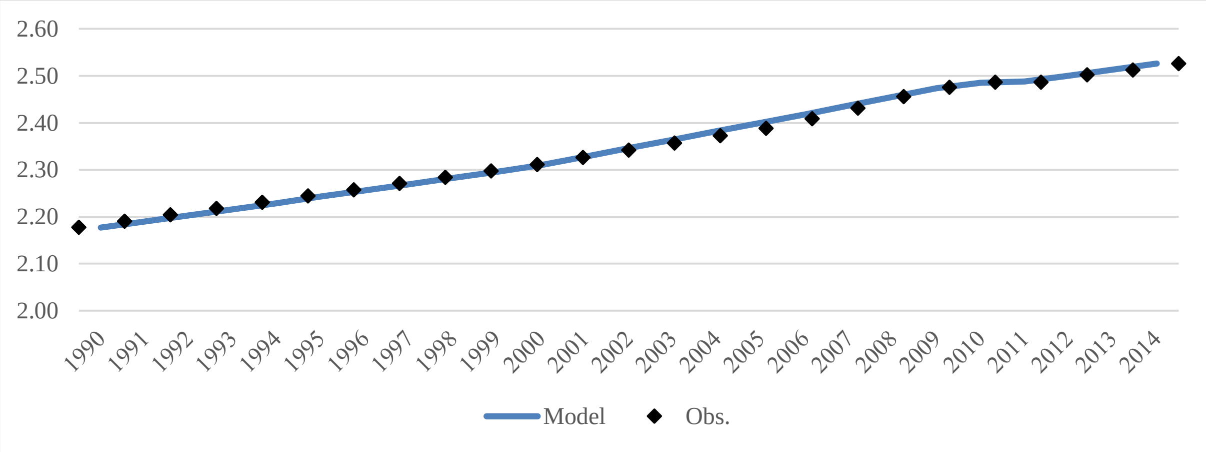

Figure 7: Number of dwellings - Model vs. Observation

4. Results & Discussions

After calibrating the building stock model with the historical data, the model was used to simulate the heating demand. To estimate the income effect multiplier for each HC, Vensim optimization module was used to estimate the coefficient “C” for the logarithmic function illustrated in figure 4.

Table 2: Estimated income effect coefficient for each household category

	Annual Income (DKK)	Coefficient “C”
HC 1	Under 150,000	2.9
HC 2	150,000-299,999	9.1
HC 3	300,000-499,999	9.4
HC 4	500,000-799,999	8.1
HC 5	800,000 DKK or over	6.1

According to table 2, the effect of rise in income on household heating demand is much more for middle-class households than lower-class and upper-class households. This is somehow expected, particularly for upper-class households. Since the heating expenses are likely insignificant compared to their income, with an increase in income, the increase in heating demand is expected to be at a much lower rate.

The next step is to estimate the effect of energy expenses on heating demand based on the historical data in two cases explained in section 2.3.
In case "A", it is assumed that the energy expenses effect covers only the effect from changes in fuel price. Therefore, based on the price elasticity reported in Econ Pöyry 2007, the impact of energy expense on heating demand is estimated for all impact categories. Subsequently, based on equation 1, heating demand for each household category was estimated and compared with observed data. The results show significant differences with observation data.
Therefore, it was decided to follow case "B", in which, the energy expenses effect includes the impacts from changes in fuel price and efficiency improvement. Based on the linear function illustrated in figure 5, the values of θ_1, θ_2 for each household category is estimated (table 3).

Table 3: Estimated energy expenses parameters for each household category

	θ_1	θ_2
HC 1	21.81	0.00
HC 2	16.71	5.71
HC 3	16.71	11.32
HC 4	11.32	16.71
HC 5	11.32	5.71

The slope of the linear function (θ_1) in the left hand side of the figure 5, represents the sensitivity to high energy expenses. According to table 3, as expected, the lower-class households are the most sensitive household categories to high energy expenses. On the other hand, the slope of the linear function (θ_2) in the right hand side of the figure 5, represents the increase in the heating demand due to the reduction in energy expenses. In other words, the higher the θ_2 the higher is the rebound effect for that household category. Based on table 3, the rebound effect is higher for middle-class households compared to lower-class and upper-class households. Then, heating demand for each household category was estimated and compared with observed data. The comparative figures for all five household categories are presented in figure 8.
According to figure 8, the model was able to capture the general trends and the differences with observation data is insignificant except for lower-class households. The values of goodness-of-fit statistics for two cases are reported in table 4.

Table 4: goodness-of-fit for heating demand in two cases

	Case A	Case B	differences
HC1	39.0%	10.4%	28.6%
HC2	28.4%	4.6%	23.8%
HC3	27.0%	6.9%	20.1%
HC4	21.6%	7.6%	14.0%
HC5	32.9%	7.3%	25.6%

The goodness-of-fit for case A is very poor, which means that price elasticity cannot solely capture all the effects from changes in energy expenses on heating demand. On the other hand, the goodness-of-fit for case B was better than case A and it verifies the capability of the suggested linear function for estimating the energy expenses impact on heating demand.

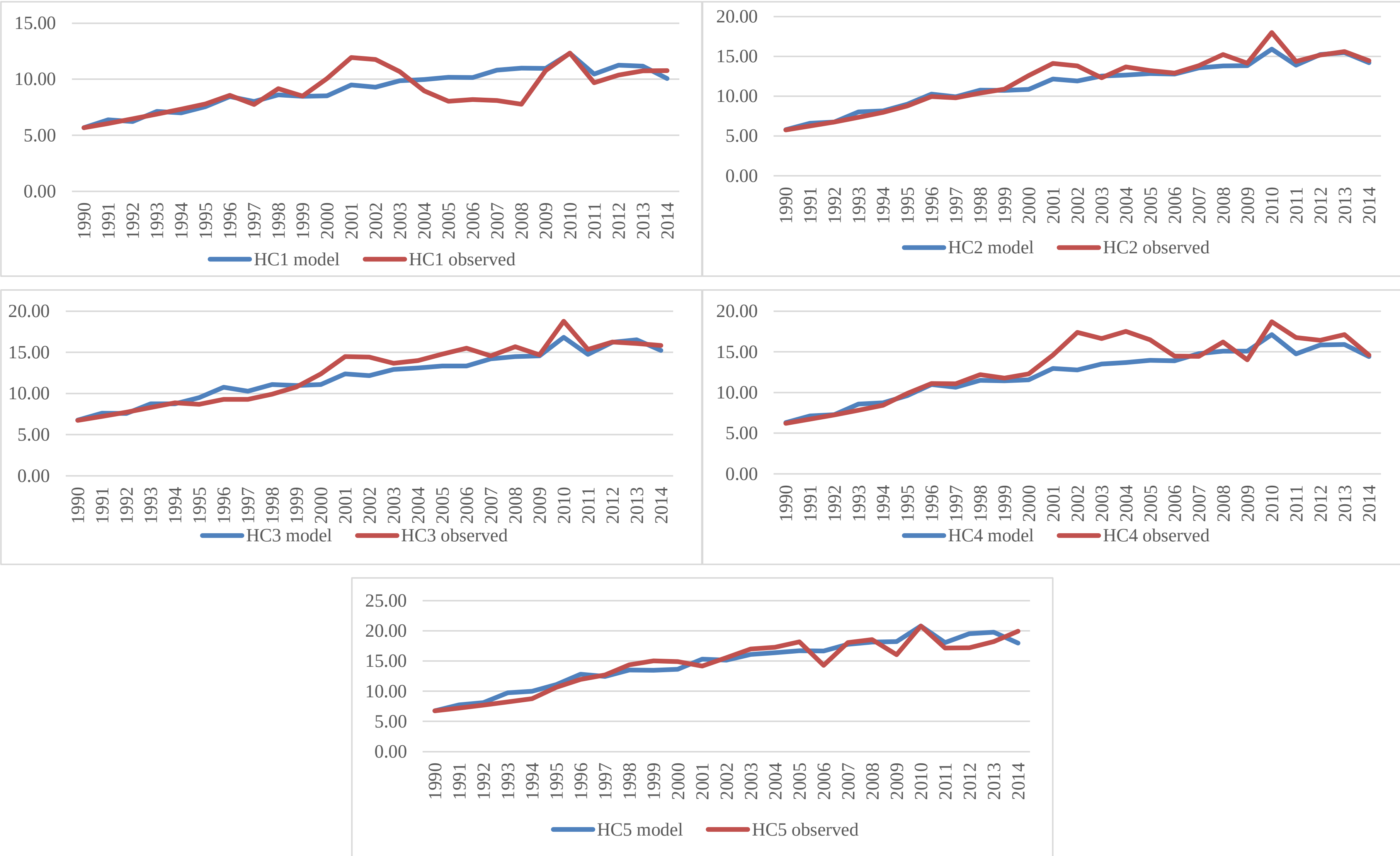

Figure 8: Energy consumption for heating for five household categories - model vs observation

5. Conclusions

While 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 because of old equipment, aging infrastructure, and lack of operations resources. Besides, energy efficiency improvement makes energy services less expensive, which could increase the consumption of those services. Therefore, this so-called direct rebound effect offsets the energy savings that may otherwise be obtained. An overlooked issue regarding the estimates of direct rebound effect for household heating, is the link between the building stock inertia and energy demand, mainly because of the analytical difficulties.

This study presents a dynamic simulation model that captures the impacts of physical processes such as aging, as well as social aspects such as households' energy conservation efforts. The focus of this study is to improve our understanding of household's energy conservation behaviors by studying the correlation between the rebound effect and the household income for five household categories. The scope of the model is set to Danish dwelling stock and the use of district heating.

Regarding the impact of energy expenses on heating demand, two cases were compared. In case "A", it was assumed that the energy expenses effect corresponds only to the changes in fuel price, while in case "B", a linear function was suggested to capture the impacts from changes in fuel price and also efficiency. Comparison of the goodness-of-fit values for two cases, illustrates that the case B is desirable, which is somehow expected, considering the more inclusive definition for energy expenses effect in case B compared to case A, in which the focus was only on price elasticity.

Based on this analysis, the effect of income increase on household heating demand is higher for middle-class households compared to lower-class and upper-class households. This is rational, as for example with an increase in the income of upper-class households, it's unlikely that the additional income is used for heating. Also, the lower-class households were found to be the most sensitive household categories to high energy expenses, while the corresponding rebound effect is very low. On the other hand, it was observed that the rebound effect is higher for middle-class households compared to lower-class and upper-class households.

Our finding emphasizes the need for further research to better understand the reasons behind rebound effect. The subsequent step is integrate the insights from this study regarding the rebound effect which depends on household income distribution in the country/region and assess the long-term benefits of energy efficiency polices. The insights from this analysis can assist decision makers on how to design an effective energy policy.

Acknowledgments

The authors would like to thank three anonymous reviewers for valuable comments on an earlier draft of this article. We wish to thank the Nordic Centre of Excellence for Strategic Adaptation Research (NORD-STAR) for providing funds for this study. The research presented in this paper contributes to the Nordic Centre of Excellence for Strategic Adaptation Research (NORD-STAR), which is funded by the Norden Top-level Research Initiative sub-programme "Effect Studies and Adaptation to Climate Change."

References

Berkhout, P. H., Muskens, J. C., and W. Velthuijsen, J. (2000). Defining the rebound effect. Energy Policy, 28(6-7): 425–432.

Danish Energy Authorities, 2014. Energy statistics 2014.

Econ Pöyry, 2007. Energiloven og energieffektivisering (The Energy Act and energy efficiency), Econ Pöyry Report 2007–071, Oslo.

Fazeli, R., Davidsdottir, B., 2015. Energy Modeling of Danish Housing Stock Using System Dynamics, 33rd International Conference of the System Dynamics Society, Cambridge, Massachusetts, USA, July 19 – July 23.

Forrester, J., 1969. Urban dynamics. MIT Press.

Frondel, M., Schmidt, C.M., 2005. Evaluating environmental programs: the perspective of modern evaluation research. Ecological Economics 55 (4), 515–526.

Groesser, S., Ulli-Beer, S., 2007. The Structure and Dynamics of the Residential Built Environment: What Mechanisms Determine the Development of the Building Stock?, in: 25th International Conference of the System Dynamics Society.

Henly, J., Ruderman, H., Levine, M.D., 1988. Energy savings resulting from the adoption of more efficient appliances: a follow-up. Energy Journal 9 (2), 163–170.

IEA, 2013. Transition to Sustainable Buildings - Strategies and opportunities to 2050. Paris, France. doi:10.1787/9789264202955-en

IEA, 2016. Nordic Energy Technology Perspectives 2016. Paris, France.

Khazzoom, J. D. (1980). Economic Implications of Mandated Efficiency in Standards for Household Appliances. The Energy Journal, 1(4): 21–40.

Kragh, J., Wittchen, K.B., 2014. Development of two Danish building typologies for residential buildings. Energy Buildings. 68, 79–86. doi:10.1016/j.enbuild.2013.04.028.

Meyer, B., 1995. Natural and quasi experiments in economics. The Journal of Business and Economic Statistics 13 (2), 151–160.

Small, K.A., Van Dender, K., 2005. A Study to Evaluate the Effect of Reduce Greenhouse Gas Emissions on Vehicle Miles Travelled. Department of Economics, University of California, Irvine.

Sorrell, S., Dimitropoulos, J., Sommerville, M., 2009. Empirical estimates of the direct rebound effect: a review. Energy Policy 37, 1356–1371.

Statistics Denmark – StatBank.dk/BOL101"

Statistics Denmark – StatBank.dk/BOL103"

Sterman, J., 2000. Systems Thinking and Modeling for a Complex World. McGraw Hill.

The Danish Ministry of Economic and Business Affairs, 2010. Building Regulations. Copenhagen, Denmark.

Yücel, G., 2013. Extent of inertia caused by the existing building stock against an energy transition in the Netherlands. Energy Buildings. 56, 134–145. doi:10.1016/j.enbuild.2012.09.022