DELIVERABLE No 4.1

Report on efficiency improvements in the household and industry sector

Due date of deliverable: August 2018
Actual submission date:

Start date of project: 01/09/2016 Duration: 36

Organisation name of lead contractor for this deliverable: Westfälische Wilhelms-Universität Münster

Revision:

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 723791.

Report on efficiency improvements in the household and industry sector

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1. Executive Summary

Despite the apparent significance of residential energy demand, few studies exist that look at the wider impacts of changes in the behavioural factors that underlie adjustments in household energy demand. Typical demand models assume that consumers are perfectly optimising agents that possess a combination of perfect information about product attributes and unbounded computational capacity to understand how each product attribute maps into utility.

In this report, we enhance the models with respect to behavioural aspects of energy efficiency and take into account behavioural shortcomings in energy service consumption, residential energy use and investment decisions. We look at the consumption of energy services of households that use electricity and build a modelling framework that allows us to analyse the impact of household's misperception of electricity prices on the derived demand for electricity and energy services. Based on the frameworks outlined in this report, the improved models can be used for the computation of scenarios and an analysis of energy efficiency policies in the EU. Using the model, we are able to take into account different behavioural shortcomings of households and see the wider impact of these biases on the derived demand for electricity, energy intensity and the associated impacts on production sectors in Europe.

Moreover, better grounded building models which can account on the one hand on building stock and on the other on household investment decisions for energy efficient goods have been developed, and calibrated using the survey data collected in the PENNY survey and using publicly available data on EU building types. These models will be subsequently linked to larger scale IAMs, helping to provide improved representation of energy demand as well as behavioural traits for investment decisions.

2. Introduction

The European Union has identified increasing energy efficiency to be one of the central objectives in the transition processes towards a low-carbon economy. To this end, the EU wants to increase energy efficiency by at least 30% until 2030 to bring about this transition, reduce its dependency on energy imports and meet its climate targets (European Commission, 2016). 25% of the total final energy consumption in the EU28 region in 2016 (Eurostat, 2017) was residential consumption thereby making up a non-negligible share of about 5% of total consumption expenditure in the EU, consumers are expected to take a more active and central role on the energy markets of the future. The EU's drive towards a more energy efficient future hence also targets the demand side of the energy markets. The idea of these policies is that households might adjust their consumption plans to obtain potential energy savings. These adjustments in the energy consumption plans of consumers are supposed to have a significant effect on the EU energy system as the producers need to take into account the changes in energy demand.

Despite the apparent significance of residential energy demand, few studies exist that look at the wider impacts of changes in the behavioural factors that underlie such adjustments in residential energy demand. Typical demand models assume that consumers are perfectly optimising agents that possess a combination of perfect information about product attributes and unbounded computational capacity to understand how each product attribute maps into utility (Allcott, 2013). However, experiments in both the psychology literature and economics literature raise serious questions about these assumptions (DellaVigna (2009), Allcott & Taubinsky (2015)).

In this report, we describe how the models that we will use in our simulations have been enhanced to explicitly take into account consumer behaviour in energy service consumption. First, we extended the computable general equilibrium (CGE) model such that we are able to look at the consumption of energy services of households that use electricity. Furthermore, we can analyse the impact of misperception of electricity prices on the derived demand for electricity and energy services. Second, we improved the representation of the building sector energy demand modelling in the WITCH IAM.

3. Behavioural shortcomings in economic models

As it has long been observed in experiments, consumers do not adopt some energy-efficient technologies despite large financial savings, a phenomenon commonly referred to as the energy efficiency gap (Jaffe & Stavins (1994), Gerarden et al. (2017)). The energy efficiency gap has implications for future energy demand projections but it is not well understood in numerical models looking at this issue.

While part of this literature primarily looks at the energy efficiency potential that might be reached with extra investments, a closely linked strand of literature analyses other behavioural explanations for inefficiencies in the consumption of energy services.[1] Households might for example be inattentive towards energy conservation or possess only imperfect knowledge about how goods are most efficiently used in the consumption of energy services. Furthermore, households seem to have limited knowledge about energy costs, although they represent a non-negligible part of their total expenditure. Focusing on electricity, Brounen et al. (2013) illustrated this limitation in knowledge with a survey of 1,721 Dutch households, in which only around 47% of the respondents are aware of their monthly electricity expenses. More recent findings by Blasch, Boogen, Filippini & Kumar (2017) indicate that consumers of energy services misperceive the costs of electricity consumption and therefore misvalue energy costs relative to their private optima. They further state that the inefficiency is indicative of structural problems faced by households such as systematic behavioural shortcomings in residential electricity consumption. More recent findings from the large sample survey conducted within the PENNY project, support these findings and expose electricity price misperceptions of -5.47% in Switzerland, 18.75% in the Netherlands, -4.76%

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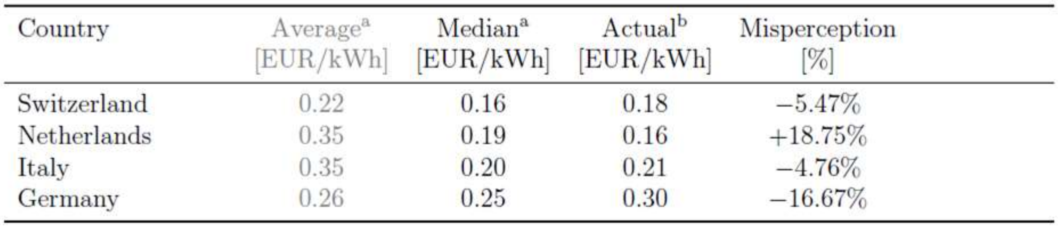
[1] see e.g. Allcott & Roger (2014), Attari et al. (2010), Harding & Hsiaw (2014) and Taubinsky (2013).

in Italy and -16.67 in Germany. Average price misperceptions in these countries are presented in Table 1[2].

Table 1: Electricity price misperception



Country	Average[a] [EUR/kWh]	Median[a] [EUR/kWh]	Actual[b] [EUR/kWh]	Misperception [%]
Switzerland	0.22	0.16	0.18	−5.47%
Netherlands	0.35	0.19	0.16	+18.75%
Italy	0.35	0.20	0.21	−4.76%
Germany	0.26	0.25	0.30	−16.67%

Source: Own calculations based on the large sample survey, Eurostat (2018) *and Elcom* (2018).

Reasons for these biased beliefs might be inattention (Gerarden, Newell, & Stavins, 2017) or a lack of energy literacy, which can be defined as an individual's ability to make informed and deliberate choices in the domain of household energy consumption (Blasch, Boogen, Filippini, & Kumar, 2017)**.**

Allcott (2010) stresses that the distinction between whether choices are driven by a misperception of product attributes and costs versus the consumer's true preferences has important economic meaning and consequences for policy implementation, because in the former case, consumers are making ex-ante decisions which will reduce their (ex-post) realised welfare. He further points out that these biased decisions can in principle be corrected through information disclosure or potentially mitigated through other policies.

The consumption of energy services is one example of such a decision. Misperceived energy costs influence the consumption decision and thereby lead to a consumption and production structure that would look different under perfect information. As emphasised by Hunt & Ryan (2015)**,** energy is typically not desired for its own sake,

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[2] Average electricity price misperception is given by the relative deviation of the median from the actual average electricity price including taxes in the respective country.

but for the energy service it provides (e.g. lighting or heating) and energy demand models, both theoretical and empirical, often fail to take account of this feature. Considering that, also the demand for appliances that use energy are affected by this misperception as energy efficiency seems not to be perceived as an important characteristic of these appliances. Due to the narrow interweaving of the involved production sectors, the misperception also has an indirect impact on other production sectors of the economy and repercussions on supply and demand of other countries. A possible overuse of energy by households for example prevents them to spend more on other consumption goods and more energy efficient appliances. Eliminating misperceptions in the residential sector therefore could turn out to increase the production in other sectors.

Household's preferences that exhibit a trade-off in consumption have great repercussions on the impact of behavioural shortcomings. Sorrell & Dimitropoulos (2008) underline that the consumption of energy services involves several interrelated trade-offs. One example is the trade-off between consuming energy services and other consumption goods as described above. Another very important modelling aspect that needs to be taken into account is the functional form that describes the energy service provision and links energy consumption to the choice for the appliances that use it, such as heaters or lightbulbs. Hence, there also exists a trade-off (i.e. substitution possibilities) among the energy services that need to be taken into account in their modelling. This trade-off has important implications for future consumption since the expenditure on such appliances can be seen as an investment by the consumer in capital goods. We can for example choose between a fridge with A label, or a more efficient one with A+++ label to obtain the same service (e.g. cooling beverages). Assuming that all other characteristics (i.e. size, colour, position, etc.) stay the same, the more expensive fridge is (usually) more energy efficient, i.e. needs less electricity to produce the same service.

To see the wider impact of these behavioural shortcomings on the derived demand for electricity, electricity intensity and the associated impact on production sectors in Germany and Europe, we apply a computable general equilibrium (CGE) model. To the best of our knowledge, only a few computable general equilibrium models exist that focus on the demand side and take into account the explicit modelling of energy services or the above described behavioural shortcomings in energy consumption.

Koesler (2013) investigates the rebound effect of an energy efficiency improvement in the provision of private transportation services within a computable general equilibrium model. The analysis features a production function in which energy used for private transport activities is paired with the means of transport to offer private transport services. In his model, he takes into account that household behaviour may be influenced by habits. Figus et al. (2017) are interested in the wider implications of vehicle-augmenting efficiency improvements. Using a partial equilibrium approach, they model private transport consumption as a household's self-produced commodity formed by a vehicle and fuel use. They extend their analysis with computable general equilibrium simulations in order to investigate the wider implications of efficiency improvements on the system-wide change in fuel use (including its use as an intermediate in production) when prices and income are endogenous.

We enhance our CGE model by explicitly taking into account behavioural shortcomings in energy service consumption. More specific, we look at the consumption of energy services of households that use electricity and analyse the impact of misperception of electricity prices on the derived demand for electricity and energy services. In these simulations, we make use of a computable general equilibrium model to take into account the endogenous price changes and the linkages between regions and markets which allow us to analyse regional and global demand effects, the impact on other production sectors and welfare effects. We also take up the critique by Hunt & Ryan (2015) and add to the discussion by introducing a more elaborate energy services consumption structure that incorporates electricity as a derived demand in the consumption of energy services. As a result, we extend the energy service consumption literature that has so far mainly focused on productivity improvements in the provision of private transport services.

We further improve the representation of the building sector energy demand modelling in the WITCH IAM following a two-step approach. First, we use the recently developed EDGE building model and further improve it by including a building stock model. Second, we use EDGE to calibrate the energy demand projections of the WITCH IAM.

The remainder of this report is structured as follows. In the next section, we formally describe the analytical frameworks of the models. We then describe the numerical models, data and calibration before we present a short outlook on our simulations.

4. Modelling frameworks for energy efficiency impact analysis

While psychologists and sociologists have described many behavioural features or biases in consumer choice towards more efficient energy services, in the recent years also economic modelling has increasingly been used to address many of these issues by providing a conceptual analysis and microeconomic models that deviate from the simple representative rational agent, and notably providing input to numerical models. In our project, we apply different types of numerical models to analyse some of these behavioural biases. Using the inputs from different Work Packages of the PENNY project, we are able to improve the representation of consumer behaviour and investment decisions for energy efficient goods in these models.

4.1 Energy Service CGE Model

In this section, we give a formal illustration of energy service consumption and the consumer's misperception of electricity prices. After that, we describe the enhanced version of the CGE model that explicitly takes into account behavioural shortcomings in energy service consumption.

4.1.1 Analytical Framework of the Consumer Decision

Since energy is typically not desired for its own sake, but for the service it provides, we need to distinguish between the energy good, and the appliances that use energy as an input. Energy is used in conjunction with an appliance which can be seen as a certain type of capital good (e.g. electric appliances, boilers, cars) that incorporates a certain (energy) efficiency in providing the required services. The energy service good is a composite of the energy good and an appliance (capital) good, e.g. the energy service "lighting" is a composite good consisting of expenditure on the energy good "electricity" and expenditure on a "light bulb". This composition can be determined by calibrating a constant elasticity of substitution (CES) function f of x units of the appliance (capital) good and e units of the energy good such that we obtain $s = f(x, e)$ units of the energy service. In our model, the consumer chooses s units of the energy service good and z units of a composite market good such that her utility from consuming these goods is maximised given her budget constraint,

$$\max_{s,x,e,z} u(s, z)$$

$$s.t. \qquad s = f(x, e)$$

$$\tilde{p}_e e + p_x x + z = M$$

We normalise the prices with respect to the price of the composite market good, i.e. the latter price (index) is set equal to one. Notice that we treat household purchases of appliances as a flow of current consumption. In reality, of course, expenditures on electric appliances is an investment in a capital good that depreciates over time and provides a service flow over its respective lifetime. We abstract from this specification in our current analytical model. We take into account that the consumer might misperceive expenses for energy services and formalise this as a systematic bias by assuming that the misperception depends on the misperceived energy price $\tilde{p}_e$. The systematic bias is therefore a consistent underestimation (or overestimation) of the energy price if $\tilde{p}_e \neq p_e$, where p_e is the true electricity price. A misperception of the price of a good results in a biased demand, i.e. a demand that would be higher or lower (depending on the sign or direction of misperception) when compared to the demand under market prices. Since we are considering consumer price misperceptions in a general equilibrium context, there is a sort of ex post situation where the real, market price of the good becomes known to the consumer at which point he is confronted with the fact that he demanded too much or too few of these goods, causing him to have spent too much, or he lacks sufficient goods.

The budget of the household is made up of the receipts from the rental of $\overline{K}$ units of primary factor capital and $\overline{L}$ units of labour, which are assumed to be fully allocated in equilibrium. It further includes any transfer payment associated with the difference between the true and the perceived energy costs. At the end of the year, the household receives her energy bill and pays the true energy price. As the consumer is assumed to be very myopic, she will not update her price beliefs but take the new budget as given. We model this as a lump-sum payment (Ψ) to the consumer and assume that this payment increases resp. reduces the budget depending on the direction of misperception.

$$M = p_l\overline{L} + p_k\overline{K} + \Psi$$

The household is assumed to be not able to associate the transfer payments with its energy service consumption and views these transfers to be independent of any decision she makes. By incorporating the misperception in this way, we are able to demonstrate the distortionary impact of the price misperception. Due to the misperception of the electricity price, the consumers demand for energy services is biased.

We can think of this household's optimisation problem as a two-stage optimisation problem that consists of a lower and an upper stage. In its lower-stage, the consumer minimises the expenditure on energy and associated appliances, to obtain the necessary units of the energy service good. In the upper stage of the optimisation problem, the household then chooses the optimal amounts of energy services s and market goods z to maximise utility.

Assuming homotheticity of the utility function, let $exp^s\,(p_x, \tilde{p}_e, s)$ denote the minimum expenditure for consuming s units of the energy service given the appliance's input price p_x and the perceived energy price $\tilde{p}_e$,

$$exp^s\,(p_x, \tilde{p}_e, s) = \min_{x,e} p_x x + \tilde{p}_e e$$
$$s.t \quad s = s(x, e)$$

Then the price of providing s can be described by $\tilde{p}_s$,

$$\tilde{p}_s\,(p_x, \tilde{p}_e) = \frac{\delta exp^s\,(p_x, \tilde{p}_e, s)}{\delta s}$$

Typically, the price of energy services p_s is not observable (Hunt & Ryan, 2015), but incorporation into the CGE model allows us to quantify the price for energy service to equal the marginal cost of the energy service provision, within the nested CES structure.

The solution to the utility maximisation problem is described by the demand function for the energy service good $\tilde{s}$,

$$\tilde{s} = d(\tilde{p}_s, M)$$

The demand for energy services $\tilde{s}$ therefore depends on the energy service (shadow) price, $\tilde{p}_s$ and disposable income M. Due to the misperception of the electricity price, the consumers demand for energy services is biased.

4.1.2 Numerical Model

In our simulation, we focus on electricity, as it constitutes the most essential energy good in the household energy service consumption. Other energy-intensive services, such as heating or private transportation, can be similarly seen as composite goods in our model. However, to enhance tractability and to concentrate on the effect of electricity price misperception, we isolate energy services that use electricity in combination with electric appliances.

To account for the aforementioned trade-offs and analyse the impact of the electricity price misperception in the provision of energy services, we incorporate the main elements of the analytical framework developed in the previous section into our computable general equilibrium (CGE) model. As we are interested in the spillover effects on production and consumption in Germany and the EU, an extension to a multi-sector, multi-region CGE model is necessary. Using the CGE model we are able to account for detailed production and consumption changes in the economy as it includes the interdependencies of factor, and it features several regions and trade linkages.

We apply the WIOD CGE model[3], which is a multi-region, multi-sector computable general equilibrium model, since it partitions the world into several regions represented by a microeconomic utility maximising consumer household where the multiple production sectors are represented in each region with a microeconomic profit maximising production household. The underlying production technology is modelled using a nested constant elasticity of substitution (CES) production function exhibiting constant returns to scale. This function consists of three nests to specify the (not necessarily constant) substitution possibilities between capital, labour and intermediate goods, $x_{(j,r)}$. The intermediate goods can be distinguished between carbon-emitting energy inputs, $x_{(eg,r)}$ and non-energy intermediate goods, $x_{(i,r)}$. Sectoral output can be used for final consumption or for intermediate use in production activities. Intermediate goods

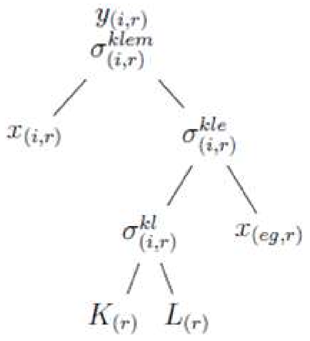

Figure 1: CGE Model production structure

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[3] For a general description of the WIOD CGE model, see Koesler & Pothen (2013).

are so-called Armington aggregates, i.e. they consist of a combination of domestic and foreign final inputs. The Armington good specification allows us to assume that goods from different origin are only imperfect substitutes, hence with different substitutability between domestic and foreign output, and between different foreign regions (Armington, 1969). The general production structure is displayed in

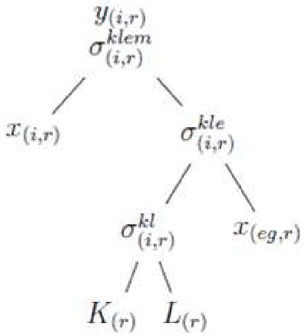

Figure 1.

Final consumption in each region is represented by a representative household that maximises utility by spending her budget or income on consumption goods. The consumer's budget is determined by the consumer's income from selling his factor endowments on the market and from possible government transfers. Households are endowed with a fixed amount of labour and capital, which is mobile across sectors within regions but not across regions. As we are mainly interested in the effects of the behavioural shortcomings in the consumption of energy services, we extend the basic utility function to feature a distinction between energy services on the one hand and other consumption goods on the other, as described in our analytical framework in the previous section. Accordingly, the utility of the representative agent in region r is given by:

$$u\big(s, x_{(eg)}, x_{(i)}\big) = \left[\alpha_{(s)} s^{\rho^{sz}} + (\alpha_{(eg)} x_{(eg)}^{\rho^{egi}} + \alpha_{(i)} x_{(i)}^{\rho^{egi}})^{\frac{\rho^{sz}}{\rho^{egi}}}\right]^{1/\rho^{sz}}$$

The consumer's utility function depicting her preferences over various bundels of goods is a nested CES function that aggregates the consumer's expenditure on non-electricity composite goods that are formed by combining non-electricity energy goods $x_{(eg,r)}$ and non-energy goods $x_{(i,r)}$ and the energy service good $s_{(r)}$.

$\alpha_{(s)}$, $\alpha_{(eg)}$ and $\alpha_{(i)}$ are the respective share parameters and the degree of substitutability consumption is given by the respective substitution parameters ρ^{sz} and ρ^{egi}. The substitution parameters are related to the respective elasticity of substitution (e.g. σ^{egi}) through $\rho^{egi} = \frac{\sigma^{egi}-1}{\sigma^{egi}}$. Within a CES function, we can adjust the substitutability among the consumed goods and thereby test the implications of possible relative changes in the composition of the consumption set. An elasticity of substitution greater than zero in the top level (σ^{sz}) enables the household to shift her consumption to other goods if she thinks energy service consumption is becoming more expensive. The structure of the utility function is shown in

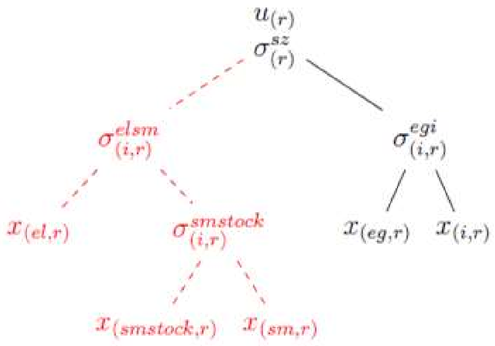

Figure 2. The red dashed line indicates the new branches we added to the CGE model in order to incorporate the energy service consumption.

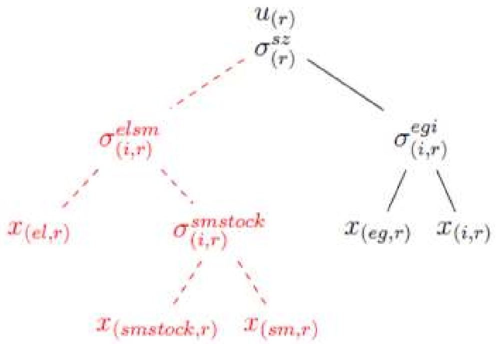

Figure 2: Household consumption structure

As we are interested in the impacts of behavioural inefficiencies on consumption, we extend the model by an energy service module that describes the provision of the energy service as described in our analytical framework. Accordingly, energy service provision in each region r is described by the CES function

$$s\left(x_{(sm)}, x_{(el)}\right) = \left(\alpha_{(sm)}\ (x_{(sm)})^{\rho^{elsm}} + \alpha_{(el)}\ (\theta_{(el)} x_{(el)})^{\rho^{elsm}}\right)^{1/\rho^{elsm}},$$

where $x_{(el,r)}$ is the amount of electricity input in households energy service production that is combined with $x_{(sm,r)}$ units of electric appliances. The degree of substitutability in the production of the energy service is given by the respective substitution parameter ρ^{elsm}, which is related to the elasticity of substitution $\sigma^{elsm}_{(r)}$ through $\rho^{elsm}_{(r)} = \frac{\sigma^{elsm}_{(r)}-1}{\sigma^{elsm}_{(r)}}$. Share parameters are given by $\alpha_{(el,r)}$ and $\alpha_{(sm,r)}$. We further include the exogenous parameter $\theta_{(el)}$ into the input productivity parameters in production functions. This parameter can be thought of as a *behavioural inefficiency* parameter in our simulations representing the inefficiencies in energy service provision that might be due to various non-technical reasons. More specifically, households might possess only imperfect knowledge about how goods are most efficiently used in the provision of energy services.[4] Therefore, a $\theta_{(el,r)} < 1$ implies that the household is using more energy than is actually needed for the

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[4] Examples of this would be cooking with a pot without putting a lid on it or driving a car at constant speed without shifting up into a more efficient gear. All these energy services might be produced more efficient without switching to a more efficient technology.

energy service. In case there is no behavioural inefficiency $\theta_{(el,r)} = 1$ which means the household is providing the energy service in the most efficient way. This allows us to incorporate behavioural productivity changes in our simulations. If the household fails to accomplish the most productive level in the provision of energy service, he will always use too much energy, regardless of the direction of the price misperception.

The result of the expenditure minimisation problem yields the energy service marginal costs for each region r

$$\tilde{p}_s(px_{(sm)}, \widetilde{px}_{(el)}) = \left[\alpha_{(sm)} \left(\frac{px_{(sm)}}{\alpha_{(sm)}}\right)^{\frac{\rho^s}{\rho^s-1}} + \alpha_{(el)} \left(\frac{\widetilde{px}_{(el)}}{\alpha_{(el)}}\right)^{\frac{\rho^s}{\rho^s-1}}\right]^{\frac{\rho^s-1}{\rho^s}}$$

where the perceived electricity price is given by $\widetilde{px}_{(el)}$. As in our analytical model, the resulting marginal energy service costs $\tilde{p}_s$ are biased. An equilibrium in this model is defined by the value of the price, activity, and utility variables such that there exists a market equilibrium for each good in the economy, such that producers make non-positive profits, and such that the consumers make non-positive net expenditure on each (aggregate) good. A market equilibrium for each good implies that the good's demand is met by its supply. The demand for each good is a function of the good's prices; here, of the good's prices as they are perceived by the consumer. In our case, this demand can hence differ from demand under market prices. This implies that, in our model, demand for certain (aggregate) goods are independent of market prices and are taken as given in finding an equilibrium. Hence supply adjusts to meet demand, either by adjusting the market price of the good or, as is the case here, by adjusting its activity level since the latter is determined by demand. Notice that a difference between perceived prices and (equilibrium) market prices of a good does not results in over- or under production of this good since demand is being met. The demand side, here the consumer, is in the end, confronted with more or less of the good than he actually needed.

The non-positive net-expenditure condition on consumption is mainly depicted using an equality and thereby it defines a price index for the underlying (aggregate) good. In our case, the misperception of the price for energy consumption results in a biased price for the energy service that needs this type of energy. Following the reasoning in the previous paragraph, this would result in biased levels of demand for all aggregate consumption goods that contain this energy service, and the consumer is subsequently, ex-post, confronted with biased levels of consumption aggregates, and hence, with a perceived welfare or utility from the consumption of these goods, that might be significantly different from the welfare the consumer obtains ex post.

With regard to our research question, there are several crucial parameters. The most important parameter is of course the degree of misperception. As we want to take into account trade-offs in the energy service consumption, we also need to account for sensitivities with regard to the respective elasticities of substitution. Including the parameter $\theta_{(el,r)}$ in the energy service production function allows us to look at the impact of a change in the input productivity of electricity in the presence of behavioural inefficiencies.

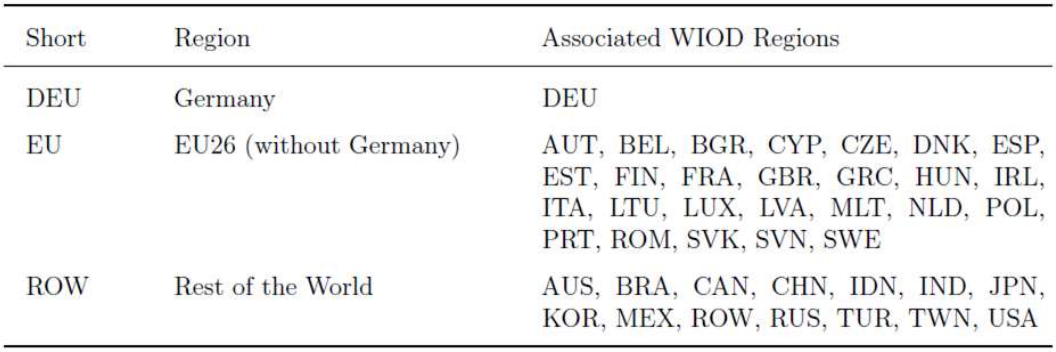
4.1.3 Data, Aggregation and Calibration

The CGE model is tailored to provide a maximum fit with the data from the World Input-Output Database (WIOD) (Timmer, Dietzenbacher, Los, Stehrer, & Vries, 2015)**.** The data comprises the flows of income and expenditures in the economy at a certain point in time calibrated to the year 2009. The model differentiates up to 40 regions and a rest of the world region and features data from 35 production sectors.

We are mainly interested in the consumption- and production effects of the provision of energy services in the presence of behavioural shortcomings. Therefore, we change the original aggregation structure of the basic WIOD CGE with regard to this aspect and reduce the sectoral disaggregation to 13 sectors. To account for the energy service consumption level, we use the region specific consumption data from the WIOD, assuming that all final demand goods from the sectors "machinery" and "electrical equipment" are combined with electricity.

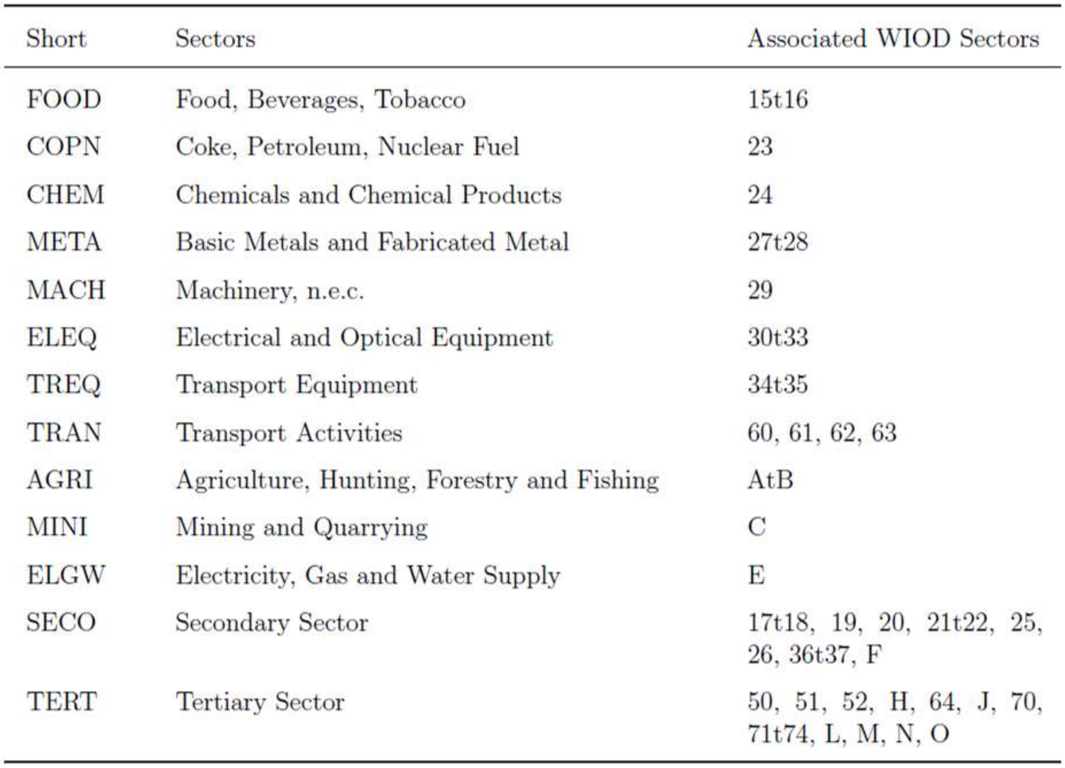
By using consumption data from AGEB (2012) and price data from BDEW (2017), we are able to separate electricity from gas and water supply in the original WIOD dataset. In our analysis, we further focus on the regions EU and Germany and create a rest of the world region that aggregates all the other regions. The aggregation scheme is displayed in Tables 2 and 3.

Table 2: Regional aggregation



Short	Region	Associated WIOD Regions
DEU	Germany	DEU
EU	EU26 (without Germany)	AUT, BEL, BGR, CYP, CZE, DNK, ESP, EST, FIN, FRA, GBR, GRC, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROM, SVK, SVN, SWE
ROW	Rest of the World	AUS, BRA, CAN, CHN, IDN, IND, JPN, KOR, MEX, ROW, RUS, TUR, TWN, USA

Table 3: Sectoral aggregation



Short	Sectors	Associated WIOD Sectors
FOOD	Food, Beverages, Tobacco	15t16
COPN	Coke, Petroleum, Nuclear Fuel	23
CHEM	Chemicals and Chemical Products	24
META	Basic Metals and Fabricated Metal	27t28
MACH	Machinery, n.e.c.	29
ELEQ	Electrical and Optical Equipment	30t33
TREQ	Transport Equipment	34t35
TRAN	Transport Activities	60, 61, 62, 63
AGRI	Agriculture, Hunting, Forestry and Fishing	AtB
MINI	Mining and Quarrying	C
ELGW	Electricity, Gas and Water Supply	E
SECO	Secondary Sector	17t18, 19, 20, 21t22, 25, 26, 36t37, F
TERT	Tertiary Sector	50, 51, 52, H, 64, J, 70, 71t74, L, M, N, O

Substitution elasticities are taken from Koesler & Schymura (2012) who exploit the time series nature of the data and estimate substitution elasticities for all sectors included in the database. Armington elasticities required by the model are taken from GTAP7 (Badri & Walmsley (2008), Hertel et al. (2008)) and mapped to WIOD sectors.

We are able to use price perception data from the large survey sample conducted within the PENNY project in Switzerland, the Netherlands, Italy and Germany[5]. Using this data, we can calibrate the model on observed consumer behaviour. Own calculations based on data from the large survey sample, presented in Table 1, indicate that there is no consistent misperception in one direction across Europe.

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[5] The German data is not yet available.

Following the recent CGE literature, emissions in the WIOD CGE model are modelled as a fictive necessary input into the production of commodities and consumption goods that is paired with the input causing the emission in a Leontief nest in the respective production function. Setting the price of this fictive input to zero the supply of the fictive input does not have any cost as long as no regulation is assumed for. Hence, if emissions are not taxed, the production costs induced by the usage of the fictive input are zero (Koesler & Pothen, 2013). As far as CO_2 emissions are concerned, the model distinguishes between energy related CO_2 emissions (arising due to the burning of fossil fuels) and process emissions (e.g. caused during the production of cement). The shares of the fictive inputs vary depending on the type of accompanied energy good.[6]

In the next section we describe how the representation of the building sector energy demand modelling in the WITCH IAM has been enhanced.

4.2 FEEM modelling framework

3.2.1 Bridging the gap between local energy behaviour and global energy models: the relevance of the building sector

Global energy system models and integrated assessment models (IAMs) are commonly used to inform policy makers about future global environmental challenges. Their strength lies in identifying cross-sectoral relations, over time and across regions, and are therefore a particularly useful tool to identify consistent strategies to meet a stringent climate target globally (Levesque, et al., 2018). In these mitigation scenarios *energy demand side changes,* such as reduced energy use or electrification play an important role to reduce emissions, both related to greenhouse gases but also other pollutants such as those affecting local air. These demand side changes are, especially in the buildings and transport sector, often associated with behavioural considerations that are heterogeneous for different users. The complexity of user heterogeneity and behavioural factors does not agree well with the scope of global models. Including more details does not necessarily

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[6] See Koesler & Pothen (2013) for more on the modelling of emissions in the WIOD model.

improve the model, and in fact, might increase the number of uncertain assumptions made, limited also by data availability, and ultimately reduce its transparency. Moreover, the many criteria affecting the choices made in the demand sector by the relevant actors cannot be well quantified and captured by the algorithms used in these global models. As a result, the models generally have a more aggregated representation of regional trends and sectoral trends, and mainly take in to account financial considerations.

By focussing on aggregated sectors and regions, these models have a stylised representation of the "average" user. This limits the models' ability to evaluate heterogeneity in demand, affecting policy opportunities or barriers and making the results less tangible for policy makers. The buildings sector, which represented 31% of the total primary energy consumption in 2016, is characterised by various forms of heterogeneity: 1) The buildings themselves, differentiated by age, location, size, and purpose (residential or public/commercial) which affects the potential of architectural solutions, such as retrofitting, to reduce energy demand; 2) The different functions for which energy is used, such as space heating, lighting or appliances, with varying patterns in usage, and allowing for different mitigation measures; and 3) The varying behaviour of the occupants, which play an important role in determining energy consumption as well. The IPCC even states that three- to five-fold difference in energy use for provision of similar building-related energy service levels are due to behaviour, lifestyle, and culture differences.

In the current representation of the buildings sector in global models there are important question that are currently unanswered:

1) *Are the demand side changes required to meet stringent climate targets achievable?*

The general trend projected by the models is a strong electrification in buildings sector. Simulations for example shows that in 2050 the share of electricity would increase to 51% (model average) compared to 28% (model average) in 2010. The buildings final energy consumption would reduce with 16% (model average) compared to baseline in 2050[7]. The question here is whether the mitigation potential of the average users is comparable to the average mitigation potential of heterogeneous users.

2) *Whether and how can we leverage additional demand side mitigation potential, for example by changing habits?*

Switching off the lights, or the heating system are related to lifestyle and consumer behaviour. This type of habits, affecting energy consumption, will differ from person to person and decision making. Individual behaviour might not be responsive to financial considerations but depend on less rational factors such as social environment or knowledge.

3.2.2 Building energy demand modelling

In order to improve the representation of the building sector energy demand modelling in the WITCH IAM, we have followed a two-step approach. First, we have used the recently developed EDGE building model (Levesque, et al., 2018) and further improved it by including a building stock model. Second, we have used EDGE to calibrate the energy demand projections of the WITCH IAM.

The EDGE model

EDGE is a newly developed model which captures energy end use demand in the buildings sector. The focus of the model is on useful energy, which is related to income, cooling degree days (CDD), heating degree data (HDD) and population density. The model is used to specifically analyse the different Shared Socio-Economic Pathways, in order to take socio economic uncertainty into consideration through different exogenous demographic and economic projections, as well as

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[7] These results are based on the four IAMs (AIM/CGE, MESSAGE-GLOBIOM, IMAGE and GCAM) that model the buildings sector separately and were part of the Shared Socio-Economic Pathways scenario development.

through parameter choices in line with the scenario narratives corresponding to different lifestyles.

As shown in Figure 3, the EDGE model is characterised by three main components. The first step collects historical data and scenario projections for fundamental drivers for the energy demand in the buildings sector to project floor space demand. Then, useful energy demand is calculated from the first step, accounting for technological progress and behavioural change linked to different future scenarios. Thirdly, useful energy is translated into final energy by changing efficiencies.

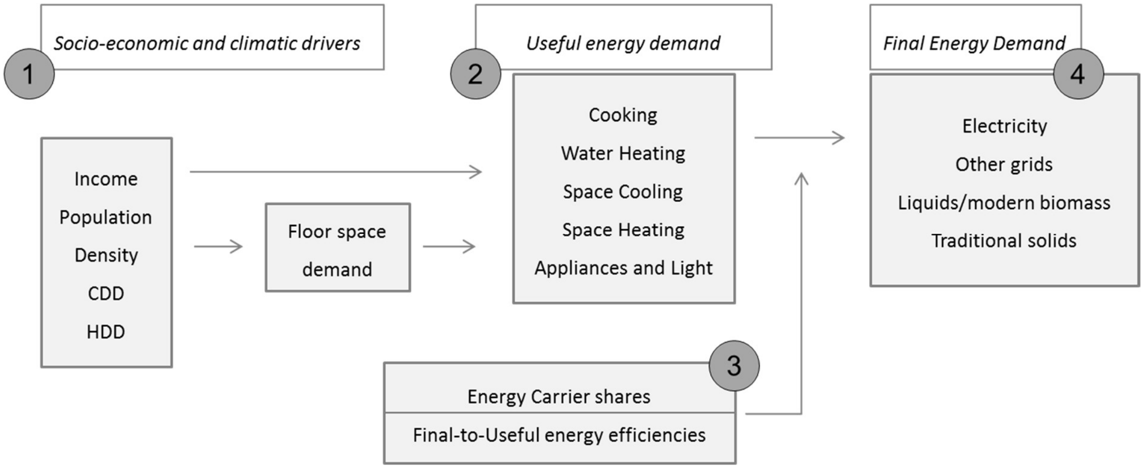

Figure 3: EDGE Flow chart (from Levesque et. al 2018)

Extensions of EDGE: the building stock model

In global energy models or IAMs, assessing climate mitigation pathways in energy efficiency in buildings plays an important role. The building energy use (in particular for space heating and cooling) is largely influenced by the building envelope, depending also on the age of the building. The long lifetime of buildings results in inertia for policies stimulating buildings efficiency and at the same time there is a strong path dependency of choice made now for the future efficiency potential. To assess the potential and associated costs of these future efficiency pathways, a representation of building stock is required. Indicating also the momentum of renovation and construction. Here we examine drivers of the buildings stock, a modelling approach and possible future projections.

Methods

Based on the European buildings stock data, an exploration of drivers of housing stock has been made. We have compared historic stock, construction, demolition to GDP and population development.

We find that there is a relation between occupied stock per capita and GDP per capita but that at approximately 0.5 stock per capita saturates. This is equal two people per occupied building. In the household size data, we see that currently no countries household size fall under 2 (See Table 4). Finland, Germany and Sweden have been approximating 2 since 1988 but never passed this value. Other countries that had in the past higher household size have decreased over the last years. The relation therefore seems to have a logarithmic form.

Table 4:Household size for a few selected countries

	1988	1994	1999	2005	2010
Germany (until 1990 former territory of the FRG)	2.22	2.25	2.16	2.11	2.03
Greece	3.09	2.94	2.82	2.73	2.65
Spain	3.54	3.31	3.24	2.94	2.67
Netherlands	2.51	2.33	2.26	2.27	2.23
Portugal	3.11	3.02	2.81	2.73	2.61
Finland	:	2.21	2.16	2.11	2.05
Sweden	:	2.16	2.17	2.09	2.14

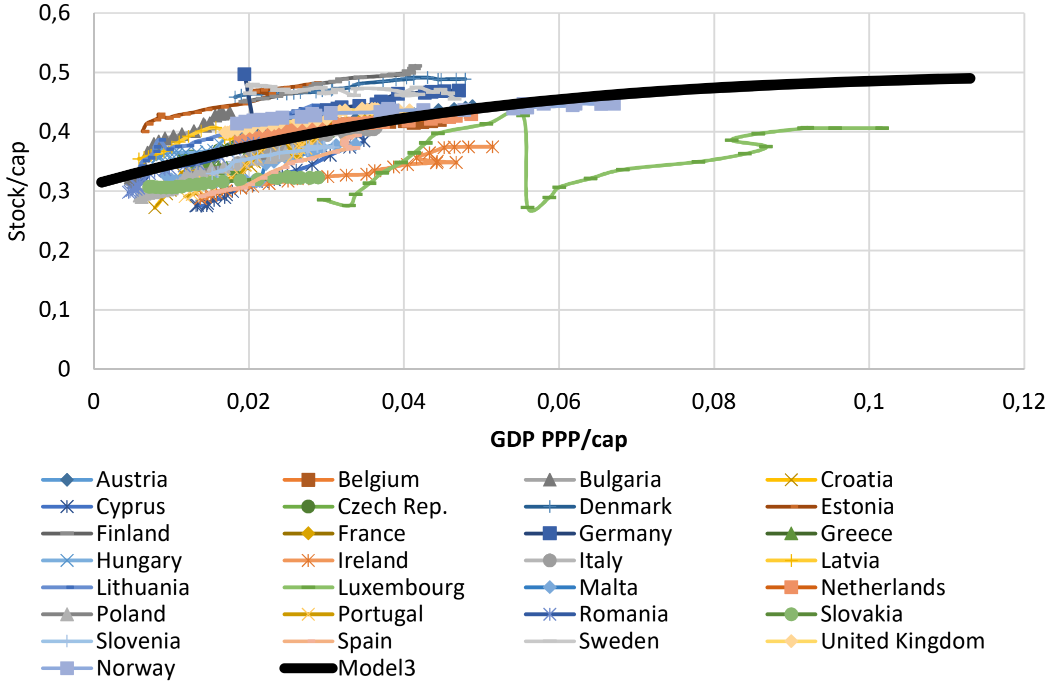

Figure 4: Occupied housing stock per capita compared to GDP per capita

Figure 4 shows the stock per capita compared to GDP per capita data. While the data grows rapidly with low GDP per capita, it saturates with higher GDP. We assume a logistic growth form relation with a max of 0.5. After this threshold, only population growth drives increased stock.

Construction

Examining the construction data (reported in Figure 5), we see that in some countries there can be a sudden increase in construction. An increase in construction can follow scarcity on the market or policy measures stimulating the housing market. After the increase we generally see that a decrease follows since this eventually can result in a housing bubble. The average construction overtime as share of the stock is 1.3%.

Those countries that show a sudden increase in construction have a large unoccupied part of the stock. Possibly, the increase in construction does not lead to more occupied houses but for example holiday houses, which will not likely result in higher energy consumption. Since we are interested in energy consumption, we focus on occupied stock and our model does not have to resemble the construction fluctuation, observed in some countries.

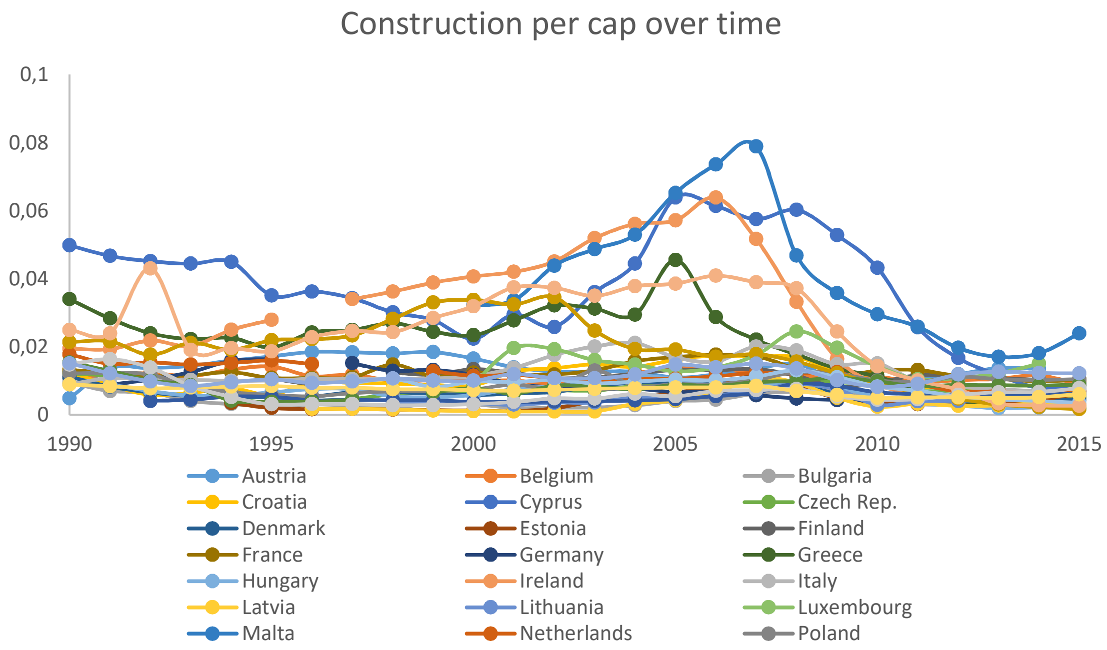

Figure 5: Construction share of the occupied stock over time

Building Stock, Construction and Demolition are related. Increased stock together with an assumed demolition rate of 0.7% globally (Levesque, et al., 2018) is assumed to be the driver of construction, following the equation below:

$$\text{Construction}_t = \text{Stock}_t - \text{Stock}_{t-1} + \text{Demolition}_t$$

Model

The logistic growth function of stock per capita, combined with the construction and demolition functions allows us to calculate historic stock following historic GDP and population development. To test our model, we run these equations from 1945 onwards to compare the calculated stock vintages to empirical stock vintages data. In addition, the calculated construction and Uvalue data are compared to empirical data.

Building vintages

Figure 6 shows an example of the vintage model results in the Netherlands in 2014. In general, the model seems to overestimate the "before 45" buildings as well as "10+" buildings. We have compared the vintages for a few parameters for each country. The share of "before 45" buildings, divide between "before" and "after 80", and the share of "after 2000". From the Uvalue data we see that "after 2000" buildings approximately have the same U Value.

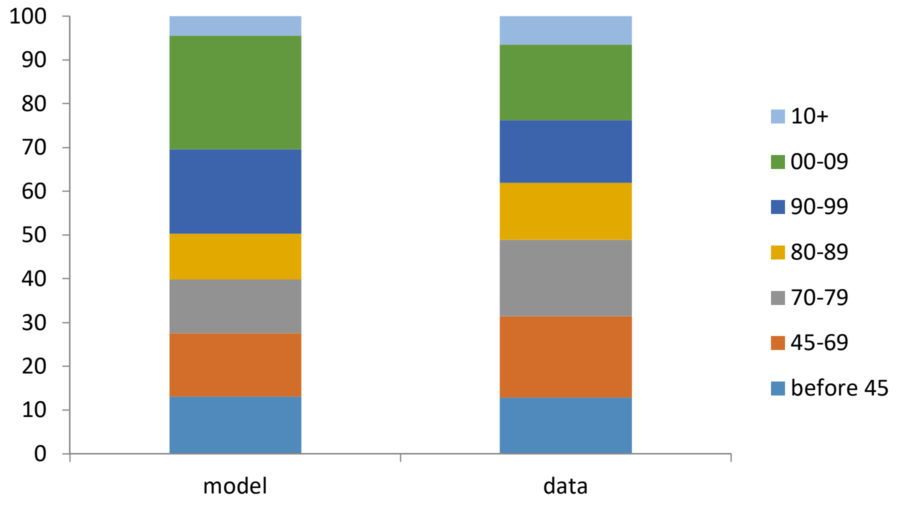

Figure 6: Model stock vintages compared to empirical data

Construction shares

Also the projected construction data is in general well in agreement with the historical data, and in certain regions, shows a striking resemblance (see below).

Figure 7: Modelled compared to historic construction data of Ireland

UValues

Uvalue data is available for 2008 for each of the building vintages for each European country. We assume that the country specific Uvalue will remain at its 2008 value. We find that the calculated U Values, compared to historic data are in reasonably well agreement and that the share of older buildings has a large effect on current energy efficiency.

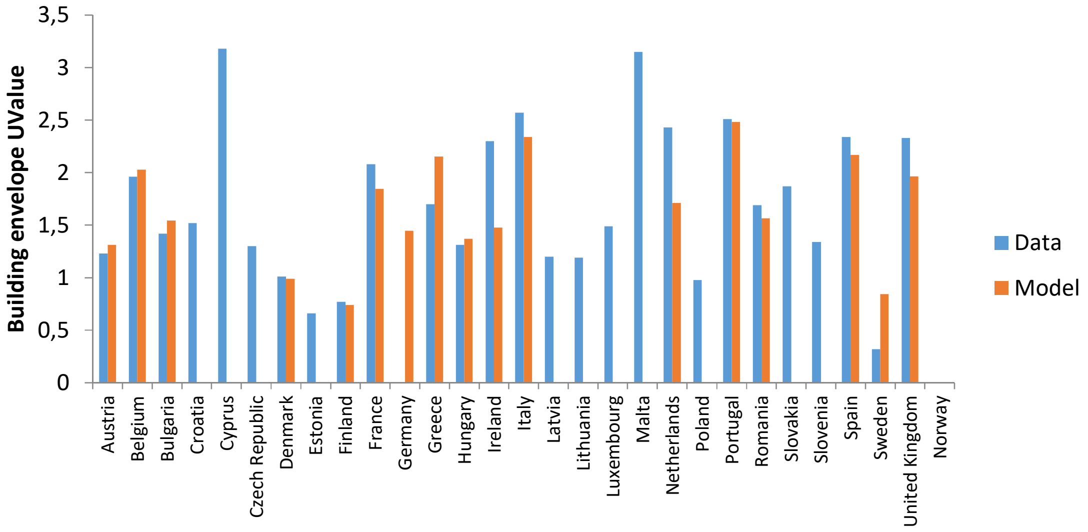

Figure 8: Modelled and empirical Uvalue

In comparison to the original EDGE model, the "optimal" Uvalue is based on current CDD and HDD. In addition, the assumption is made that while above 15.000 $/cap the optimal Uvalue is reached, below there is a linear relation. The effect is most likely that they project much lower Uvalues then assumed by the stock model (we would need to check).

Calibration of WITCH through EDGE

The extended EDGE model will be used to calibrate the more aggregate WITCH IAM. WITCH features a CES production function, whereby efficiency is governed through efficiency parameters, which are calibrated to match historical record. These parameters are either fixed or evolve exogenously in the model. EDGE will allow calibrating these parameters to match the building energy demand across a variety of different drivers. To this end, we will use the Shared Socio-economic Pathways (SSP) framework, which portrays 5 different future worlds, characterised by different demographic, economic, behavioural and technological assumptions.

3.2.3 Cluster analysis on the PENNY database to inform an agent based model

As a parallel contribution, we have carried out empirical work on the PENNY survey in order to assess and categorize consumers' behaviour with the aim of calibrating an agent based model (ABM). The MUSE ABM, has been developed by Imperial College.[8] It is a global energy system covering a variety of sectors, specifically aimed at modelling investment behaviour. A building sector has been developed which allows portraying a variety of typologies of household characteristics.[9] As always with ABM, the main issue regards calibration, since these models are very data intensive.

The PENNY survey provides detailed information about energy use, energy literacy and investment behaviour of several thousand households in different countries. As

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[8] https://www.sustainablegasinstitute.org/home/muse-energy-model/

[9] see https://spiral.imperial.ac.uk/bitstream/10044/1/57588/2/2B-Sachs_Agent-Based_Model.pdf

such, it can be used to categorize household types into a tractable number of clusters, which can then be inputted into the MUSE ABM. A collaboration between the MUSE team and FEEM has been established with the aim of jointly carrying out empirical work and calibrating the MUSE model.

Regarding clustering variables, we have included socio-demographic variables (income, range, education, size), energy efficiency behaviour variables (lighting habits), environmental preference, energy service level variables (electricity use, efficiency gap), and electricity consumption. See the next table for the definition of the variables.

Table 5: Definition of categories for ordinal variables

Variable	cat 1	cat 2	cat 3	cat 4	cat 5	cat 6	cat 7
Incomeclass	0-1000	1000-2500	2500-3500	3500-5000	5000-7000	>7000	
age_range	<15	15-24	25-44	45-64	65+		
educ_level	Primary or lower	Lower secondary	Vocational/ upper secondary	University (3-yr)	University (5-yr/ postgrad)		
Hhsize	1-person	2-3 people	4-5 people	6 or more people			
Lightsoff	Never	Rarely	Sometimes	Regularly	Always		
Switchoff	Never	Rarely	Sometimes	Regularly	Always		
env_aggregate	very low	low	slightly low	average	slightly positive	high	very high
effgap1	very low	low	medium	high	very high		
sumW2	very low	low	medium	high	very high		
el_cons_2016	very low	low	medium	high	very high		

K-means clustering has been conducted with cluster numbers ranging from 2 to 20. As shown in Figure 9, there is convergence with cluster number. An optimal 16 cluster has thus been identified and used for the analysis.

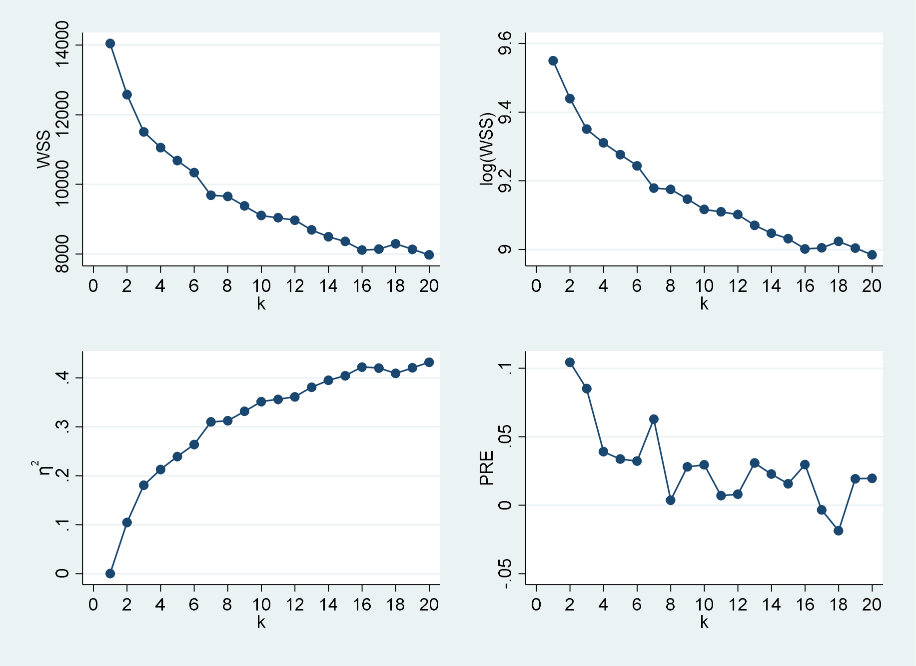

Figure 9: Visualisation of the WSS, eta-sq and PRE curves for cluster solutions 1-20

The figures below provide a visual representation of the inter-cluster differences in variables: socio-demographics (income, education, household size, age range), environmental preference aggregate, energy service level variables, energy efficiency behaviour variables and electricity consumption.

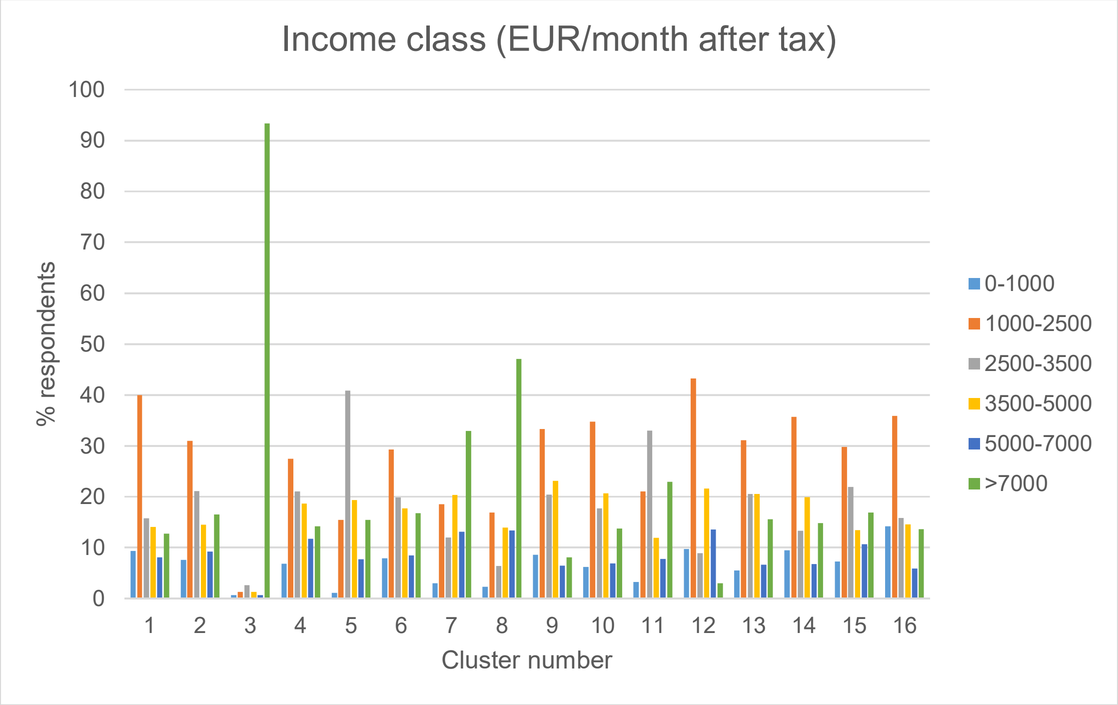

Figure 10: Income class

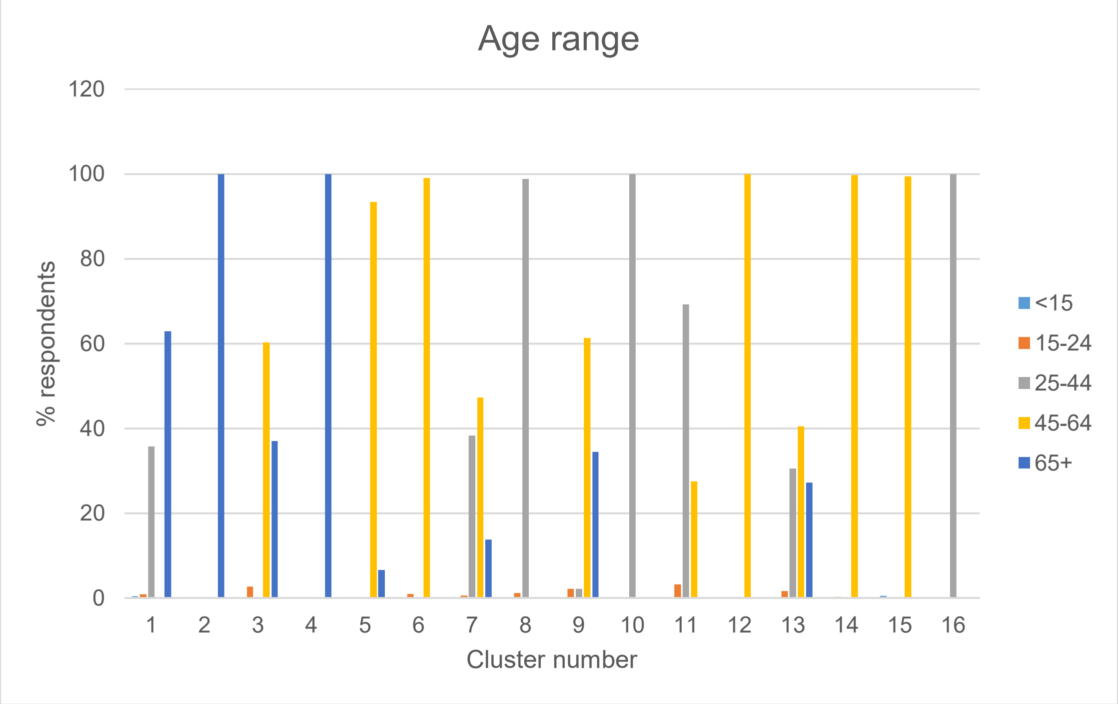

Figure 11: Age range

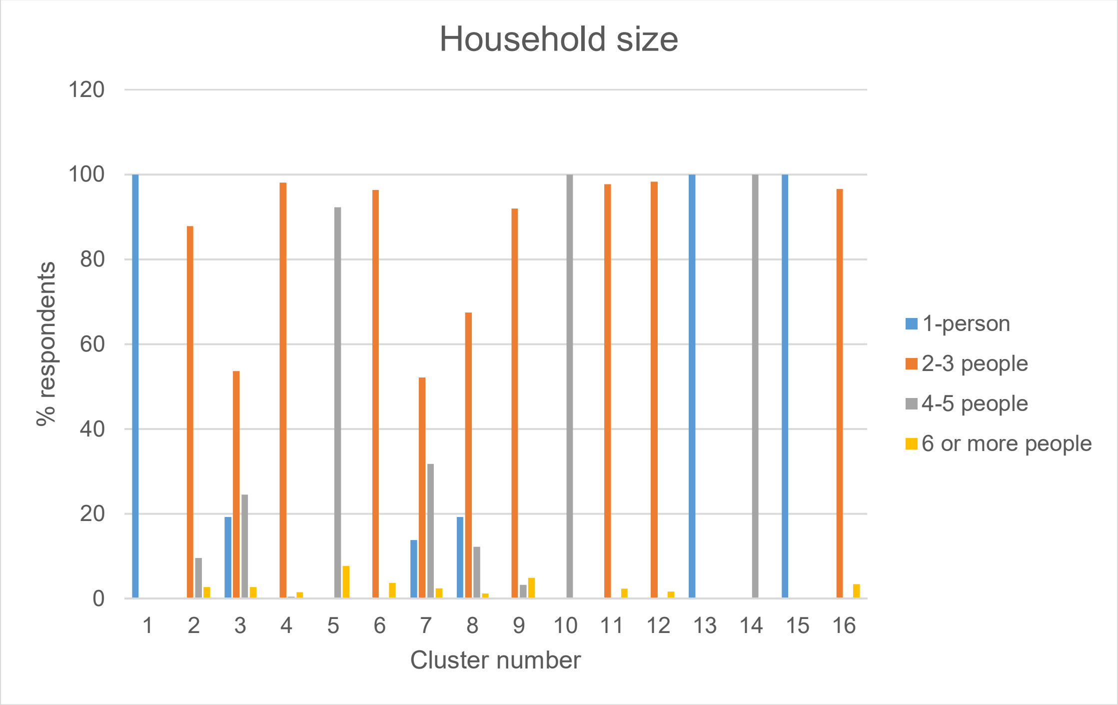

Figure 12: Household size

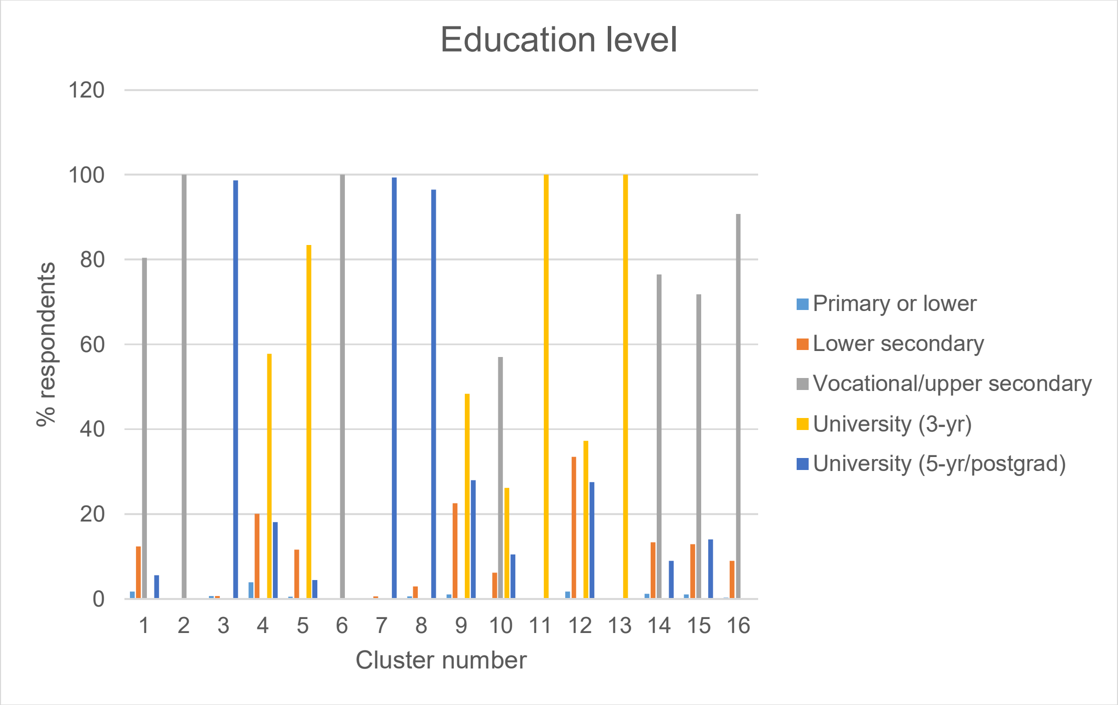

Figure 13: Education level

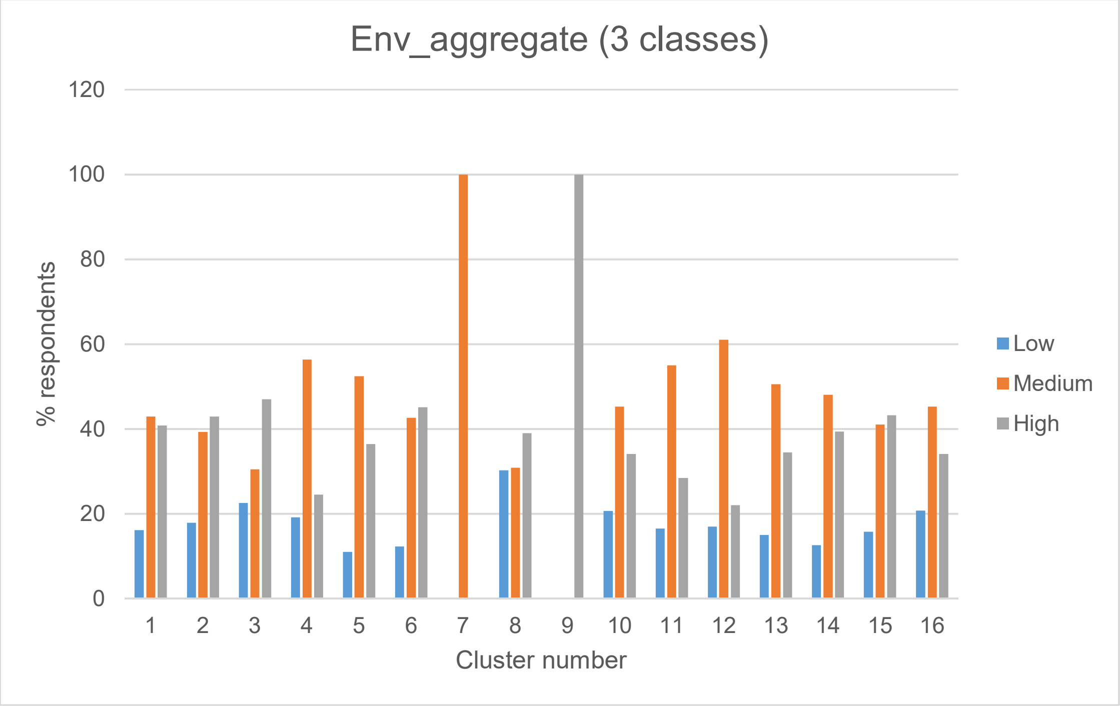

Figure 14: Environmental aggregate parameter

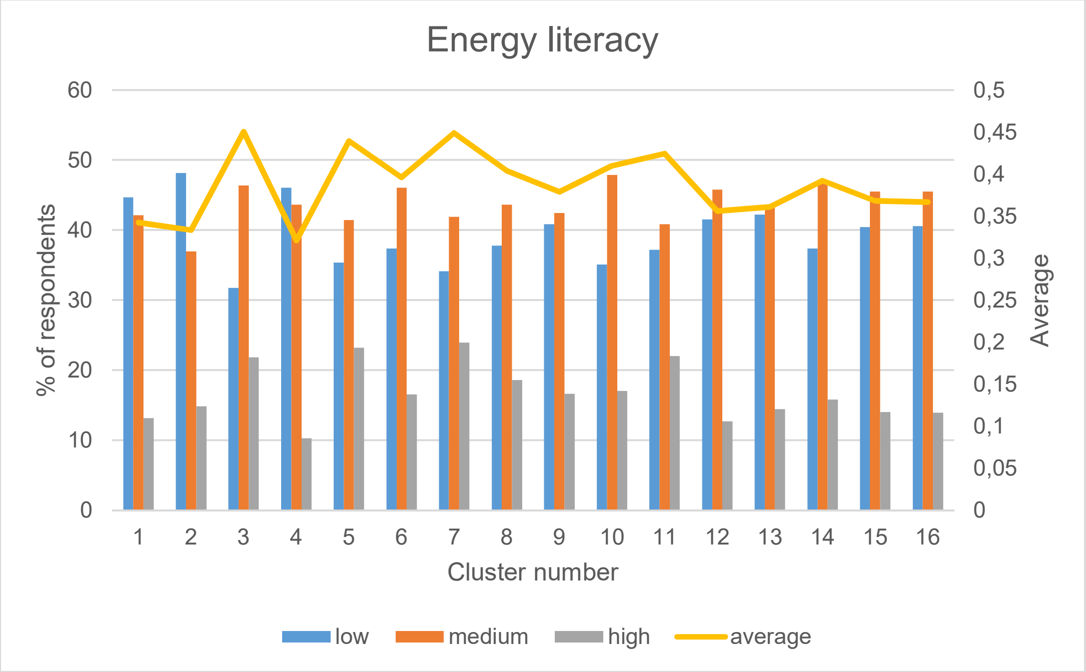

Figure 15: Energy literacy

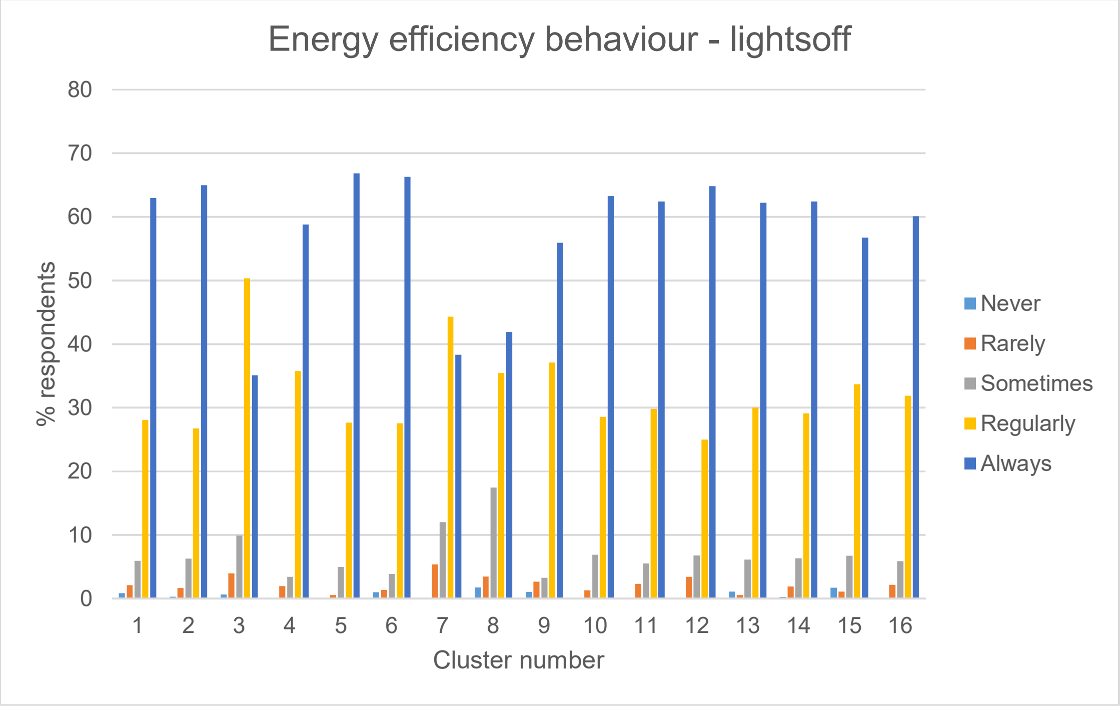

Figure 16: Energy efficiency behaviour – lightsoff

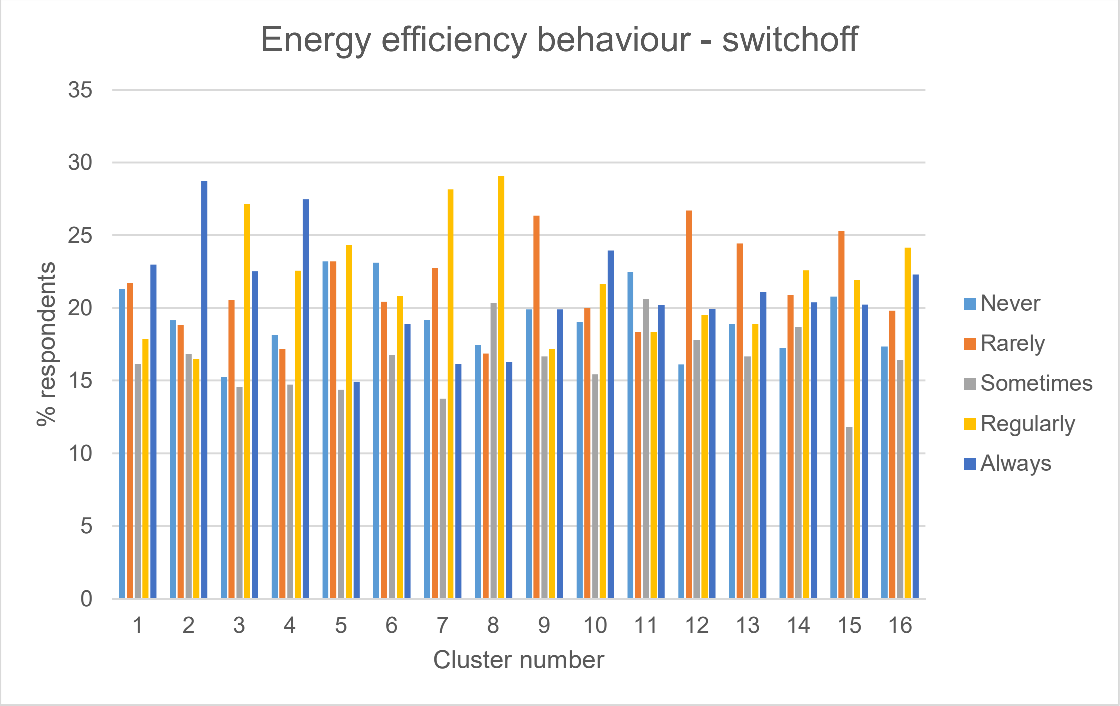

Figure 17: Energy efficiency behaviour – switchoff

The significance of differences between groups in the different variables was analysed. Kruskal-Wallis equality-of-populations rank test was used on ordinal variables, and ANOVA was also used as an additional test. Results have indicated significant differences between clusters for several variables, especially socio-economic ones, but also environmental and energy.

The identified 16 clusters will be provided as input to the ABM MUSE. The empirically calibrated model will be used to develop scenarios of energy efficiency investment behaviour, which will also inform the more aggregate IAM WITCH.

5. Conclusion

In this report, we enhanced the models by explicitly taking into account behavioural shortcomings in energy service consumption and residential energy use. We look at the consumption of energy services of households that use electricity and build a modelling framework that allows us to analyse the impact of household's misperception of electricity prices on the derived demand for electricity and energy services. Price misperception result in biased demands for certain goods and aggregates of goods by the consumers. The economy adjusts its output levels for these goods in order to maintain an equilibrium. We refer to this equilibrium as the equilibrium perceived by the consumers und price misperceptions, or shortly the perceived equilibrium. This inefficient perceived equilibrium can be compared with the usual efficient market equilibrium in order to compute the social cost of price misperceptions.

As we will show in our numerical analysis, households' preferences that determine the trade-offs in consumption have great repercussions on the impact of behavioural shortcomings. Based on the frameworks outlined in this report, the improved models can be used for the computation of scenarios and an analysis of energy efficiency policies in the EU. We are now able to take into account different behavioural shortcomings of households and see the wider impact of these biases on the derived demand for electricity, energy intensity and the associated impacts on production sectors in Europe.

Moreover, better grounded building models which can account on the one hand of building stock and on the other of household investment decisions for energy efficient goods have been developed, and calibrated using the survey data collected in the PENNY survey and using publicly available data on EU building types. These models will be subsequently linked to larger scale IAMs, helping to provide improved representation of energy demand as well as behavioural traits for investment decisions.

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