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System Dynamics Modeling of Households' Electricity Consumption and Cost-Income Ratio: a Case Study of Latvia

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Abstract **– Increased energy efficiency of the building sector is high on the list of priorities for energy policy since better energy efficiency would help to reduce impact on climate change and increase security of energy supply. One aim of the present study was to find a relative effect of growth of demand for energy services due to changes in income, energy consumption per unit of demand due to technological development, changes in electricity price and household income on household electricity consumption in Latvia. The method applied included system dynamics modeling and data from a household survey regarding the relationship between electricity saving activities and the electricity cost-income ratio. The results revealed that, in direct contrast to the expected, a potential reduction of the electricity consumption is rather insensitive to electricity price and electricity cost-income ratio, and that the efficiency of technologies could be the main drivers for future electricity savings. The results suggest that support to advancement of technologies and faster replacement of inefficient ones rather than influencing the energy price could be effective energy policy measures. The model, developed in the study could be used in similar assessments in other countries.**

Keywords **– Consumer behavior; electricity; energy efficiency; households; system dynamics**

1. INTRODUCTION

It is nowadays nearly axiomatic that society needs to increase energy efficiency of a building sector considering its sheer role in total energy consumption. Reduced energy consumption would help balance demand with production from renewable energy sources and would reduce the carbon footprint. With this aim, the European Union revised its directives concerning energy efficiency and performance of buildings [1], [2] putting more ambitious targets for the reduction of energy consumption. Policy makers may have the following question: what is a feasible level for targets, considering the dynamics of technological development, willingness of energy users to adopt these new technologies and increase of demand for energy services, propelled by an increase of prosperity? And what could be the role of financial incentives, e.g. associated with subsidies, taxes, price increase; normative requirements, e.g. efficiency standards, bans; as well as public information campaigns and environmental awareness of consumers? Studies show [3] that by using the existing technological solutions and by improving building insulation, using energy-efficient lighting and appliances, and installing more advanced climate controls in buildings, even big urban areas could reach a substantial part of their carbon reduction targets. However, it is also often found, that diffusion of the technological solutions could be rather slow with part of energy savings rebounding back due to increased demand for energy services. This is demonstrated by a

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study done in Germany [4], which showed a rather slow adoption of efficient lighting technologies and an up to 47 % increase of the demand for lighting as a result of increased energy efficiency. Recognizing slow adoption of new energy-energy efficient lighting technologies, consumer behavior is considered in techno-economic modeling of energy systems by using the *GAMS/TIMES/VEDA* platform, and describing the consumers through virtual technologies with attributes similar to tangible technologies [5]. However, only the household lighting sector is considered in the study, and heating and cooling is left for future analysis. Studies of impact of consumer behavior on electricity demand in India [6] result in the conclusion that decisions made by consumers are decisive factors of energy consumption. Energy efficiency policies, designed without taking into account economic decision "irrationalities" of consumers, may be inefficient in reaching designated targets, as is shown by research based on behavioral economics and psychology [7]. Monitoring data of smart electricity meters in Southern California reveal that a simple feedback about electricity costs do not alter the behavior of consumers significantly, and careful consideration of information provided in a feedback has to be provided [8]. As another study shows [9], installation of smart meters in Latvia, however, may have led to about 23 % of electricity reduction and some of it may be attributed to "psychological factors". Nevertheless, it is also claimed that feedback provided by the smart meters alone may not be sufficient to reduce energy consumption in the longer term, and therefore household behavior has to be modeled on a systemic level, considering also dynamics [10]. Agent-based modeling of consumer behavior shows that the EU ban on incandescent light bulbs could prove to be the most effective way to reduce electricity use for lighting [11]. Technological limitations are also important, and we may be too optimistic about the impact of energy price incentives on change in consumer behavior, as a study of Swedish households indicates [12]. The study shows that electricity real time pricing, possible with the introduction of smart meters, could bring only 2 % to 5 % of daily electricity cost reduction due to limitations of load shifting from high- to low-price hours. The importance of technological aspects is also supported by a study of household electricity demand using data from a survey and smart meters [13] in Latvia. Results of the study show that about 13 % of electricity can be saved in a few years as a result of the improvement of energy efficiency of electric appliances, and the importance of behavioral aspects is also recognized.

A review of the previous research allows to conclude that, considering the intertwined effects of technological development, growth of prosperity and behavioral aspects on the energy efficiency, additional studies, combining technical, economic (i.e. energy price changes) and social aspects, and considering the dynamics of non-linear relations of these aspects, feedbacks and delays would provide valuable insight to the topic on a systemic level. Therefore, a research question for the present study was: what is a relative effect of growth of demand for the energy services due to changes of an income, the energy consumption per unit of the demand due to the technological development, changes of electricity price and household income on household electricity consumption? An answer to the question may facilitate design of a policy for promoting energy efficiency improvements by indicating the most effective leverage points for intervention as well as suggesting which factors may be left to technological development and market forces. A focus of the study is on the residential electricity consumption for the provision of the following energy services: lighting, use of electric appliances, climate control (heating, cooling) and hot water supply. System dynamic modeling is used as a method since it is well suited for analysis of dynamics of complex systems with feedbacks. System dynamics has a long history of application for analysis of various aspects of the power sector [14], including also electricity market regulation issues [15], which is a considerably new topic due to the relatively recent deregulation of the power sector in many countries. The modeling approach is also successfully applied to studies of electricity demand in the household sector, e.g. the study in the Netherlands on the effect of diffusion of smart meters, increase of number of ICT equipment and technological advancement of electric appliances on the power consumption [16]. However, use of the system dynamic modeling for socio-technological studies of the consumer sectors with an aim to increase the efficiency of energy and other resource use can be considerably expanded.

The present study narrows down the behavioral aspects and considers only residential consumer motivation to save electricity in response to changes in electricity cost-income ratio. An argument for that research choice was an opportunity to observe a response of the residential electricity demand to a substantial price increase (i.e. by circa 45 %) when the households joined the liberalized electricity market in Latvia in 2015. This increase was a result of freeing the regulated and cross-subsidized household electricity prices to market forces. A study of the electricity price elasticity of demand of households based on survey data from 11 OECD countries provides evidence for the substantial importance of the electricity price in determining consumption [17]. It is also recognized that one drawback of the study is the lack of instruments to explicitly address an issue of endogenous character of the price, and that it is important to account for temporal variation. The present study attempts to avoid these deficiencies by considering the electricity price endogenously and changes the modeled system over time. In addition, a fixed value of the price elasticity of demand is not able to capture change of a slope of the elasticity as consumption changes. With system dynamic modeling we can explicitly capture feedback from the consumption to the elasticity. A model of the present study is calibrated with data from Latvia but could be used for analysis in other countries and regions as well.

2. METHODS

The system dynamic modeling was used as the method in the study due to its ability to provide a modeler with well suited and convenient instruments for analysis of dynamics of complex systems with inclusion of feedbacks and delays. The study analyzed dynamics of household electricity consumption which depend on two important feedbacks – the feedback from electricity consumption to electricity cost-income ratio (and further to a motivation to save electricity) and the feedback from electricity consumption to electricity price, also affecting electricity cost-income ratio (Fig. 1). In addition, a household survey regarding the relation of implemented electricity saving measures and the electricity cost-income ratio was carried out and this functional relationship was used in the model to characterize the link between the electricity cost-income ratio and the motivation to save electricity (Fig. 1).

2.1. Model Structure

A dynamic hypothesis is based on the assumption that the motivation to save electricity is driven by the electricity cost-income ratio (Fig. 1), which, in turn, depends on electricity consumption, electricity price and income.

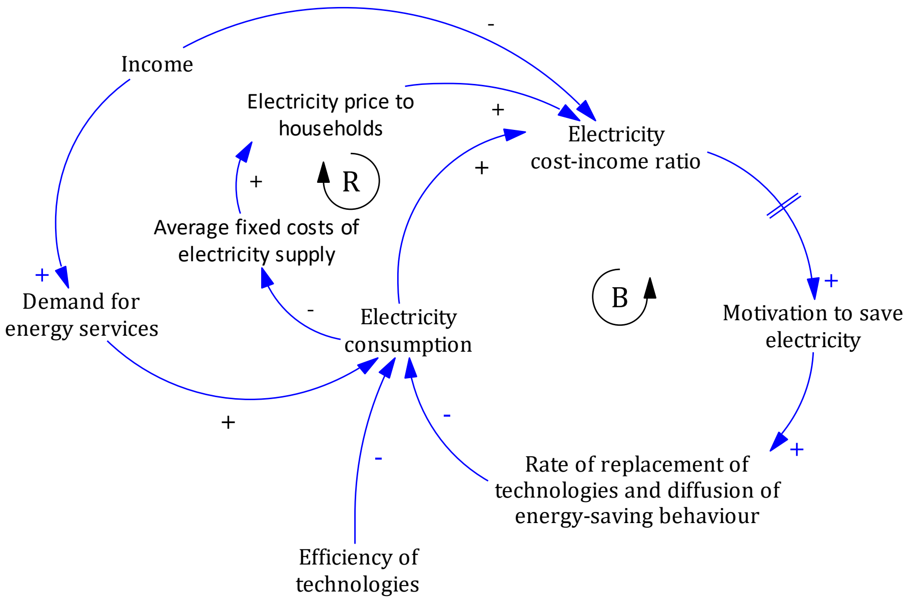

Fig. 1. Dynamic hypothesis – a causal loop diagram (CLD) illustrating the main feedback processes.

A structure of the studied system can be represented by one reinforcing and one balancing loop (Fig. 1). Decreasing electricity consumption as a result of the increased motivation to save electricity reduces the electricity cost-income ratio and thus balances-out the effect of the motivation. The balancing loop illustrates a re-bound effect of energy savings. On the other hand, decreasing electricity consumption increases the average fixed costs of electricity supply which, in turn, drives up the electricity price for households and the electricity cost-income ratio, thus reinforcing the motivation to save electricity. The increased motivation feeds back to electricity consumption by decreasing it even more and increasing the price of electricity further ceteris paribus. Growth of the income has two effects (Fig. 1):

– It increases the demand for energy services, i.e. lighting, heating, cooling;
– Decreases the electricity cost-income ratio, thus pushing electricity consumption upwards. The electricity consumption is reduced by increasing efficiency of technologies, leading to reduced electricity consumption per unit of energy service provided.

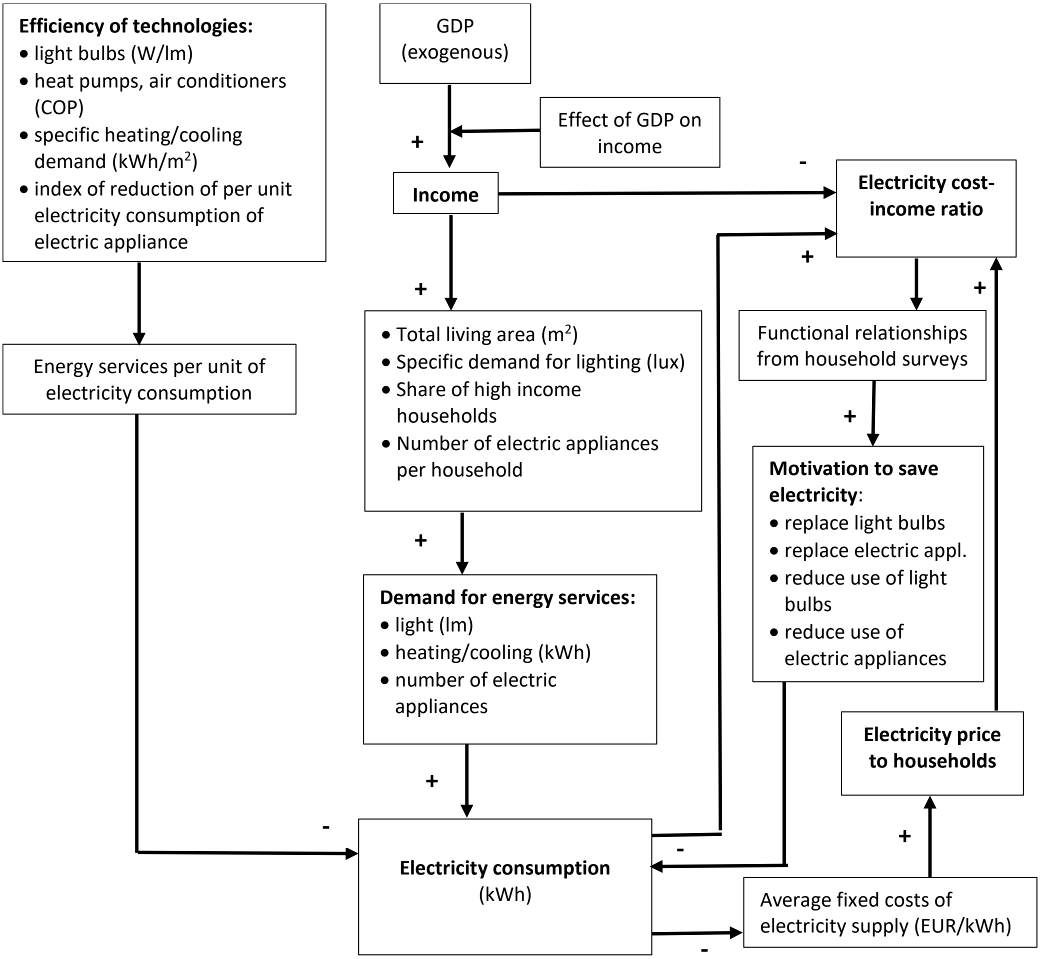

Fig. 2. Structure of the model – a sector diagram.

The model is organized (Fig. 2) according to the structure reflected by the causal loop diagram. A gross domestic product (GDP) is taken as an exogenous parameter for determination of the dynamics of income. The data regarding GDP increase, household characteristics (living area, types and number of lighting, heating, cooling equipment, electric appliances and hot water heaters) were obtained from statistical databases [18]. The data of household electricity consumption and the prices for the years 2014–2016 were obtained from the electricity company "AS Latvenergo". The average fixed costs of electricity supply are calculated based on the assumption that the initial total fixed costs of electricity supply to end-users do not change. Thus, with calculating change of the electricity consumption, the variation of the electricity price to households can be determined endogenously. The initial efficacy and goal for efficacy of the light bulbs were characterized by using European Commission regulations [19], and materials of experts in the field [20]. The functional relationship between the electricity cost-income ratio and the motivation to save electricity was obtained from a household survey in Latvia (more details on the survey are provided below).

The main stocks in the model are efficiency characteristics of the new equipment – light bulbs, electric appliances, heat pumps and air conditioners (Fig. 3) as well as shares of the old and the new equipment (Fig. 4). Efficiency of the new equipment is modeled assuming the "goal seeking" behavior, which may be a good assumption considering a diminishing return of efforts, invested in the development of a particular technology. Decrease of the specific heating and cooling requirements (kWh/m^2) are also understood as increase of the efficiency of technologies and is modeled the same way.

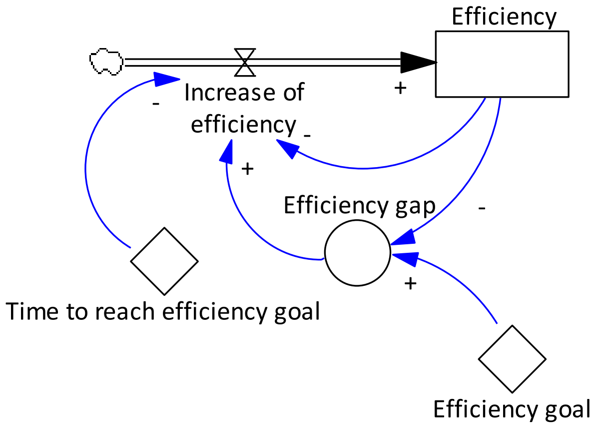

Fig. 3. A stock-and-flow diagram representing change of the efficiencies of technologies (light bulbs, household electric appliances, heat pumps, air conditioners) and specific (per unit of living area) heating/cooling consumption.

Increase of the electricity cost-income ratio (Fig. 4) motivates a certain fraction of households to replace old light bulbs and electric appliances which still could be operated with the new ones, i.e. at a rate which is faster than would be required if following the normal lifetime of those units. Decrease of the electricity cost-income ratio would create an opposite motivation. There are no outflows, associated with deprecation of these stocks, made from the stocks representing the new equipment due to a relatively short time span of modeling comparing to the potential life-time of the new equipment. Analysis of longer time periods would require considering those outflows as well. The varying electricity cost-income ratio also influences the motivation to reduce use (hours of use) of the light bulbs and the electric appliances, i.e. change the behavior of use. The motivation to replace equipment of change behavior is obtained as follows:

Motivation = Share of respondents and *Share of respondents = f (electricity cost-income ratio),*

where the relation between the *Share of respondents* and the *electricity cost-income ratio* is obtained from the household survey (Fig. 6 and Fig. 7).

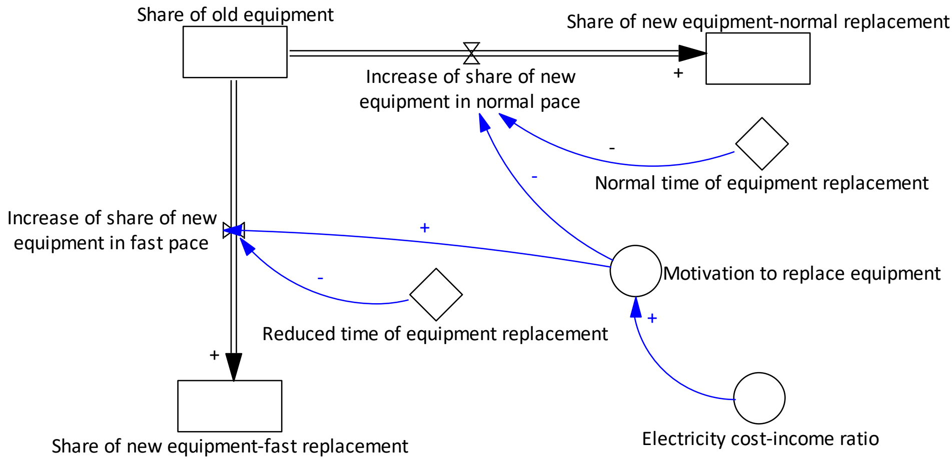

Fig. 4. A stock-and-flow diagram representing replacement of old equipment (light bulbs, electric appliances) with new equipment.

A survey of 700 households was carried out in Latvia during 2015 in order to quantify the relation between the electricity cost-income ratio and the motivation to save electricity, as included in the dynamic hypothesis (Fig. 1). The aim of the survey was to find out what electricity saving measures were actually implemented by the households in response to an increase in the electricity cost-income ratio (Fig. 6 and Fig. 7). Analysis of the survey data revealed two groups, i.e. the low- income and the high-income households can be distinguished with higher electricity cost-income ratio among larger fraction of the first group (Fig. 5). Approximately 80 % of the low-income households from the survey group spend circa 8 % of income on electricity bills whereas for the high-income households this ratio is roughly 4 %–5 % (Fig. 5). Although not large, a difference was also observed in electricity saving activities in response to increase of the electricity cost-income ratio among the two household groups (Fig. 6 and Fig. 7). Therefore, it was decided to model these two groups as separate parts. An additional description of the survey can be found in [21]. The time span for the modeling was determined as January 1, 2014 – January 1, 2021.

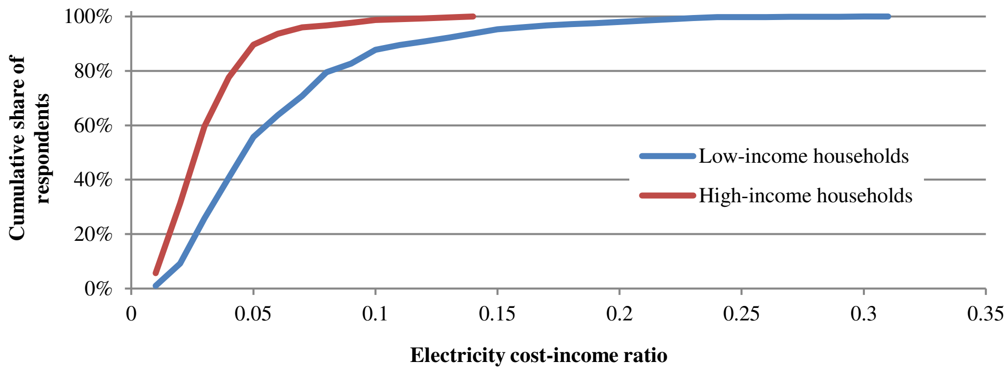

Fig. 5. Relation between the cumulative share of respondents and the electricity cost-income ratio in the low- and high-income households.

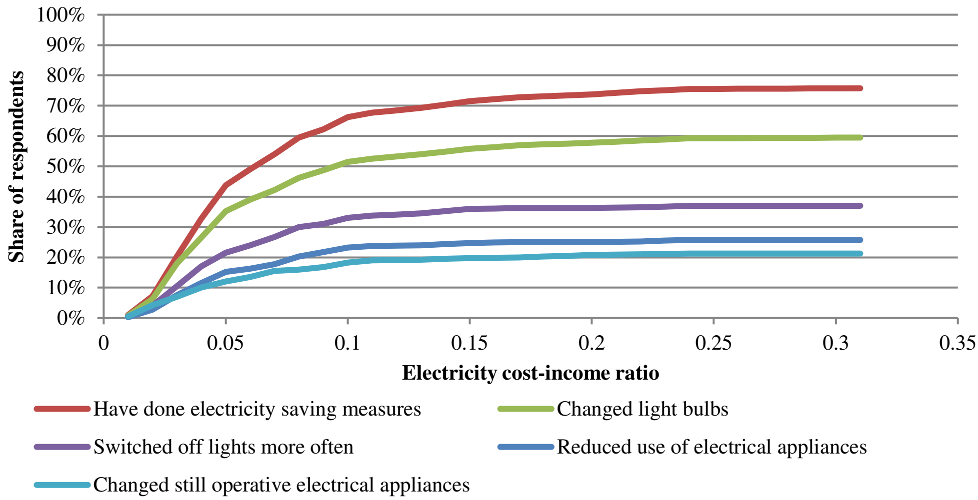

Fig. 6. Relation between the share of respondents and electricity saving measures accomplished during the last three years, and the electricity cost-income ratio within the low-income households.

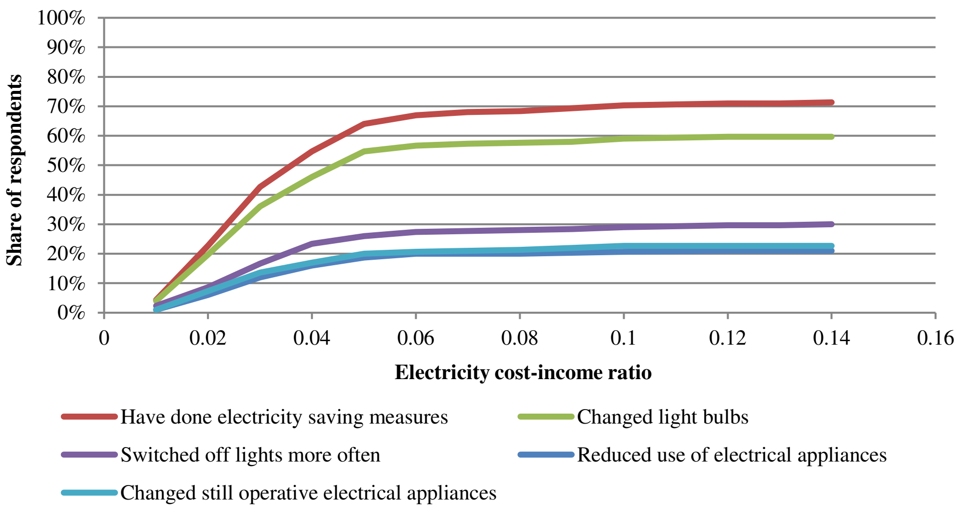

Fig. 7. Relation between the share of respondents and electricity saving measures accomplished during the last three years, and the electricity cost-income ratio within the high-income households.

2.2. Model Validation

The model was validated using structural and behavioral tests [22]. Both data of the actual electricity consumption and the calculated results show initial decline of electricity consumption (although the calculated consumption does not exhibit the same extent of decline as the actual) with subsequent increase in the year 2015 to the level which is still lower than the initial consumption (Fig. 8). The calculated increase of the consumption during 2015 is explained by an increase in the number of electric appliances due to growth of income (included as an effect of income on number of electric appliances in the model).

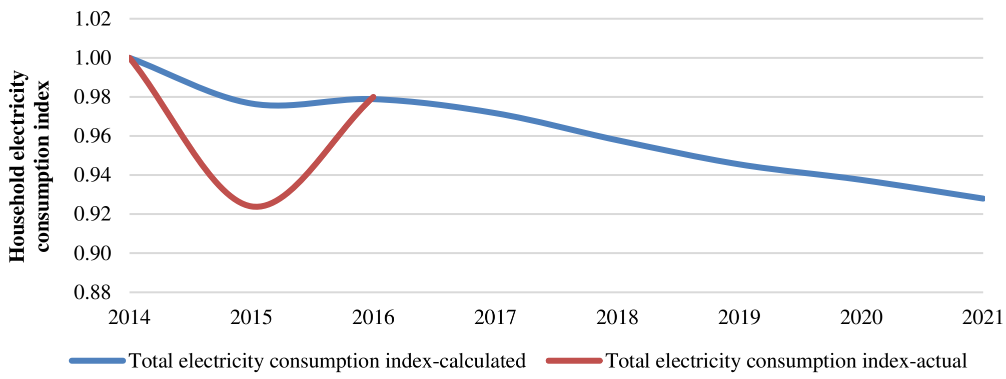

Fig. 8. Total household electricity consumption index – calculated results and actual data (the initial consumption: 1887 GWh/year).

The calculated and the actual indexes coincide during the year 2016 and the results of the model indicate further decline in electricity consumption, starting with the year 2016. As will be discussed in more detail in the "Results and Discussion" chapter below, this can be explained by the rate of increase of energy efficiency of technologies being larger than the rate of increase of demand for the energy services.

It is expected that reduced time of replacement of old light bulbs and electric appliances with the new ones would lead to even more rapid decrease of the electricity consumption since the new equipment have higher efficiency. This is demonstrated by the calculated results (Fig. 9), when time of replacement of the equipment is set to nearly zero value.

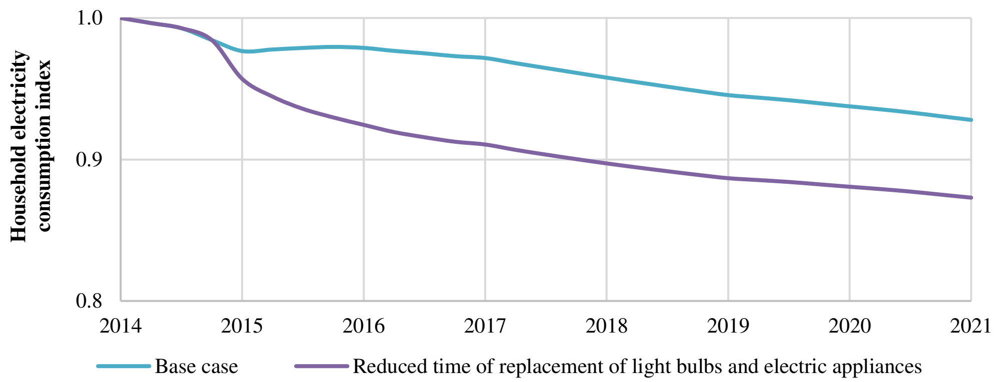

Fig. 9. Total household electricity consumption index – base case (the reference mode) and the case with time of replacement of light bulbs and electric appliances being nearly 0 (the initial consumption: 1887 GWh/year).

Additional tests, i.e. consistency of units, change of time step, tests with extreme values were carried out to gain confidence in the model. Outputs of the model, as partly demonstrated in the "Results and Discussion" section, e.g. with relation between electricity-cost income ratio and motivation to replace light bulbs (Fig. 10 and Fig. 11), seem to change in a "logical way" in response to inputs and therefore it was concluded that the model can be used for the intended assessment.

3. Results and Discussion

Results of the model show that, under the current assumptions and dynamic hypothesis, the total residential electricity demand may decline in the considered time span (Fig. 8). Although the indexes of change of the electricity-cost income ratio and the resulting indexes of the motivation to replace light bulbs (the trend is similar for the motivation to replace electric appliances and change behavior) in both household groups decrease beyond the year 2016 (Fig. 10 and Fig. 11), these indexes still remain above the value 1. It can be noticed that a considerable increase of the electricity price in 2015, resulting in similar increase of the electricity cost-income ratio and motivation to replace light bulbs, does not lead to a drastic drop of electricity consumption.

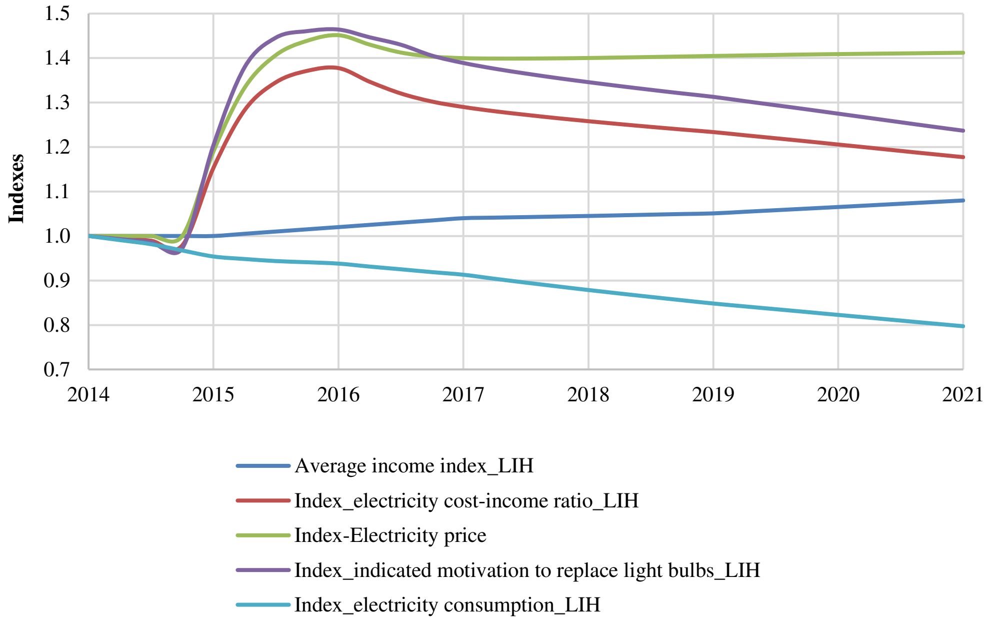

Fig. 10. Indexes of electricity price and low income household (LIH) electricity consumption, average income, electricity cost-income ratio, indicated motivation to replace light bulbs.

The index of electricity consumption in the high income households increases (Fig. 11) because of increasing share of the high income households due to economic growth. If the share of the high income households is set constant in the model then electricity consumption decreases in both groups.

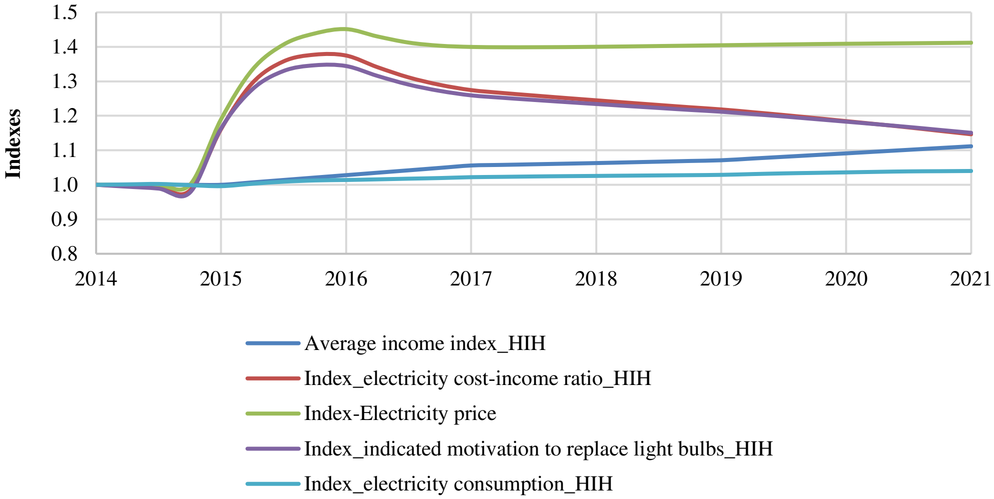

Fig. 11. Indexes of electricity price and high income household (HIH) electricity consumption, average income, electricity cost-income ratio, indicated motivation to replace light bulbs.

The electricity price increases only slightly, due to increasing average fixed costs of electricity supply as a result of declining total consumption (Fig. 10 and Fig. 11). The electricity cost-income ratio after 2016 is brought down by a combined effect of increasing income, outpacing increase of the electricity price, and decreasing electricity consumption. By comparing the calculated values of the electricity cost-income ratio (Fig. 12) with the values from the household surveys (Fig. 6 and Fig. 7), it is observed that the calculated values are within a range in which a slope of change of the motivation to save electricity depending on change of the electricity cost-income ratio is quite steep for the both household groups. Therefore, it can be claimed that the electricity cost-income ratio is within the region where the motivation to save electricity is rather sensitive to the ratio.

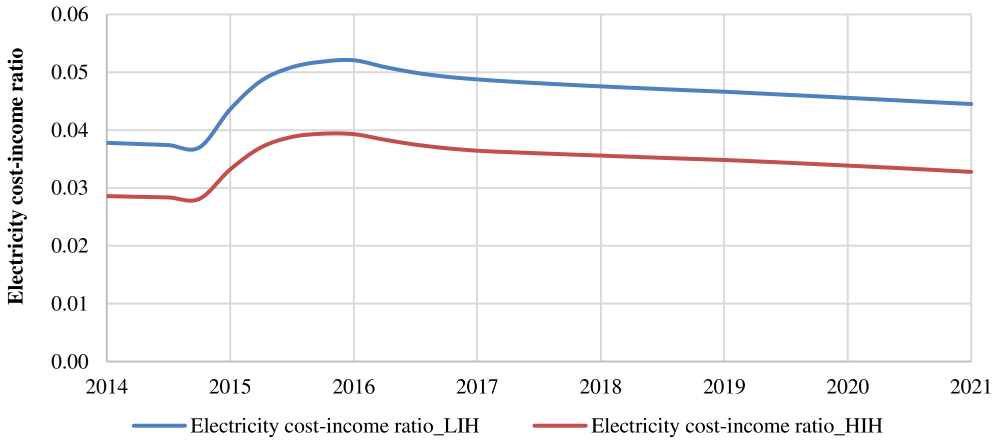

Fig. 12. Electricity cost-income ratios in low (LIH) and high (HIH) income households.

To explain the obtained results and also to answer the research question put forward in the "Introduction", several scenarios, in addition to the reference or base case, were analyzed (Fig. 13). First, by increasing the efficiency of technologies, behavior of use and the demand for energy services constant, the model can have an additional validation test since electricity consumption should remain constant under these assumptions, as it does. When the efficiency of technologies and behavior of use is left constant but the demand for energy services increases due to increase of an income, a quite substantial increase of electricity consumption can be observed. And to the contrary, when the demand for energy services remains constant but the efficiency of technologies and behavior of use do not, an even more considerable decrease of electricity consumption results.

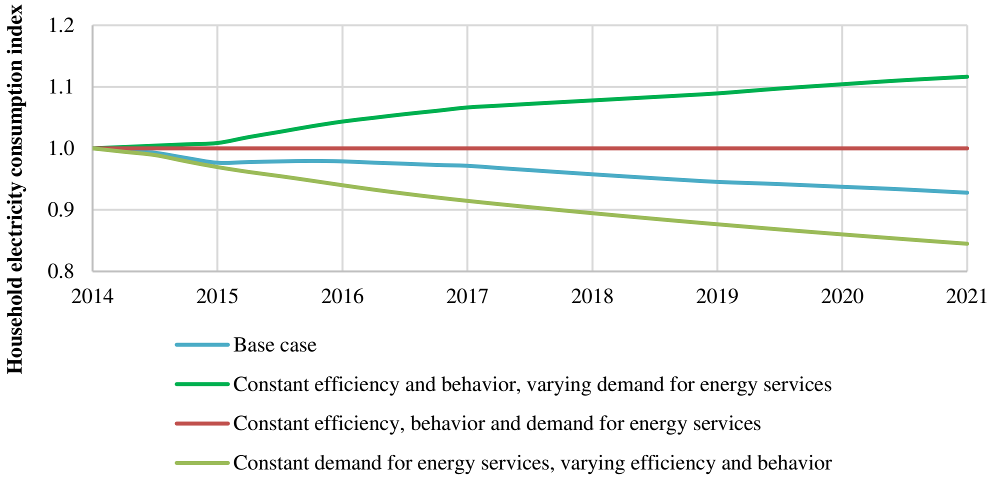

Fig. 13. Total household electricity consumption index for the base case (the reference), the case with constant efficiency of technologies and no change of behavior (reduction of use of light bulbs and electric appliances, no replacement of electric water heaters with alternatives), the case with constant efficiency (the same assumption as for the previous case) and constant demand for energy services (lighting, use of electric appliances, heating and cooling), the case with constant demand for energy services (as for the previous case); (the initial consumption: 1887 GWh/year).

An additional test of sensitivity of electricity consumption to the electricity price was made when making it constant and comparing it with results of the base case (Fig. 14). When the electricity price is constant, the resulting electricity consumption is slightly larger but a difference with the base case is not profound. When the electricity price is set constant along with a constant demand for energy services, the results show that a difference with the scenario with constant demand for energy services but varying electricity price (Fig. 13) is very little, i.e. electricity consumption is only by circa 1 % larger in the case with constant electricity price. It is probably worth noting that no difference of electricity consumption of the base case and the case with constant electricity price until 3rd quarter of 2015 is due to an information delay between the electricity cost-income ratio and motivation to replace light bulbs, willingness to replace electric appliances and electric water heaters, as well as reduce use of light bulbs and electric appliances. The information delay is used for technical reasons, i.e. to avoid circular references, but may as well be justified by reality, since an increase of the electricity cost-income ratio may be perceived and trigger some action with a time delay.

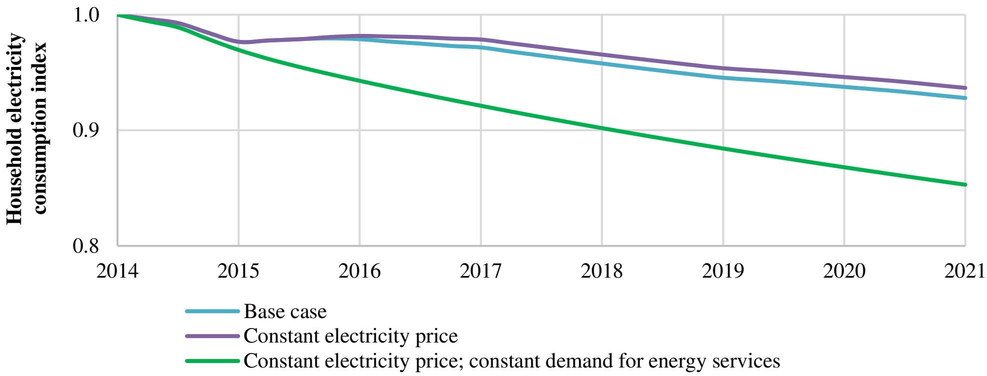

Fig. 14. Total household electricity consumption index for the base case (the reference), the case with a constant electricity price, and the case with a constant efficiency of technologies and no change of behavior (no reduction of use of light bulbs and electric appliances, no replacement of electric water heaters with alternatives) and constant demand for energy services (lighting, use of electric appliances, heating and cooling); (the initial consumption: 1887 GWh/year).

Similar results were found in a study made in China which shows that the short-run electricity price elasticity of demand is small with a tendency to decrease as living standards grow [23]. It is probably still too early to claim with confidence that the results of this study point to a relatively low effect of the electricity cost-income ratio and the electricity price to consumption, but the results can suggest several directions for the future research and improvements of the model. First, one of the deficiencies of the model which could be eliminated is more accurate modeling of efficiency attributes of equipment. In the present model, the efficiency of all new equipment of the same type is assumed to be the same and equal to the current level of technological development. It would be more correct to account that new equipment is a mix of units with differing energy efficiency characteristics which depend on time of "purchase" by a household. Furthermore, considering that a "goal-seeking" character of efficiency change leads to a quite rapid increase during the initial time periods, it is important to assess the sensitivity of electricity consumption to assumptions regarding the values of goals and time to reach those goals. In additional to those "technical" aspects, research could be extended by including additional social factors which may lead to changes of consumer behavior. Namely, integration of the results from sociological studies on impact of environmental awareness, information level, "behavior of neighbors and friends", etc. in addition to economic factors, in system dynamic modeling would provide more insight to potential future energy savings. Considering the influence of specific factors which depend on a region which is studied, e.g. income and electricity price level, climatic conditions, etc., it would be worthwhile to expand similar studies to other regions.

4. Conclusions and Recommendations for Policy Design

Results of the present study suggest that, under current modeling assumptions and input, electricity savings which may result in a household sector in the future could be rather insensitive to the electricity cost-income ratio, and would be mainly driven by a change of efficiency of technologies. Effect of an increasing income and a resulting growth of demand may be quite strong drivers for upward trends of consumption. Thus, the dynamics of electricity consumption may be mainly determined by competing rates of the technological development and growth of prosperity if such psychological factors as environmental awareness, downsizing, as well as information level and demography are left aside. For a policy design, the results may mean that more attention should be paid to support of advancement of technologies and faster replacement of the inefficient ones than to influencing the price of energy. However, further studies on dynamic energy consumer systems with combined technical and social factors would facilitate an effective energy efficiency policy design.

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