A system dynamics-based model of the socio-technical systems of household energy and carbon emissions

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Abstract

There have been concerns over sustainability issues around the world, especially when it comes to the way energy is used and corresponding environmental impacts in the form of climate change, global warming, etc. Reduction in household energy consumption is seen as a way to curtail this menace. This paper argues that the issue of household energy consumption and CO_2 emissions (HECCE) is a complex technical and social phenomenon that needs to be understood from both engineering and social science perspectives. This research used the concept of socio-technical systems as the theoretical framework. The research applied system dynamics as both the methodology and tool to model HECCE. The result is a population of outcomes for the HECCE in the form of space heating, hot water, artificial lighting, appliances, and cooking. The tool produced is an intuitive one with the capability of replicating reality as evidenced from the outcomes of validation done. Sensitivity analysis of different policy levers (occupants' behaviour, insulation level, etc) can therefore be done with the tool. It is concluded that the outcomes of this study would go a long way in helping decision makers draw more realistic policies for household energy consumption which is critical to the CO_2 emissions reduction agenda of the government.

Keywords: household energy, household carbon emissions, socio-technical systems, system dynamics

1. Introduction

There have been concerns over sustainability issues around the globe, especially regarding how energy is used up and the corresponding CO2 emissions. In the UK, about 27.5% of total energy consumed is used up in dwellings and CO2 emissions attributed to dwellings alone is around 26% of the UK's total carbon emissions. As such, the domestic sector of the UK's economy is chosen as the centre of focus for both mitigation and adaptation agendas with a view to meeting the CO2 emissions reduction target of 80% by 2050 based on 1990 levels as prescribed by the Climate Change Act of 2008. To meet this target, UK government has initiated a number of policies as measures against this menace. These policies target strategies like improving fabric insulation and energy efficiency, uptake of micro-generation, green deal, and the host of others. There is then the need to evaluate different scenarios for future household energy consumption and carbon emissions (HECCE) regarding these strategies in order to determine their effectiveness in meeting carbon reduction agenda of the Government as provided by law.

To this end, there are quite a number of different energy related models that were developed in UK with the sole aim of analysing energy consumption and consequently carbon emissions in dwellings. Some of these tools have the capability of projecting into the future energy consumption. Among these models are the building research establishment's housing model for energy studies (BREHOMES) that was developed by Shorrock and Dunster (1997), the Johnston model developed by Johnston (2003), the UK carbon domestic model (UKDCM) developed by Boardman *et al.* (2005), the Decarb model developed by Natarajan and Levermore (2007), the community domestic energy model (CDEM) developed by Firth *et al.* (2010), and the host of others. These models provided the policy makers with the policy advice tool. However, the models are significantly different in terms of the level of disaggregation, which then determines there suitability in offering adequate policy advice. Also, the algorithms developed for these models are based on building physics, statistics, or hybrid of the first two. For statistical models, some of them employed different statistical methods like the use of regression analysis. While statistical-based models have proved useful in some respect, the method has failed to provide much detail and flexibility and therefore has limited capability in evaluating the impact of a wide range of energy policy strategies (Fung, 2003). Further to this, the methods fail to account for complexity and inter-dependencies in model variables.

To address the deficiencies of building physics, statistical and hybrid-based energy models, researchers (Shipworth, 2005; 2006; Motawa & Banfill, 2010; Oladokun *et al.*, 2012a; 2012b) advocate and propose the use of socio-technical systems (STS) as an approach that is capable of solving the problem of complexity due to high inter-dependencies, chaotic and non-linearity of the variables involved as well as feedback loop structure of HECCE influencing variables by contributing to the dynamic nature of the system under investigation. Obviously, it is necessary to acknowledge that the issue of HECCE is a complex STS that must be appropriately understood as a system since the characteristics of the parts making up this system cannot be viewed individually. In an earlier study conducted by Oladokun *et al.* (2012a), it was found out that system dynamics SD) is well placed in modelling STS based on its ability to handle all the characteristics of the STS as described above. In addition, SD is capable of being used as learning laboratory for policy evaluation and optimisation since it has been previously used under different domains (Davis & Durbach, 2010; Chi *et al.*, 2009). It is on the basis of this that the research used system dynamics as both the methodology and tool for the STS of HECCE.

2. Research Aim and Objectives

The overall aim of the research upon which this paper is based is to develop the dynamic model of socio-technical systems of household energy consumption and related carbon emissions with a view to improving the understanding of the complex nature of HECCE by providing a reliable tool to policy makers for testing different policy strategies. The following are the specific objectives of the paper:

i. To present causal relationships of some of the socio-technical variables influencing household energy consumption and carbon emissions, and

ii. To develop the dynamic model of the social-technical systems of household energy consumption and carbon emissions.

3. Theoretical Framework

The theoretical framework for the study is hinged on the concept of STS from the systems theory perspective. The concept of STS emerged from the studies undertaken by the Tavistock Institute, London especially during the post-war reconstruction of industry (Trist, 1981; Cartelli, 2007). Cartelli (2007) reported that the emergence of this concept is highly necessary in pursuit of a fit between the work force and machine during the introduction of technological systems for work automation when it was found out those workers are resistant to technological innovation. Since then, the concept has come into luminance. This concept has been previously discussed somewhere else (Oladokun *et al.*, 2012a) and a brief description of it is given based on the account of Walker *et al.* (2008). STS as a concept is founded on two main principles. The first one is the interaction between the social and technical sub-systems that set the conditions for successful (or unsuccessful) system performance. They argued that the interactions are comprised partly of linear "cause and effect" relationships, the relationships that are normally "designed", and partly from "non-linear", complex, even unpredictable relationships, which are those that are often unexpected. Soft, which is socio, does not necessarily behave like the hard, which is technical (Walker *et al.*, 2008). That is, people are not machines. They further mentioned that with growing complexity and interdependence that the "technical" can start to exhibit non-linear behaviour. STS as a methodology of systems-based approach of scientific inquiry is then used to handle this kind of complexity. The second of the two main principles, is that "optimisation" of the two sub-systems must be sought. That is, the need for 'joint optimisation' of the two sub-systems. Dwyer (2011), however, used a generic model to illustrate this concept of as shown in Figure 1. Interested readers are then encouraged to see Dwyer (2011) and Oladokun *et al.* (2012a) for more.

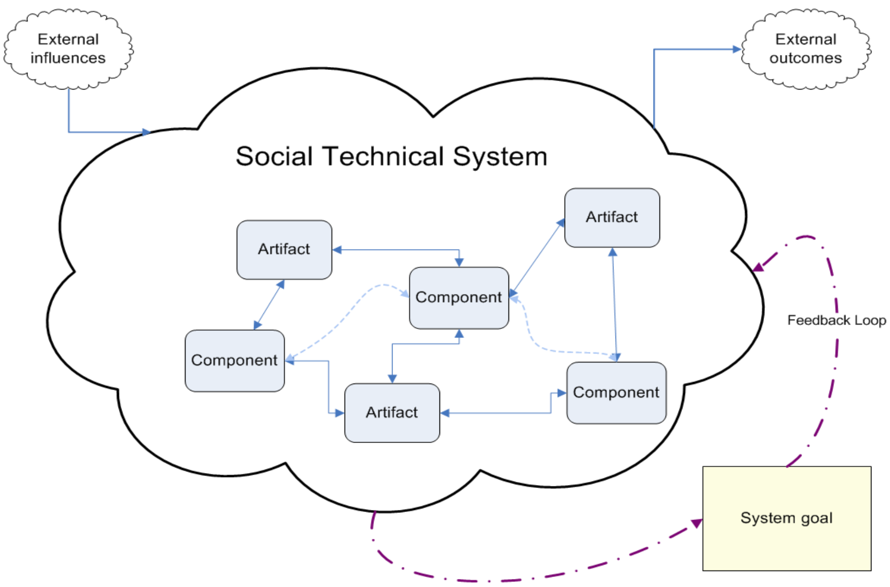

Figure 1: A model of a socio-technical system
[Source: Dwyer (2011)]

Relating the generic model of Dwyer (2011) to the problem under investigation, the dwelling system (dwellings' physical parameters and dwellings' dynamic variables) as shown in Figure 2, is comprised of an interplay between the dwelling system itself with occupants system (occupants' comfort variables, behavioural variables and household characteristics) and the environment (climatic variables, economic variables and policy/regulations variables). All of these work together as a system in order to develop the dynamic of household energy consumption and CO_2 emissions.

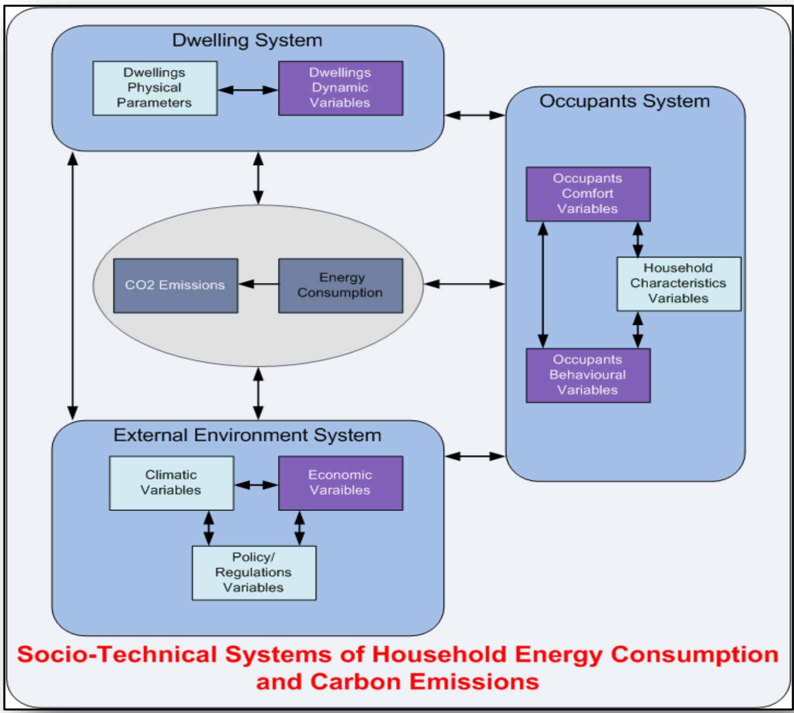

Figure 2: Conceptual model

4. System Dynamics Methodology

Over the years, the SD methodology that was introduced by J.W. Forrester in the 50s, has evolved and developed itself into a very powerful multi-disciplinary subject. It is indeed a computer-aided approach that has the capability of aiding policy analysis and design. The approach uses systems perspective that is governed by information feedback and mutual or recursive causality to understand different systems. The methodology encompasses different stages. According to Sterman (2000) the stages are problem articulation, dynamic hypothesis, model formulation and simulation, testing, and policy formulation and evaluation. The research process firm up for the study is shown in Figure 3 after due cognisance to the stages given by Sterman (2000). This shows the major tasks performed. Literature review was conducted in order to establish the gaps in knowledge and shape the direction for the study. Once the gaps are established in knowledge, the research aim and objectives were then formulated. Another round of literature review was carried out in order to identify the STS variables influencing HECCE. This then leads to the initial causal loop diagram (CLD) for various variables identified based on literature. Experts' judgement on the CLD was then sought by interviewing ten seasoned professionals in the field selected with the use of purposive sampling. The outcome of this exercise produced a final CLD for the model. The stock and flow diagrams (SFD) are then developed and the variables are related together with the use of equations. It is necessary to state that the relationships were developed based on simple arithmetic in addition to some special functions within the software (Vensim) to achieve certain computational tasks. Also, the equations were developed by exploring the strength of regression analysis and structural equation modelling on some of the model variables. The relationships developed were based on historical data as collected from different sources like the UK's department of energy and climate change, metrological department, office of National statistics. Some relationships were based on the results of knowledge elicitation exercise to represent certain non-linear relationships. To run the simulation, Vensim SD software was used. The simulation was run from 1970 to 2050 using Euler integration method with a time step of 1. The behaviour exhibited by the output is then explored and the model tested and validated accordingly.

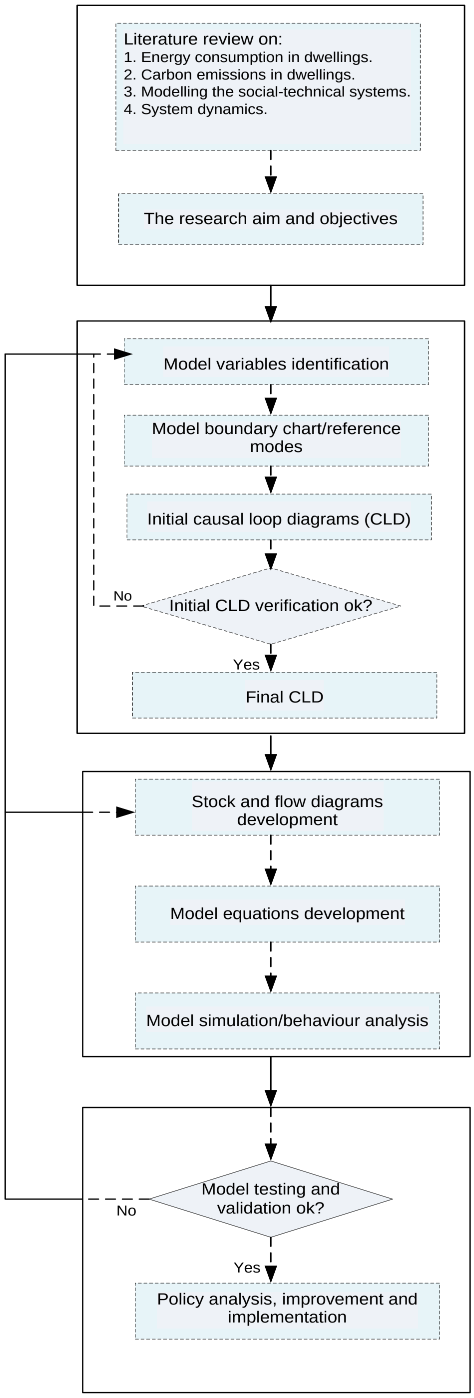

Figure 3: Research Process

5. Model Results and Validation

5.1 Dynamic hypothesis

This section gives the results of the research by showing some CLDs (dynamic hypotheses) upon which the study is based. Figures 4 and 5 show some of the outcome of the interviews held with the industry practitioners. Figure 4 captures the high level dynamic hypothesis of the socio-technical variables hypothesised to explain household energy consumption. The main drivers of energy consumption as depicted in Figure 4 are space heating, hot water usage, lighting, and energy consuming appliances and cooking. Internal heat of the dwellings determines occupants' thermal comfort in the dwelling and this in turn gives the amount of space heating required by the occupants. Physical characteristics of the dwelling are external to the model and have roles to play in determining the dwelling's internal heat. Likewise, the behavioural intention to consume energy or lifestyle on the part of the occupants and energy prices have effects on the amount of energy consumed for space heating, hot water usage, lighting, and energy consuming appliances and cooking. The main driver of CO_2 emissions is energy consumption and effect of CO_2 emissions results in some unfavourable climatic effects like bad weather in terms of external air temperature, rainfall, *etc.* This is then assumed to regulate energy prices in terms of international fuel prices and consequently dwellings' internal heat in the form of external air temperature. This is what the model depicts.

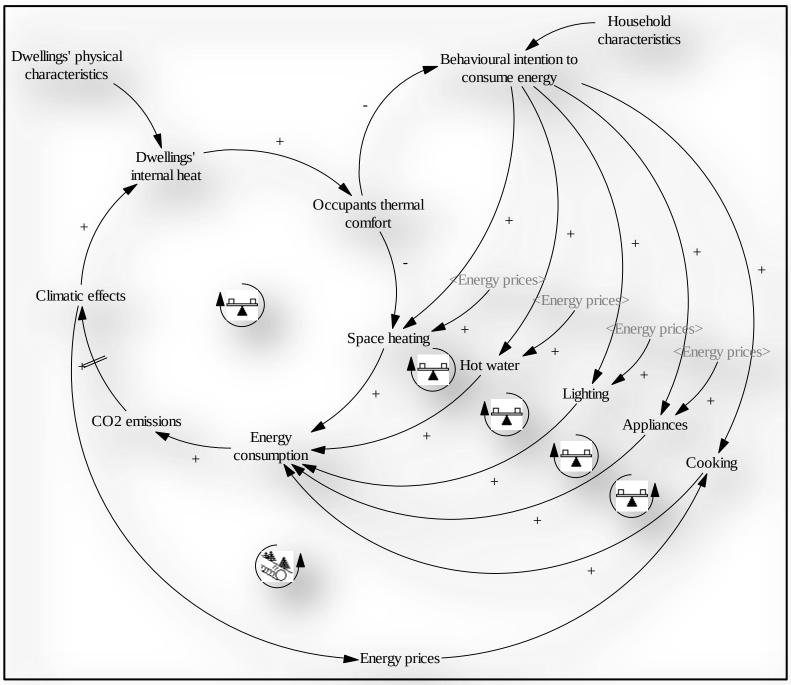

Figure 4: High level causal loop of STS of energy consumption and CO_2 emissions in dwellings

Figures 5 shows an example of one of different sub-models as indicated in the high level model of Figure 4. Precisely, Figure 5 captures the dynamic hypothesis of some of the variables driving dwelling internal heat sub-model. In the main body of the research, CLDs are drawn for each of the sub-models and all of them are linked together to work as a system.

This then depicts a holistic view of different socio-technical variables hypothesised to explain household energy consumption and CO_2 emissions.

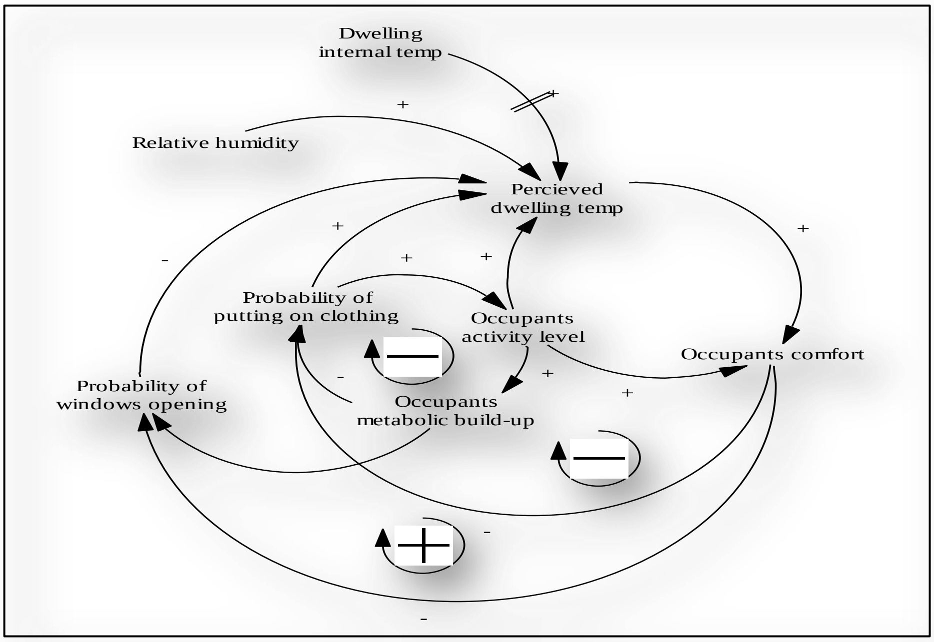

Figure 5: An example of occupants thermal comfort sub-model

5.2 Analysis of the model output

The results of the model in terms of household energy consumption are shown in Figures 6 (a, b, c, d, and e). Figure 6 therefore illustrates average annual energy consumption per household based on end-uses in the UK. This is modelled for space heating, hot water, lighting and appliances and cooking energy consumption. The trend indicates that space heating energy (Figure 6a) has been moving in an upward direction since 1970 until 2004 when it begins to fall apart from 2010 (which is due to bad weather condition of 2010). The model shows that future space heating energy would follow a downward trend due to improved energy efficiency as a result of stringent building regulations. Further to this, the model suggests that hot water energy use (Figure 6b) has dramatically gone down since 1970 and will continue in this direction. The trend of cooking energy (Figure 6c) has been on a downward direction since 1970 and continues like that until 2050. This may be due to changes in lifestyle through saving in cooking energy. The simulation result of the model as shown in Figure 6d suggests that household appliances energy use has been on the increase since 1970 and tends to decline in the year 2016 till 2050. For household lighting energy (Figure 6e), which remains a small fraction of total household energy also follow an upward trend since 1970 until 2004 when begins to gradually come down. In all (Figure 6a, b, c, d, and e), the trends exhibited by the model behaviour are consistent with historical data.

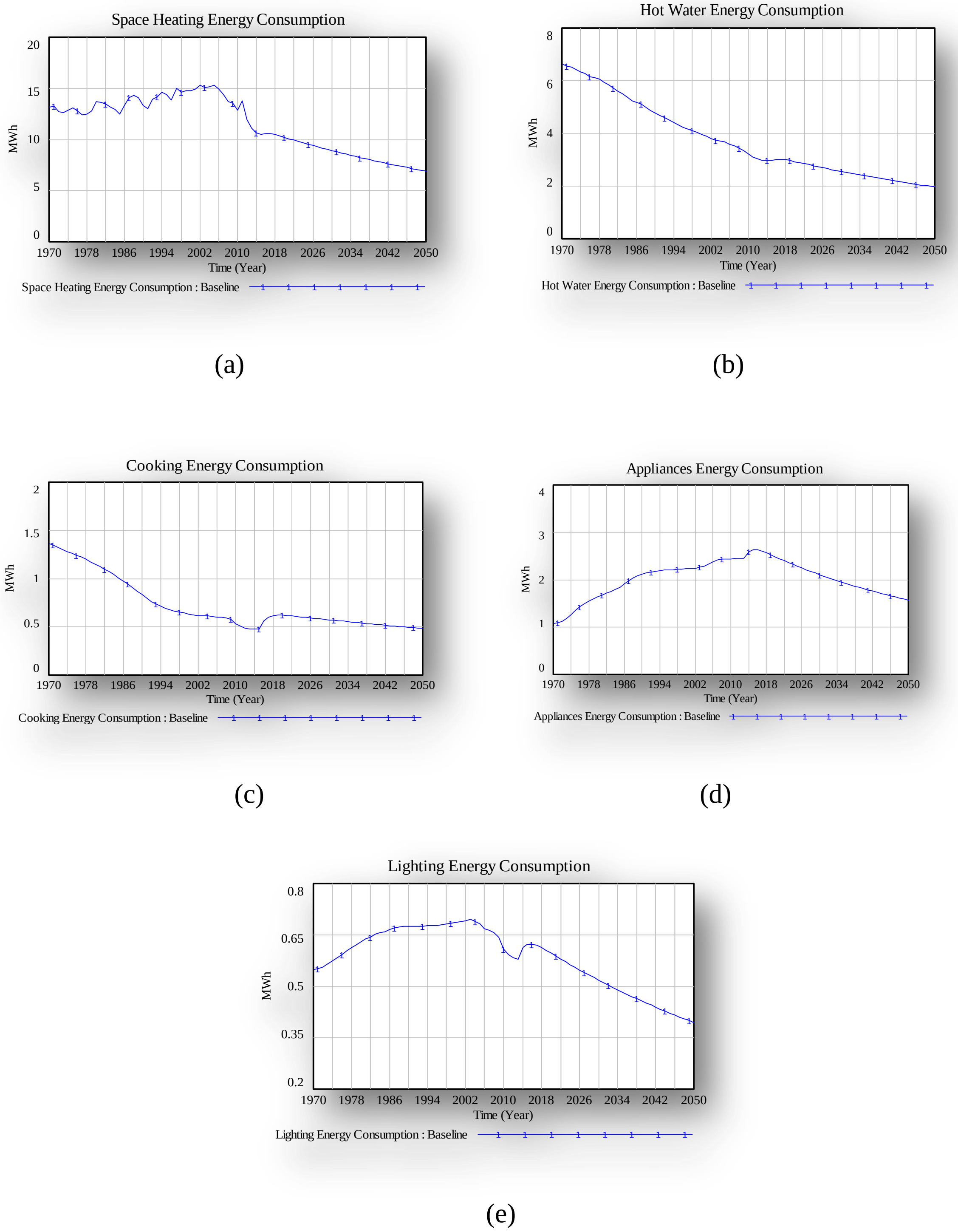

Figure 6: Energy consumption per household

5.3 Model Validation

The research firm up a rigorous validation process for the outputs of the model. In order to test and validate the model developed in this paper, three different approaches were used to include: model structure and behaviour validation with system dynamics tool (Vensim), model behaviour validation with industry practitioners, and validation with historical data. In the case of the first approach, a number of tests (Groesser & Schwaninger, 2012) were used to know whether or not the model's equations are technically right or not. Some of the techniques are parameter verification, structure verification, parameter adequacy, dimensional analysis, integration error and extreme value tests. All these tests were conducted in Vensim software and the results are good. In additional to the feedback from the industry practitioners, the baseline model outputs were compared with historical data and the results show a good fit. Two examples are shown in Figures 7 and 8 to depict the fit between the model output of space heating energy consumption and historical data (Figure 7), and the model output of hot water energy consumption and historical data (Figure 8).

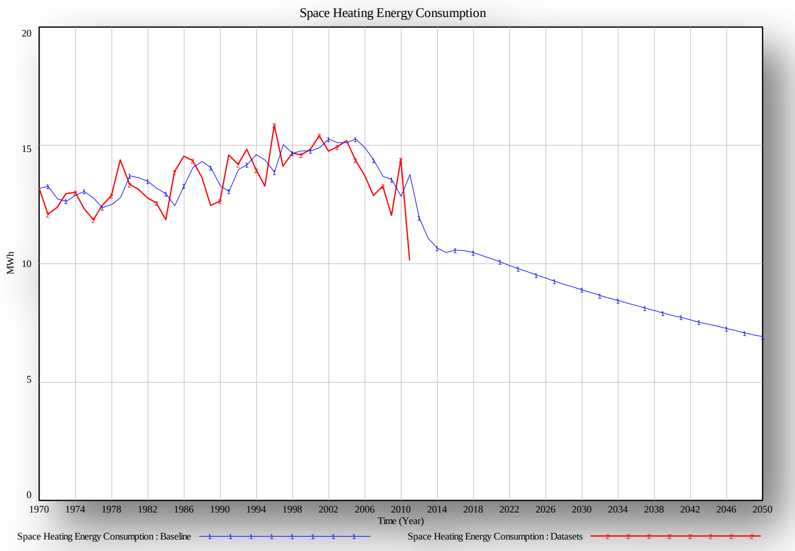

Figure 7: Validation of space heating energy consumption with historical data

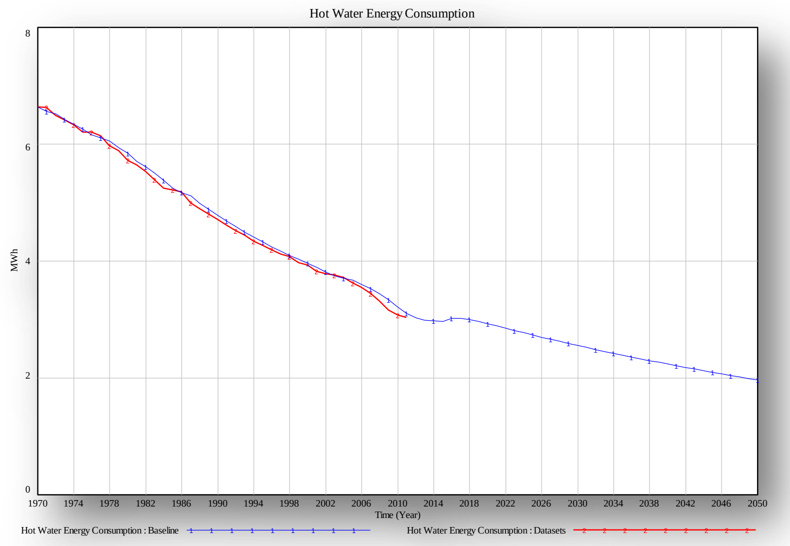

Figure 8: Validation of hot water energy consumption with historical data

6. Conclusions

This paper has been able to present the dynamic hypotheses of some variables influencing HECCE. The paper goes further to develop the dynamic model of the STS of HECCE. The results demonstrates the efficacy of system dynamics tool in adding to the understanding of complex STS of energy consumption and CO_2 emissions in dwellings while at the same time gives the behaviour of household energy consumption for future years. To this end, authors advocate that there are many interrelated variables at play, the analysis of which will further help in relieving the pressure being mounted by the need to significantly reduce energy consumption and meet the CO_2 emissions reduction targets. Therefore, this study has contributed to the body of knowledge in the area of energy studies by producing interrelationships among different variables hypothesized to influence HECCE from systems thinking perspective. Also, the study adds to the pool of policy advice tool for use by the policy makers in the field.

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