MODELLING THE COMPLEX SOCIO-TECHNICAL SYSTEMS OF HOUSEHOLD ENERGY AND CARBON EMISSIONS: A SYSTEM DYNAMICS APPROACH

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ABSTRACT

As a result of the challenge of the climate change, governments at different levels around the world are urgently seeking solutions to the problem of carbon emissions. This paper reports the modelling effort of the socio-technical systems (STS) of household energy consumption and carbon emissions (HECCE) from the system dynamics (SD) perspective. This is with a view to providing the policy makers with a policy advice tool regarding the HECCE in the UK. The study uses the pragmatist research strategy involving the collection of both qualitative and quantitative data to develop the model. The models capture the complex intrinsic interrelationship among the occupants, dwellings, and environment and subject same to both the qualitative and quantitative data. The paper discusses insights from the model regarding the future profiles of HECCE. The study concludes that the model in this paper can serve as a decision support tool for policy makers in testing different scenarios regarding the HECCE before implementation.

KEYWORDS: *Carbon emissions; complexity; household energy; socio-technical systems, system dynamics*

1.0 INTRODUCTION

Governments at different levels around the globe are urgently seeking solutions to the problems emanating from energy consumption and CO_2 emission in all spheres of economy. This is because of the challenge of climate change and other related effects as a result of CO_2 emission. For example, the evidence from the United Nations Department of Economic and Social Affairs (UNDESA, 2010) suggests that the climate change effects due to CO_2 emission could cause increase in global temperature of up to 6^{o}C. This invariably results in extremes weather conditions. To this end, different initiatives and schemes of government have targeted a number of policies at reducing energy and CO_2 emissions, and housing sector of the economy is not an exception. In the United Kingdom (UK), based on the evidence from the Office of National Statistics (ONS), energy consumption in buildings alone is about 42.3% of which domestic sector accounts for around 27.5% of the total UK's energy consumption in the year 2008 (ONS, 2009). Correspondingly, domestic CO_2 emission stands at about 26% of the total UK CO_2 emissions (Natarajan *et al.*, 2011). It is against this background that the domestic sector of the economy is chosen as a focal point for mitigation and adaptation agendas. As such, UK Government has initiated quite a number of strategies aimed at

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reducing household energy consumption and CO_2 emissions (HECCE). This is mainly due to the importance accorded this sector of the economy in realising a target of 80% reduction by 2050 based on 1990 level as enshrined in the Climate Change Act of 2008. Many researchers (Bartiaux & Gram-Hanssen, 2005; Bin & Dowlatabadi, 2005; Yun & Steemers, 2011; Abrahamse & Steg, 2011; Kelly, 2011) have conducted comprehensive studies regarding the issue of HECCE, but only a handful of them illustrated the kind of complexity involved. It is noteworthy to argue that those studies theorised the HECCE based on the development of many underlying frameworks shaping the field of energy studies as reflected in the works of Ruffell (1977), van Raaij and Verhallan (1983), Anderson (1985), Ajzen (1991), Lutzenhiser (1992), Hitchcock (1993), Stokes, Rylatt, and Lomas (2004). Of these studies, it was only the work of Hitchcock (1993) that suggest the use of systems theory to understand and model the HECCE. This is based on the fact that the systems-based approach to model HECCE holistically looks at the web of interactions that exist among different elements of HECCE systems. As such, several researchers (Hitchcock, 1993; Shipworth, 2005; 2006; Motawa and Banfill, 2010; Kavgic *et al.*, 2010; Natarajan *et al.*, 2011; Oladokun *et al.*, 2012a; 2012b) argue the use of socio-technical systems (STS) – a subset of systems theory; as an approach capable of aiding in understanding and modelling the kind of complexity existing in HECCE systems. This is as a result of high inter-dependencies, interrelationships, chaotic nature and non-linearity of the variables involved in this research domain (Oladokun *et al.*, 2012a). Further, it needs to emphasise that STS is one of the methodologies of the systems-based approach of scientific inquiry which models the complexity of real systems' elements and relationships (Motawa and Oladokun, 2015). Modelling complexity enables capturing the interdependent and multi-causal structure of the elements of STS and determining the efficacy of different change strategies. This helps in analysing the non-linear behaviour of the studied systems where changes in input are neither proportional to changes in output, nor is the input to output relationship fixed over time. Therefore, the theoretical framework for this study is hinged on the STS as drawn from the concept of the systems theory.

It needs to emphasise that researchers have used different approaches to model HECCE at different levels of resolution. A review and full description of these approaches/methodologies/techniques have been reported somewhere else at different times such as: Strachan & Kannan (2008), Bohringer & Rutherford (2009), Tuladhar *et al.* (2009), Swan & Ugursal (2009), and Kavgic *et al.* (2010). These approaches vary considerably in terms of requirements, assumptions made, the predictive abilities (Oladokun *et al.*, 2012b), and epistemological foundations of the models. There are three epistemic approaches identified in the literature under which modelling HECCE are classified as: top-down, bottom-up, and hybrid (Kavgic *et al.*, 2010; Kelly, 2011); and the approach in use at any point in time is aptly influenced by the target audience of such a model. Approaches to modelling HECCE have, however, received a wider criticism from the research circle (Natarajan *et al.*, 2011). This criticism came from the point of view that those models still use deterministic approach rather than looking at it from the non-deterministic perspective. Also, majority of these modelling approaches find it difficult to model a combination of qualitative and quantitative (soft and hard data) variables together. This difficulty stems from the fact that the issue of HECCE involves a web of interaction between the householders, the technology put in place in

the dwellings and the wider socio-economic-climatic environment systems. This then calls for an approach that is able to cope with this kind of difficulty.
In the earlier work of Oladokun *et al.* (2012a), they identified the characteristics of the research problems that fall within the purview of STS and conducted a comparative analysis of the modelling techniques that deal with such problems. The result of their analysis favours system dynamics (SD) as an approach capable of modelling complex systems, which invariably model the STS of HECCE based on the fact that SD models can capture multiple interdependencies, dynamic situation, non-linear relationships, 'hard' and 'soft' data, feedback processes, and use as a learning laboratory (Sterman, 1992; 2000). This paper therefore reports the modelling effort geared towards the complex STS systems of energy consumption and carbon emissions in the UK housing sector using the SD approach. This is to display the kind of interactions, interrelationships, and inter-dependencies that exist among the dwellings, occupants and environment systems and highlight that these systems work together seamlessly in an integrated manner. Consequently, the results of this study is capable of providing the policy makers with a decision making tool upon which different scenarios regarding HECCE can be tested before implementation. The next section briefly discusses the concept of SD.

2.0 THE CONCEPT OF SYSTEM DYNAMICS

SD that was introduced by Jay Forrester in the late 50s is an emerging multi-disciplinary field of study that deals with the analysis of complex systems. It is, indeed, a powerful and well-established methodology and tool for modelling and understanding feedback structure in complex systems (Ansari & Seifi, 2013; Zhao *et al.,* 2011; Ranganath & Rodrigues, 2008). Coyle (1997) describes SD as an approach that "deals with the time-dependent behaviour of managed systems with the aim of describing the system and understanding, through qualitative and quantitative models, how information feedback governs its behaviour, and designing robust information feedback structures and control policies through simulation and optimisation". As opined above, SD deals with 'feedback' processes grounded in theory of modern feedback control and nonlinear dynamics. Further to this, it is built on 'cause and effect' relations among different variables influencing the system under investigation (Ranganath & Rodrigues, 2008) and indeed a "method to enhance learning in complex systems" (Sterman, 2000).

Presently, SD has developed itself into a unique and very powerful tool that finds applications in a wide range of fields, where the behaviour of a system is to be studied (Ranganath & Rodrigues, 2008). For example, SD has found application in energy and environment (Balnac *et al.,* 2009; Yudken & Bassi, 2009). Within the energy consumption and carbon emissions domain (Feng *et al.,* 2013; Wu & Xu, 2013; Oladokun *et al.,* 2012b), SD models have been developed and applied in different contexts and not limited to energy efficiency (Davis & Durbach, 2010; Motawa & Banfill, 2010; Dyner *et al.,* 1995) and energy policy evaluation (Chi *et al.,* 2009; Naill, 1992; Ford, 1983). It needs to clearly state that within the energy policy evaluation domain, which is the main focus of this research, Ford (1983) used SD to generate different policy analysis scenarios regarding electricity planning in the United States (US). Similarly in the US, Naill (1992) adopted SD approach to model policy related to energy supply and demand for better energy planning in the US economy. Likewise within the same context in the UK, Chi *et al.* (2009) considers SD as an approach to understand the dynamics of the UK natural gas industry in order to formulate a long time energy policy. While some of these studies reinforce the application of SD approach to energy policy evaluation, there is, however, paucity of sufficient evidence to support that due attention has been paid to the issues relating to HECCE from system dynamics perspective. The next section gives a detailed description of the method used for the research.

3.0 RESEARCH METHODS

In SD literature, different authors suggest different, but overlapping, stages involved in any SD modelling efforts. For example, Wolstenholme (1990) simply identifies two phases to include diagram conceptualisation, and analysis and simulation phases. Randers (1980) however goes beyond the two phases identified by Wolstenholme (1990) to suggest four stages comprising of model conceptualisation, formulation, testing, and implementation. Sterman (2000) gives problem articulation, dynamic hypothesis, model formulation and simulation, testing, and policy formulation and evaluation as the main stages involved in any SD process. Robert *et al.* (1983), Richardson and Pugh (1999), and Ranganath and Rodrigues (2008) are of the opinion that any SD modelling efforts should incorporate the following stages: problem identification, system conceptualisation, model formulation, analysis of model behaviour, model evaluation, policy analysis and improvement, and policy implementation. In this study, we firm up a SD research process of four main stages that incorporates all the dimensions identified by Robert *et al.* (1983), Richardson and Pugh (1999), and Ranganath and Rodrigues (2008). Figure 1 depicts the research process for the study. This includes the timeline, major tasks performed, and the methodology employed to achieve each of the tasks.

The first stage (Figure 1) is more of problem formulation for the research and properly defines the problem by reviewing extant literature in the subject. This involves literature review along the line of energy consumption and CO_2 emissions in dwellings, modelling the STS and SD, which eventually led to identification of gaps in knowledge. Consequently, the research aim and objectives were established. The second stage as shown in Figure 1 is the system conceptualisation. This involves identification of model variables and establishment of model boundary, which includes the reference modes based on review of extant literature and reports and documents from UK Government departments like the Department of Energy and Climate Change (DECC). The variables identified are related to one another in order to establish the causal relationships and feedback structure within the system under study. This then leads to the initial formulation of the 'cause and effect' relationships among those variables in the system and pictorially represented them by what is called *causal loop diagrams* (CLDs). The study achieved the CLDs for the system under study with the use of SD software (Vensim DSS version 5.11). The CLDs represent sets of dynamic hypotheses for the study. It is necessary to note that the initial CLDs were based on the knowledge elicitation of the modellers as dictated by the available evidence from the literature, and UK Government documents and reports. Input from the experts as well as industry practitioners on the subject is then captured in the form of knowledge elicitation based on interview. This is to verify the initial CLDs that were purely based on the knowledge elicitation of the modellers alone. This exercise witnessed removal and addition of some causal links and variables until the final CLDs were achieved. The experts and industry practitioners who took part in the interview were selected based on purposive sampling frame as motivated by their requisite wealth of experience in the subject. It is worth mentioning that at this stage the final CLDs do not indicate the stock or the flow but merely indicates the influence of one variable on the other.

Stage three of the research process (Figure 1) involves model formulation and behaviour analysis. Formulating the model requires representing the model using the *stock and flow diagrams* (SFDs). The SFDs show a pictorial representation of the behaviour of the system in the form of accumulation (stock) and flow (rate), and it is achieved with the use of SD software. It needs to emphasise that mere CLDs or SFDs do not result in SD. This will constitute SD when the variables in the model are related together in terms of equations and model simulation performed. So, model equations are developed based on a combination of three different approaches: the use of SD functions in Vensim software, regression analysis and structural equation modelling. In building the equations, the model is subjected to various data sourced and collected from a number of different sources in UK such as: DECC, Metrological Department, and ONS. Once the system configuration is found to be okay, the simulation is then run based on Vensim SD software from 1970 to 2050 with a year time step and the use of Euler form of integration type.

Stage four (Figure 1) concludes the research process with model validation and evaluation including policy analysis, improvement and implementation. Model validation involves testing and verifying the model structure and behaviour and sensitivity analysis with the use of SD functions within the Vensim software. Validation against historical data was performed based on the available historical data and the predictive ability of the model assessed to reveal its ability to mimic reality in the future. We also engaged the experts and industry practitioners previously contacted at the second stage of the study to assess the model output in terms of its behaviour whether or not it meets their expectations based on their experience in the field. Additionally, we carry out policy analysis based on the policy levers introduced in the model, by running a number of policy scenarios with the model upon which decisions regarding HECE may be based (although, this is not discussed in this paper). The next section of this paper discusses the model architecture.

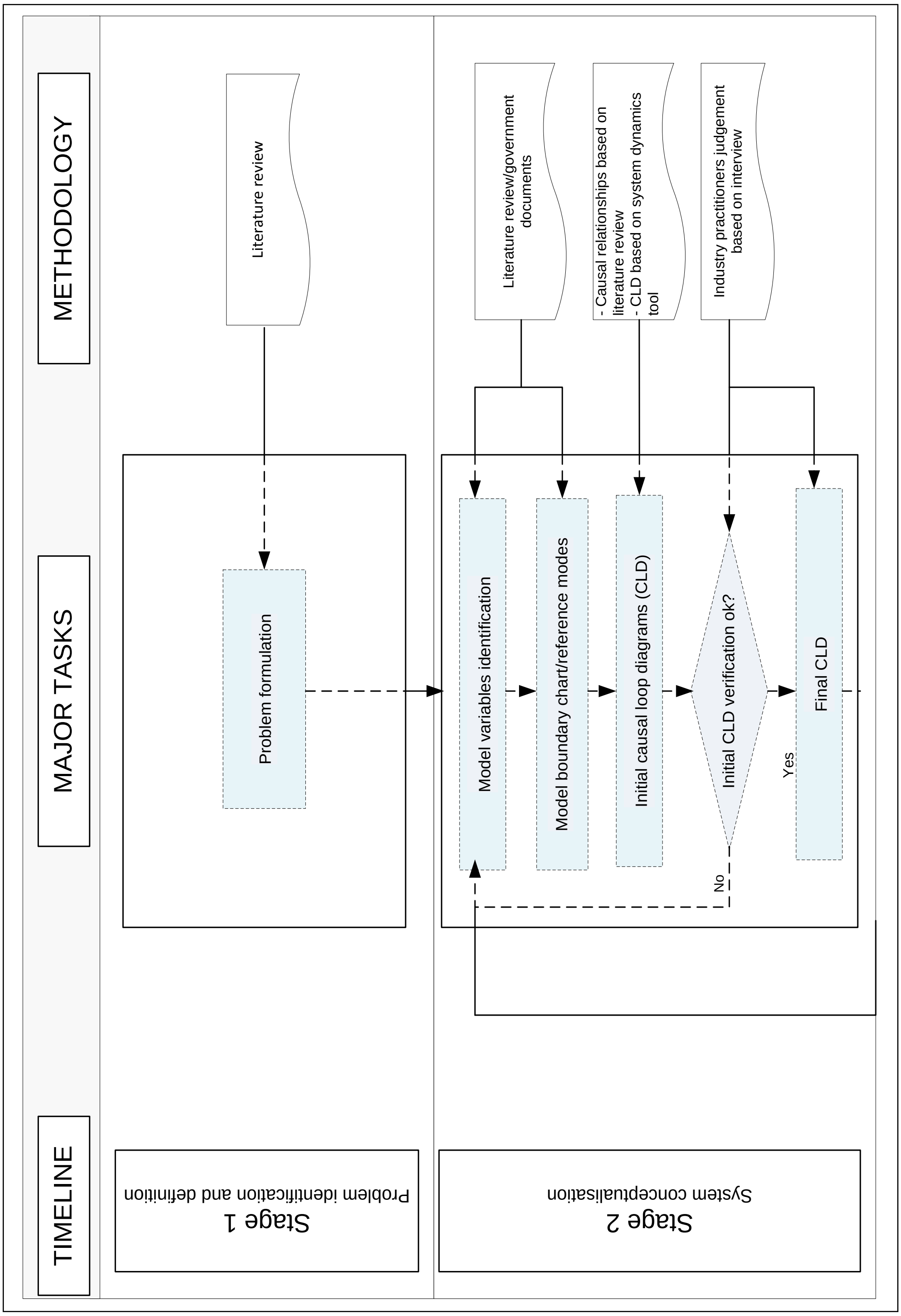

Figure 1. Research Process

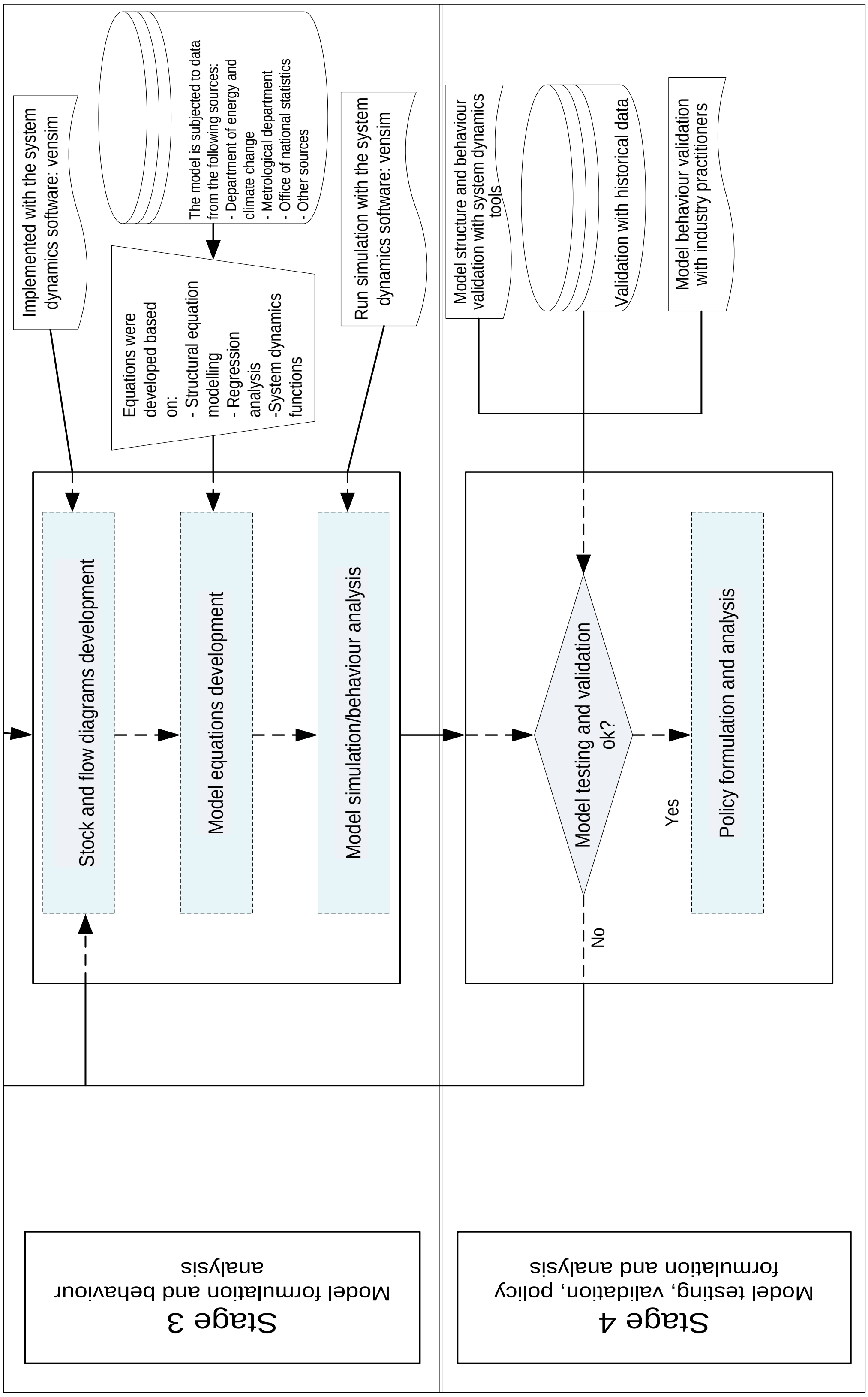

Figure 1. Research Process (continued)

4.0 MODEL ARCHITECTURE

The model architecture gives the system conceptualisation and formulation of the modelling effort and shows the different components/modules of the model. The model conceptualisation and formulation are discussed below.

4.1 System conceptualisation

Energy and CO_2 emissions issues are highly complex systems in which quite a number of decisions need to be made on a continual basis. Considering the amount of details and information required, any attempt to model all the activities within this domain constitute an effort in futility. As such, a model of such would be undesirable mainly because its complexity would obscure the dynamic nature of the parameters being observed. To this end, the research needs to carefully select a level of aggregation in order to ensure that the model built sufficiently gives all the essential parameters and policy levers required. The research combined both the top-down and bottom-up approaches in selecting all the variables and as such, all the variables are aggregated at the level of policy makers in top level management regarding HECCE. The research tries to model the interaction among the dwelling system, occupants system, and external environment system as shown in Figure 2. This is to reveal the intrinsic interrelationships existing in the STS of HECCE.

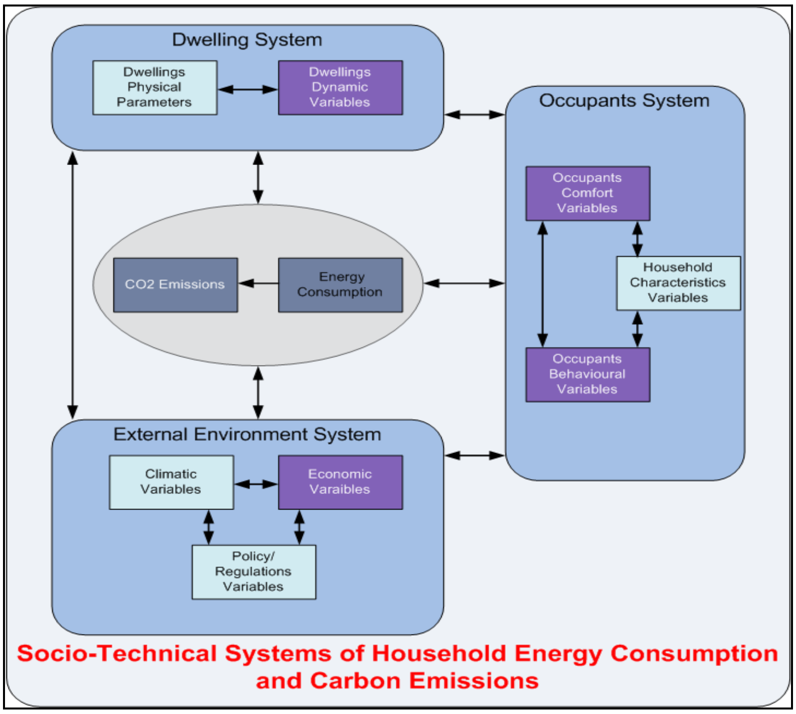

Figure 2. Model Architecture

4.1.1 Causal loop diagrams (CLD)

The CLD as dynamic hypotheses are essential tool in SD and it is not only the foundation upon which the quantitative models are built, but is also a valuable device in its own right for describing and understanding systems (Coyle, 1997). This device provide qualitative explanation of the underlying structure operating in a system in the form of 'cause and effect'. At an aggregated level, the block diagram showing the interrelationships and interdependencies of different components of the model architecture is illustrated in Figure 2. From those components making up the model architecture, the high level CLD (dynamic hypothesis) for the socio-technical variables hypothesised to explain HECCE was drawn as shown in Figure 3. The major drivers of energy consumption are shown to include (Figure 3) 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 the 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.

Importantly, a CLD is constructed by incorporating the various variables associated within a system. Casual loops show how each variable relate with one another. That is, the relationship between any two variables is annotated by the use of an arrow connecting them together. A positive relationship means an increase in arrow tail variable would cause an increase in arrow head variable and vice-versa, whereas a negative relationship means an increase in arrow tail variable would cause a decrease in arrow head variable and vice-versa. Dynamics exhibited by the system under study are achieved based on the feedback loops of the CLDs. As such, feedback loops can be positive or negative. Positive feedback loops (reinforcing loops) denote that the system increase or decrease indefinitely, whereas negative feedback loops (balancing loops) stabilise over time.

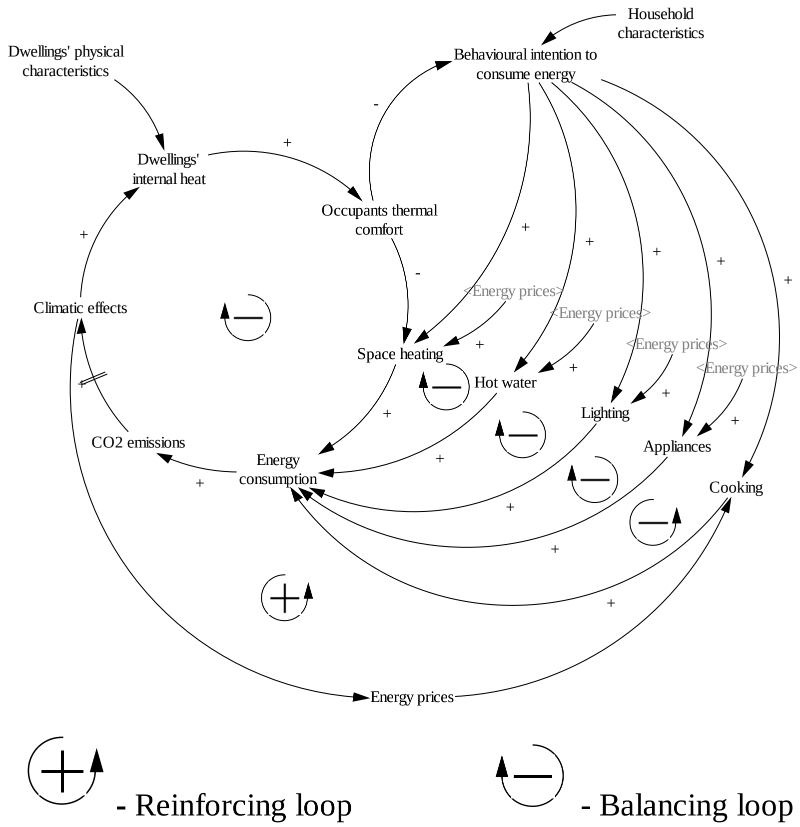

Figure 3. High level CLD for the STS of HECCE

It is necessary to state that all the major components of Figure 3 like "dwellings internal heat", "occupants' thermal comfort", "energy consumption and CO_2 emissions, *etc.* are further developed. For example, Figure 4 shows a detailed CLD developed for the "occupants' thermal comfort" module. In this module, we produces a causal model of different variables hypothesised to affect occupants' thermal comfort herein refers as occupants' comfort. We postulate that the major variables that drive occupants' comfort here are "occupants' activity level" and "perceived dwelling temperature". It needs to mention that "perceived dwelling temperature" is at the heart of this causal model with five different inflows from "relative humidity", "dwelling internal temperature", "occupants' activity level", "probability of putting on clothing", and "probability of windows opening". All these variables are interrelated in a non–linear way and work seamlessly together as shown in Figure 4. A total of three different feedback loops (with two negative and a positive feedback loops) are constructed for the module. The first balancing feedback loop involves [occupants' comfort – probability of putting on clothing – perceived dwelling temperature], while the second one takes the following variables [occupants' activity level – occupants metabolic build-up – probability of putting on clothing]. Additionally, the reinforcing loop involves [occupants' comfort – probability of windows opening – perceived dwelling temperature]. The behaviour of the model is expected to be predominantly dictated by the multi-loops within the CLD.

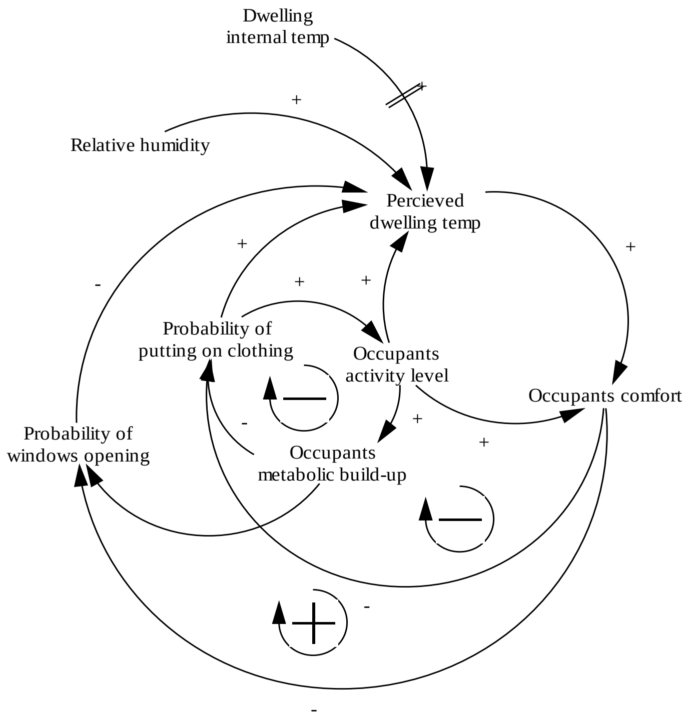

Figure 4. CLD for occupants' thermal comfort module

4.2 Model Formulation

Dynamic hypotheses (CLDs) are useful, without any iota of doubt, in many situations. However, they suffer from a number of limitations among which are their inability to capture the stock and flow structure of systems (Sterman, 2000). Hence, there is the need for SFDs for the models as they form the basis for model simulation. At this stage, the variables/parameters in the causal relations developed are transformed into SFDs. The SFDs distinguish the model parameters into the controlling 'flow' acting as regulators and 'stock' where accumulations take place. Accumulations characterise the state of the system and generate information upon which decisions and actions are based. Stocks give systems inertia and provide them with memory. Stocks create delays by accumulating the difference between the inflow to a process and its outflow. By decoupling rates of flow, stocks are the source of disequilibrium dynamics in systems. The parameters in the model are linked together with equations in preparation for simulation. For the household energy consumption and CO_2 emissions modules, an example of SFD for the "occupants' thermal comfort" CLD shown in Figure 4 is shown in Figure 5. Equations of the two main stocks are given in Equations (1) and (2).

Occupants Comfort (t) = INTEGRAL [perceived dwelling internal temperature, occupants comfort (t_0)] (1)

Occupants Metabolic Build-up (t) = INTEGRAL [occupants activity level + perceived dwelling internal temperature, occupants' metabolic build-up (t_0)] (2)

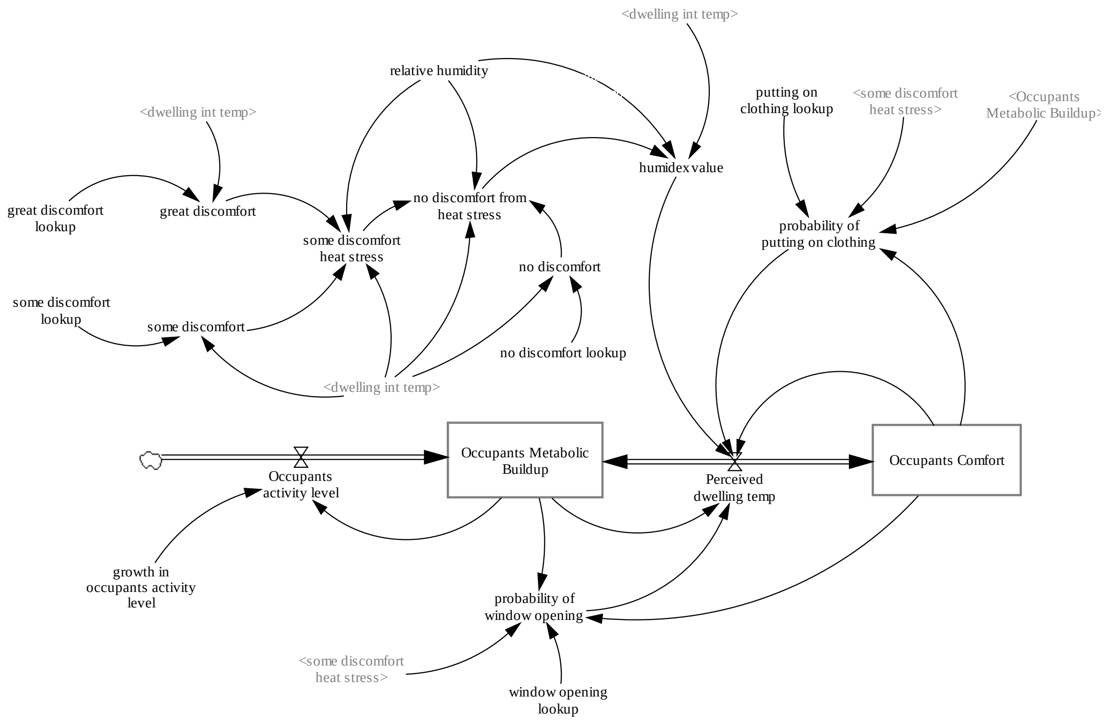

Figure 5. SFD for occupants' thermal comfort module

5.0 THE BASELINE MODEL OUTPUT BEHAVIOUR

The simulation of the STS of HECCE developed by this study generates quite a number of insights based on simulation run from 1970 to 2050. The results of interest from the model are further explored in a greater detail in order to carry out a further analysis and study the behaviour generated. The behaviour exhibited by the model for HECCE is therefore discussed in this section.

5.1 Household energy consumption

Figure 6 shows the trend of energy use for space heating, hot water, cooking, lighting, and appliances. The graph indicates that space heating energy is by far took the biggest chunk of UK household energy consumption. This 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). This model shows that the space heating energy would follow a downward trend, which may be due to improvements in energy efficiency as a result of uptake of fabric insulation and other areas of government campaign like stringent building regulation. It is further argued that this downward trend as revealed by the model results may be due to energy costs, which has been on the increase since 2004. The model suggests that hot water energy use has dramatically fallen since 1970 and continues in this downward trend as shown in Figure 6. The reason that may be adduced for this trend may be connected to reduction in heat loss from hot water tanks due to improved lagging of hot water pipes and tanks coupled with improvements in household heating systems that is being witnessed due to changes to building regulations.

Generally for household cooking energy (Figure 6), the trend has been on a downward direction since 1970 until 2016 with a steep slope till 1990s and the downward trend seems levelling since year 2000. This downward trend may be due to changes in lifestyle through saving in household cooking energy. However, there is an event overturn in the year 2016 which saw household cooking energy slightly increased before following a gentle downward slope until 2050. The reason that could be adduced for this trend could be explained as a result of a decline in the size of households. This is due to the fact that cooking energy per head is claimed to be higher in single-person households [Energy Saving Trust (EST), DECC, & (Department of Environment, Food and Rural Affairs (DEFRA), 2012]. For household lighting energy (Figure 6), which remains a small fraction of total household energy also follow an upward trend since 1970 until 2004 when begins to gradually come down. This decline may be as a result of Government's policy of the Carbon Emissions Reduction Target (CERT), which ensures that energy-consuming incandescent bulbs are replaced in homes with energy-efficient ones. However, there is a kind of event overturn in the year 2014 as postulated by the simulation results that there would be a slight increase in household lighting energy before following a gentle decline in 2016 till 2050. This may be as a result of likely increase in the lighting points in homes especially in the kitchens and bathrooms, which are even most times of higher specifications. The model suggests witnessing this surge will immediately see a change in policy by using high energy – efficient bulbs in the affected areas, which may take up to two years before seeing changes.

The simulation result of the model as shown in Figure 6 suggests that household appliances energy use has been on the increase since 1970. This result is consistent with historical data (Palmer & Cooper, 2012). The reasons for this trend are explained based on three factors that could be responsible. Firstly, the trend may be due to the fact that many homes now acquire electric gadgets more than before, which continue to grow, based on changes in occupants' lifestyle and their access to more disposable income. Secondly, owning these gadgets alone may not result in surge in household appliances energy if they are not put into use. So, the rate at which these gadgets are being put into use has been on the increase. This may probably due to changes in lifestyle as previously opined. Additionally, changing to the use of energy – consuming appliances for some tasks or games that were previously or traditionally completed manually as well as using homes as offices may be responsible for this surge. Thirdly, the results of the study conducted by EST *et al.* (2012) indicate that the use of cold appliances like freezer and large fridges has been on the increase and they constitute about 50% of the household appliances energy use. Further, there has been growth in the use of microwaves to thaw out frozen food. Combining all these together has seen household appliances energy on the increase. However, there is an event overturn in and around 2016 as dictated by the result of the simulation that household appliances energy will follow a gentle decline till 2050. This result may be due to different on-going research efforts at improving the energy efficiency of cold appliances, which would witness a deployment of even more energy efficient cold appliances in the coming years as this has a lion share in household appliances energy use.

Figure 7 show the trend exhibited by both the average annual household energy consumption and total annual household energy consumption. It is necessary to state that average annual household energy is determined as a summation of different average household energy consumption based on use as discussed above. The trend for average annual household energy consumption follows the pattern exhibited by average household space heating energy consumption. This may be explained by the fact that household space heat energy has the biggest chunk of UK household energy. Similarly, total annual household energy consumption follow the same trend as this was estimated for the whole UK housing stock. The output of average annual household energy consumption is multiplied by the number of households which has been growing over the years due to conversion of some office buildings to homes. However, the effect of the growth in number of households may have amplified the total annual household energy consumption for the UK housing stock.

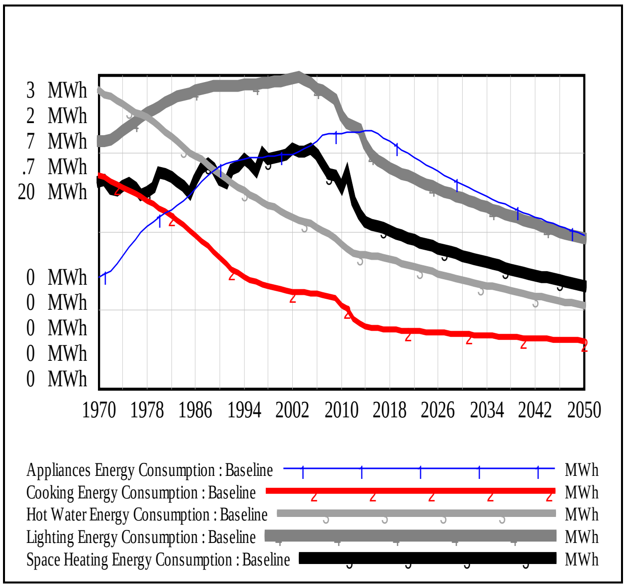

Figure 6. End-uses household energy consumption

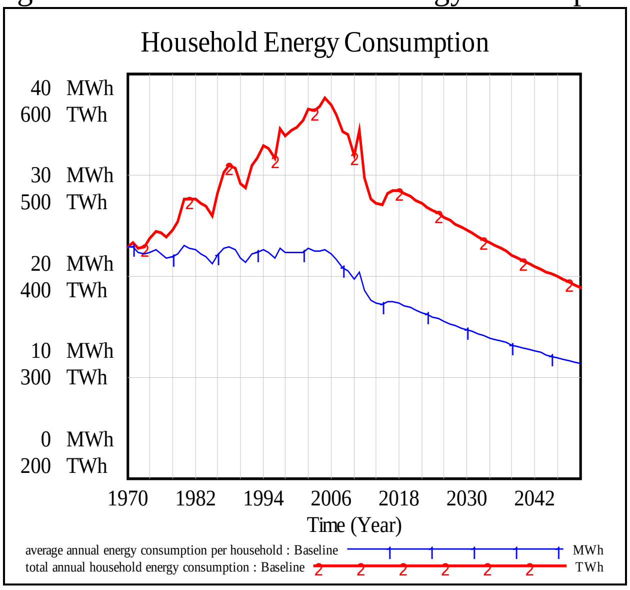

Figure 7. Household energy consumption

5.2 Household CO_2 emissions

Figure 8 show the graphs of household carbon emissions by end-use, while Figure 9 show that of household carbon emissions in terms of average annual household and total household respectively. These results are profound as the behaviour exhibited by household carbon emissions by end-use (Figure 8) as well as the one shown in Figure 9 is similar to the ones demonstrated by household energy consumption by end-use (Figure 6), and average and total annual household energy consumption (Figure 7) respectively. This trend may be due to the fact that carbon emissions are as a result of energy consumption. However, the dominant type of energy consumed by householders would go a long way in moderating household carbon emissions. Assessing the average annual carbon emissions per household and total annual household carbon emissions, it was noted that carbon emissions has been on a downward direction since 1970. That is, average annual carbon emissions per household have fallen remarkably since 1970 and the model projects that the trend will be sustained till 2050 based on the carbon reductions agenda of the government. The output is in no way different from the trend witness in historical data (Palmer & Cooper, 2012) as the trend (Figure 9) follows a 'lumpy' trend with troughs and peaks that corresponds to mild and severe weather conditions.

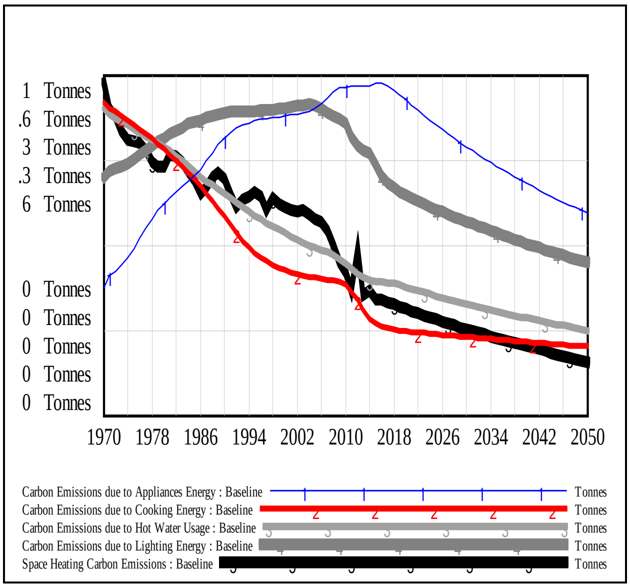

Figure 8. End-uses household carbon emissions

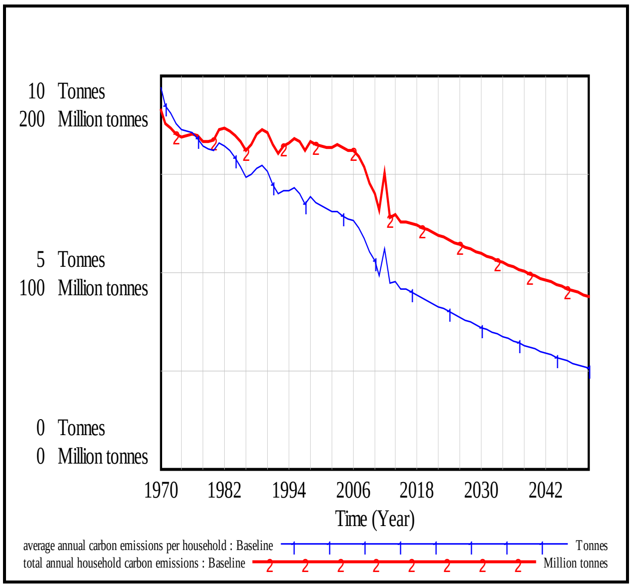

Figure 9. Household carbon emissions

6.0 MODEL TESTING AND VALIDATION

Researchers acknowledge that model testing and validation is an important aspect of any model-based methodology like SD (Barlas, 1996; Ranganath & Rodrigues, 2008) and as such, a crucial step that is not to be disregarded whatsoever. It is significant in the sense that validity of the results emanating from the model is heavily dependent on the validity of the model itself. Coyle (1977, 1997) argues that model testing and validation is the process of testing the soundness and correctness of construction of models while establishing confidence in its usefulness. Hence, this exercise proves the credibility of the outputs from the model and ascertains that the results accurately represent reality. However, some researchers argue that model testing and validation is a controversial one (Barlas, 1996) because there is no single approach that would allow the modellers to ascertain that their models have been validated. Further to this controversy, Sterman (2000) contends that complete model validation is practically impossible and as such more emphasis needs to be laid on model testing in order to build confidence that the model is adequate for the intended purpose.

There are quite a number of tests to assess the validity of SD models. This is generally divided into structure-oriented and behaviour pattern tests (Forrester & Senge, 1980; Barlas, 1985; 1996; Richardson & Pugh, 1999; Sterman, 2000; Groesser & Schwaninger, 2012). The tests include and not limited to (1) structure-oriented tests – boundary adequacy, structure assessment, dimensional consistency, parameter assessment, extreme conditions, and integration error, (2) behaviour pattern tests – behaviour reproduction, behaviour anomaly, family member, surprise behaviour, sensitivity analysis, and system improvement. Because of space restraint, all validation tests performed cannot be reported. However, details about each of the validation tests conducted have been reported somewhere else (Oladokun, 2014; Motawa & Oladokun, 2015), which prove the credibility of the model results. Figures 10 to 14 therefore, show examples of behaviour reproduction test performed for end-uses household energy consumption (space heating, hot water, cooking, lighting, and appliances energy consumption).

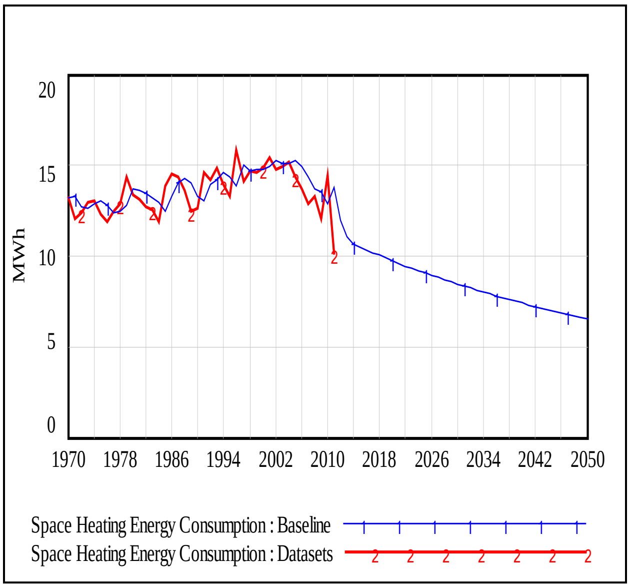

Figure 10. Space heating household energy

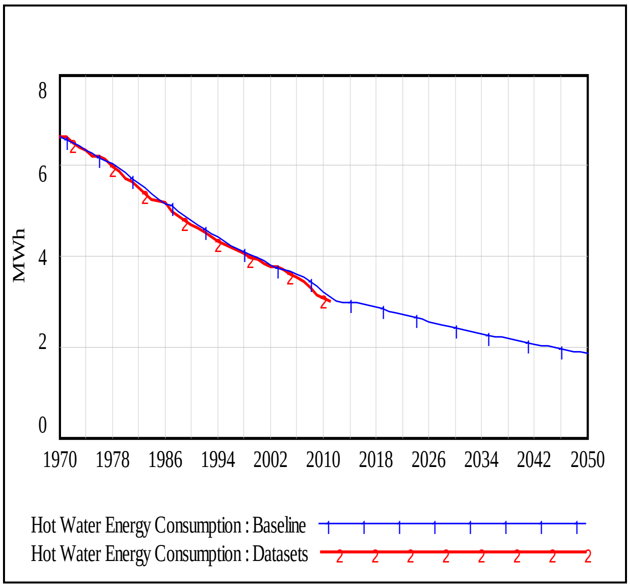

Figure 11. Hot water household energy

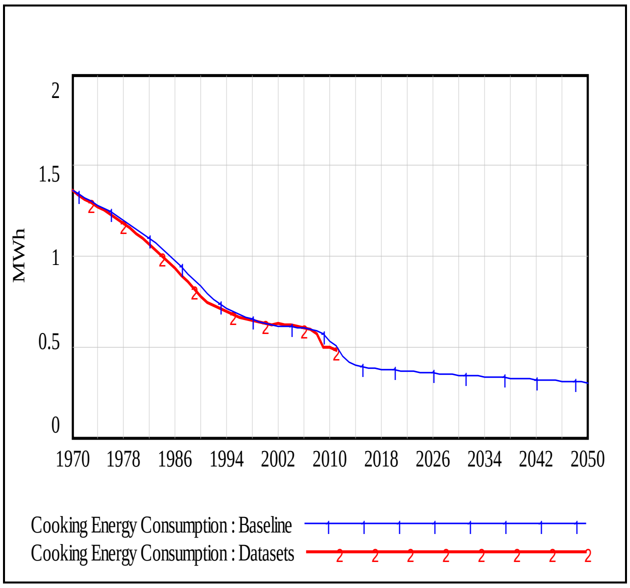

Figure 12. Cooking household energy

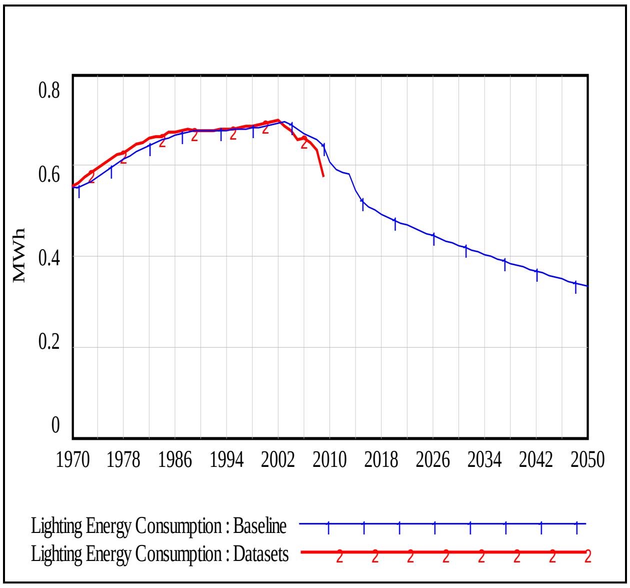

Figure 13. Lighting household energy

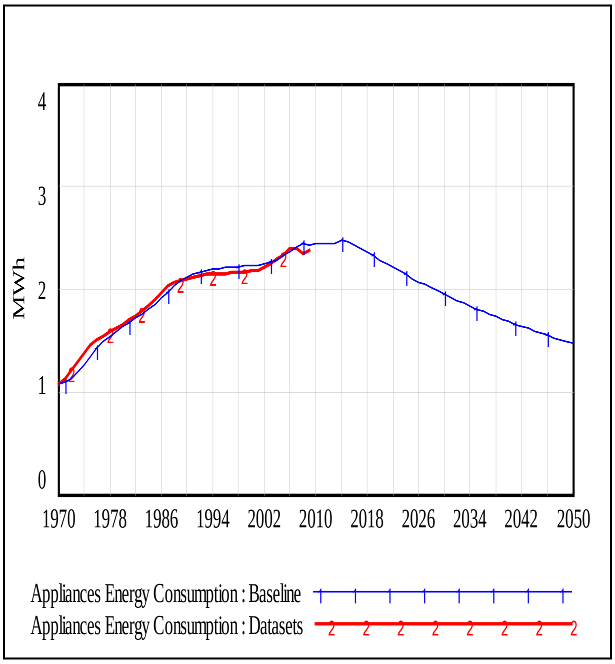

Figure 14. Appliances household energy

8.0 CONCLUSION

This paper has shown a SD model capable of simulating the HECCE in the UK. The paper presented the model built from the qualitative and quantitative data sources with input from energy experts and industry practitioners. The developed model showed the complex intrinsic interrelationships and interdependencies among the STS of occupants, dwellings, and environment. The originality of the research in this paper lies in the application of SD approach in showing the future trends of HECCE in the UK. This is in an attempt to meet the carbon emissions reductions targets of the UK government as enshrined in the Climate Change Act of 2008.

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